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Fertilizer Raw Material Resources of Africa

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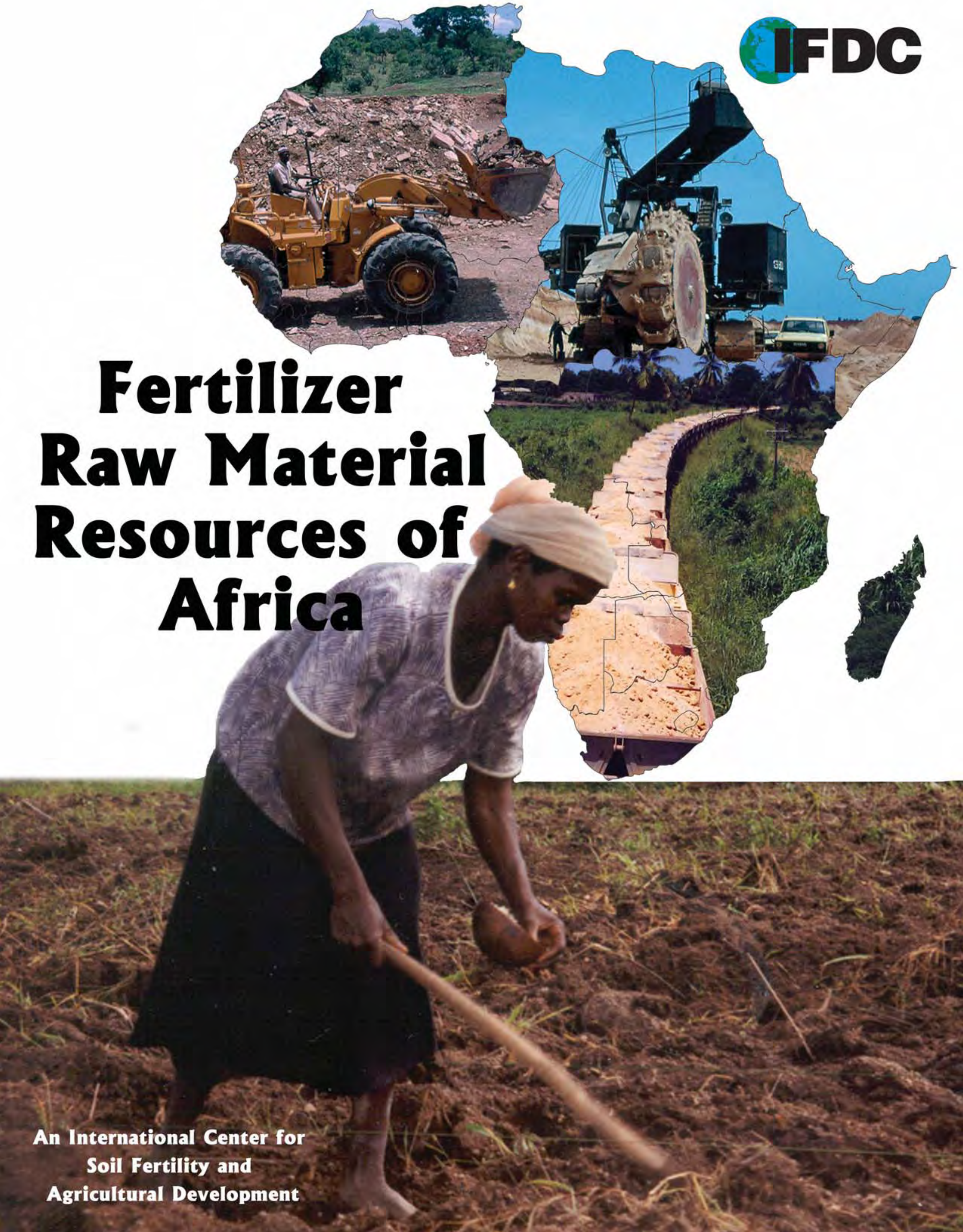

Fertilizer Raw Material Resources of Africa

An International Center for
Soil Fertility and
Agricultural Development

Fertilizer Raw Material Resources of Africa

by

Steven J. Van Kauwenbergh
Principal Scientist and Program Leader – Fertilizer Materials Program
Research and Market Development Division

An International Center for Soil Fertility
and Agricultural Development

P.O. Box 2040
Muscle Shoals, Alabama 35662, U.S.A.

www.ifdc.org

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IFDC—An International Center for Soil Fertility and Agricultural Development
P.O. Box 2040
Muscle Shoals, AL 35662 (U.S.A.)

Telephone: +1 (256) 381-6600
Telefax: +1 (256) 381-7408
E-Mail: general@ifdc.org
Web Site: www.ifdc.org

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Fertilizer Raw Material Resources of Africa

Foreword

African ministers of agriculture passed a resolution calling for the development of Africa's fertilizer industry in support of the Comprehensive Africa Agriculture Development Programme (CAADP) at FAO's 23rd Regional Conference for Africa in 2004 in Johannesburg, South Africa. That resolution helped catalyze the Africa Fertilizer Summit, held in Abuja, Nigeria, 9–13 June 2006.

The resolution noted that fertilizer use in sub-Saharan Africa is only about 9 kg/ha, compared with 150 kg/ha in the "Green Revolution" countries of East and Southeast Asia. Ironically, Africa possesses significant natural gas resources and exports large quantities of phosphates, while importing manufactured fertilizers at costs that small-scale farmers cannot afford.

The ministers recommended that the Secretariat of the New Partnership for Africa's Development (NEPAD) and IFDC give top priority to the development of Africa's fertilizer industry to make fertilizers more widely available, and affordable, for smallholder farmers. A viable and sustainable fertilizer industry depends largely on the availability of raw materials of suitable quality, and at reasonable cost.

In 2005, IFDC initiated a comprehensive study of raw material resources that could be used for increased local or regional fertilizer production in Africa, as well as a review of past and current production. The study resulted in this publication, Fertilizer Raw Material Resources of Africa by Steven J. Van Kauwenbergh, IFDC Principal Scientist.

This reference documents raw material resources for nitrogen fertilizer products (oil, natural gas, coal); phosphate fertilizers (phosphate rock); and potassium fertilizers (potash salts). It also documents potential sulfur resources, an essential raw material for many types of phosphate fertilizer production.

This publication is one of IFDC's contributions to meeting the CAADP objectives, and those of the Africa Fertilizer Summit.

Amit Roy
President and
Chief Executive Officer

Preface

In August 2005, I was called to a meeting with Dr. Amit H. Roy to discuss a new initiative, the Africa Fertilizer Summit. In order to meet CAADP objectives and in conjunction with the Summit, Dr. Roy requested that I develop a comprehensive IFDC reference document on the fertilizer raw material resources of Africa. Although IFDC and other organizations often focus primarily on sub-Saharan Africa, the scope of this document was to include all of Africa.

Due to the urgency and rather monumental nature of the task at hand, I surrendered my duties as Program Leader of the Fertilizer Materials Program during the course of September and October 2005, while performing initial literature searches and gathering information. It soon became apparent that the document could be much larger than the 100-200 pages originally envisioned. The Africa Fertilizer Summit was eventually set for June 2006. A draft of the document was provided to participants on a compact disk distributed at the Africa Fertilizer Summit, June 9-13, 2006, in Abuja, Nigeria.

During the initial stages of writing the document, it became obvious that significant background information was needed for any nonspecialist reading the document to understand the descriptions and analyses of the fertilizer raw material resources of individual countries and the potential for further use. Chapters I through IV provide this background information. Chapter I is devoted to an introduction to fertilizers, their importance, and an overview of the world fertilizer industry. Chapter II gives a rather comprehensive overview of how the most common fertilizers are manufactured. Chapter III outlines the origins of fertilizer raw materials; how they are produced; characteristics and quality factors; and production, resources, and reserves on a worldwide basis. Chapter IV is intended to give the reader an appreciation of the considerable analysis and study required in planning and implementing mining and fertilizer production projects, particularly in developing countries. While it was my objective to simplify and make these chapters as readable as possible, especially for those readers who are not technically oriented, these are highly complex subject areas. Hopefully there is also more than enough detail for the technically oriented reader.

The country descriptions give a general overview on each country and a brief description of the geology which determines the known and potential fertilizer raw material resources. A simplified geologic map is presented for each country with the general locations of individual deposits. Nitrogen, phosphate, potassium, and sulfur resources, when applicable to individual countries, are described in that order.

There are considerable differences in the length of individual country descriptions. Obviously, some countries are more endowed with fertilizer raw materials than others. The amount of information available on these resources in many countries varies considerably due to the state of development of various countries, remoteness of various regions, time period when investigations were carried out, degree of involvement of private versus government agencies and resulting generation and dissemination of written reports, effects of geopolitical conflicts, and other factors. Also, IFDC scientists have gathered more information on fertilizer raw materials in countries where IFDC has been actively involved in resource development projects and in the agricultural sector.

Much of the information presented in this volume was gathered over the course of a 22-year career at IFDC working with samples from hundreds of phosphate deposits around the globe and supervising research groups dealing with the processing of nitrogen, phosphate, potash, and other types of fertilizer. More specifically related to the development of this document, I have had the opportunity to participate in projects in 16 African countries and have worked with phosphate rock, sulfur, and limestone samples from over 40 deposits and 30 countries within Africa. This project was indeed an opportunity to bring all this information together under one cover. Hopefully the information in this publication will prove useful and will help potential investors, donors, and policymakers to make informed decisions concerning the development of fertilizer raw material resources within Africa.

Acknowledgments

Many individuals assisted in the production of this document and their contributions are gratefully acknowledged. I am grateful to Jean Riley, IFDC Librarian, who has gathered information over the course of many years and performed numerous literature searches for this project. Lynda Young coordinated the IFDC Word Processing Unit’s efforts. Janice Gautney, Jane Goss, Vickie Hollandsworth, and Carol Slaton typed the manuscript. Elijah Evans, IFDC Geographic Information Systems Specialist, provided geologic maps. Donna Venable and Lynda Young assembled the artwork and figures. Donna Venable designed and typeset the document.

Numerous chemical analyses and other types of analyses have been performed at IFDC over the years; IFDC staff, chemists, and laboratory technicians contributing in this area include Dr. Talaat Lawendy, Dr. E. Rick Austin, Bobby Biggers, Billy Biggers, Celia Calvo, Dr. Rex Clayton, Vanessa Keel, and Marilyn Williams.

Donald R. Waggoner, Consultant, and Lisa Thigpen, Editor, proofread initial drafts of the manuscript. Beth Roth assisted with the final proofreading. Jerry Cape, Mining Consultant, Florida (U.S.A.), read sections of the manuscript. Dr. Gert van de Linde, South Africa, proofed the South Africa section. I am grateful for their comments.

Dr. Thomas W. Crawford, Jr., Director of the IFDC Research and Market Development Division (RMDD), read sections of the document. Dr. Crawford also insulated me from the daily business of the RMDD and allowed me to focus on the work at hand.

Dr. Guerry McClellan, now with the University of Florida, was my first supervisor when I came to IFDC. I learned much of what I know about phosphate mineralogy and geology under his guidance. Similarly, much of what I know concerning the production of fertilizers was gleaned from the late James J. Schultz, former Director of the IFDC Outreach Division.

This document simply would not have become a reality without the vision, support, and encouragement of Dr. Amit H. Roy.

Acronyms and Abbreviations (Organizations)

AECI	African Explosives and Chemical Industries Limited
AFC	Abu Qir Fertilizers and Chemical Industries Company
AFD	Agence Française de Devéloppement
AGC	Agence de Gestion et de Cooperation entre la Guinee-Bissau et la Senegal
ALG	Autorité de Développement Intégré de la Région du Liptako Gourma
AOAC	Association of Official Analytical Chemists
APC	Arab Potash Company
API	American Petroleum Institute
BG	British Gas
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
BMZ	Bundesministerium für Wirtschaftliche Zusammenarbeit und Entwicklung
BP	British Petroleum
BRGM	Bureau de Recherches Géologiques et Minières
BRPM	Bureau de Recherches et Participations Minières (Morocco)
BUMIFOM	Bureau Minier de la France d'Outre-Mer
BUMIGEB	Bureau des Mines et de la Géologie du Burkina Faso
CAADP	Comprehensive Africa Agriculture Development Programme
CEA	Commissariat à l'Energie Atomique
CEDEAO	Communauté Economique des Etats de l'Afrique de l'Ouest
CEPI	Centre d'Etude pour la Promotion Industrielle
CFL	Coromandel Fertilizers Limited
CFM	Caminhos de Ferro de Mozambique
CGG	Compagnie Générale de Geophysique
CGMW	Commission for the Geologic Map of the World
CGSC	Calub Gas Share Company
Chemplex	Chemplex Corporation (Pvt.) Ltd.
CIDA	Canadian International Development Agency
CIL	Coal India Limited
CIM	Champion Industrial Minerals Inc.
CIRAD	Centre for International Cooperation in Agronomic Research and Development
CMDT	Compagnie Malienne pour le Développement des Textiles
CNPC	China National Petroleum Company
COFAN	Companhiá de Fosfatos de Angola
COGEMA	Compagnie Générale des Materiès Nucléaires
COTOMIB	Compagnie Togolaise des Mines du Bénin
CPG	Compagnie des Phosphate de Gafsa
CSPT	Compagnie Sénégalaise des Phosphates de Taiba
CVRD	Companhia Vale do Rio Doce
DAIMINA	Developing Agri-Inputs Market in Nigeria Project
DGM	Direction de la Géologie et des Mines
DGMG	Direction Générale des Mines et de la Géologie
DGSM	Department of Geological Survey and Mines
DNGM	Direction Nationale de la Géologie et des Mines
DRC	Democratic Republic of the Congo
EBIC	Egyptian Basic Industries Co.
ECOWAS	Economic Community of West African States
EDF	European Development Fund
EFC	Egyptian Fertilizer Company

EFIC	Egyptian Financial and Industrial Company
EGPC	Egyptian General Petroleum Corporation
EIA	Energy Information Administration
ELMICO	Ethio-Libyan Mining Company
ENMC	El Nasr Mining Company
ENMINSA	Empresa Nacional Minera del Sahara
ENPC	El Nasr Phosphate Company
EPA	Environmental Protection Agency
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
Ferphos	Enterprise Nationale de Fer et de Phosphate
FGN	Federal Government of Nigeria
FOSFANG	Fosfatos de Angola
FSU	Former Soviet Union
GCT	Groupe Chimique Tunisien
Gécamines	La Générales de Carvières et des Mines
GNPC	Ghana National Petroleum Corporation
GOB	Government of Burundi
GSN	Geological Survey of Nigeria
GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit
GUPCO	Gulf of Suez Petroleum Company
IBI	International Business Investments
ICRAF	International Center for Research in Agroforestry
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
ICS	Société des Industries Chimiques du Senegal
IEDC	International Energy Development Corporation
IEFC	Indo Egyptian Fertilizer Company
IFA	International Fertilizer Industry Association
IFAD	International Fund for Agricultural Development
IFC	International Finance Corporation
IFDC	An International Center for Soil Fertility and Agricultural Development
IFFCO	Indian Farmers Fertiliser Cooperative Ltd.
IFG-TG	International Fertilizer Group-Togo
IFREMER	Institut Français pour la Recherche en Mer
IMACID	Indo Maroc Phosphore
IMC	Egyptian General Executive Organization for Industrial and Mining Complexes
INRAN	National Institute of Agronomic Research
IOF	Indian Ocean Fertilizers
IPC	Iran Petrochemical Corporation
ISO	International Standards Organization
ISRIC	International Soil Reference and Information Centre
JCI	Japan Consulting Institute
JICA	Japan International Cooperation Agency
KIMA	Egyptian Company for Chemical Industries
KSRC	Kenya Superphosphate Research Company
MDEXCO	Mbeya Exploration Company

MEM	Ministry of Energy and Mines
MINEX	Mineral Exploration Department
MIPCO	Minjingu Phosphate Company
MMFL	Minjingu Mines and Fertilizer Ltd.
MOPCO	Misr Oil Processing Company
NAFCON	National Fertilizer Company of Nigeria Ltd.
NAMCOR	National Petroleum Corporation of Namibia
NCGC	North Carolina Ground Calcined
NCGF	New Consolidated Gold Fields
NCZ	Nitrogen Chemicals of Zambia
NDC	National Development Corporation
NEPAD	New Partnership for Africa’s Development
NMC	Nigerian Mining Corporation
NNPC	Nigerian National Petroleum Corporation
NOC	National Oil Corporation (Libya)
NOCK	National Oil Company of Kenya, Limited
OCP	Office Chérifien des Phosphates
OMNIS	Office de Mines Nationales et Industries Strategique
OMRG	Office Mauritanien de la Recherche Géologique
ONAREM	Office National des Ressources Minières
OPEC	Organization of Petroleum Exporting Countries
ORSTOM	Office de la Recherche Scientifique et Technique Outre Mer
OTP	Office Togolais des Phosphates
Petrangol	Fina Petroleos de Angola
PETRONAS	Petroliam Nasional Berhad (Malaysia)
PetroSA	Petroleum Oil and Gas Corporation
Petrosen	Société des Petroles du Senegal
PGS	Petroleum Geoservices
PMC	Palabora Mining Company Ltd.
PNC	Power Nuclear Corporation (Japanese)
RMDD	Research and Market Development Division
RMRDC	Raw Materials and Research and Development Council
Samandor	SA Manganese Simor Ltd.
SAMIA	Société Arabe des Industries Métallurgiques
SAR	Société Africaine de Raffinage
Senelec	Société Nationale d’Eléctricité du Sénégal
SIL	Saitake International
SMB	Société Minière du Benin
SNG	Société Niger Gypse
SNH	Société Nationale des Hydrocarbures
SNIM	Société Industrielle et Minière
SNPC	Société Nationale des Pétroles du Congo
SODEMI	Sociéte pour le Développement Minier de la Côte d’Ivoire
SOFREMINES	Société Française d’Etudes Minières
SOMIMO	Société Minière du Moyen-Ogoové
Sonangol	Sociedad Nacional de Combustiveis de Angola

SONAREM	Société Nationale de la Recherche et d'Exploitation (Mali)
SONAREM	Société Nationale de la Recherche Minière (Algeria)
SONICHAR	Société Nigériene de Charbon
SPDC	Shell Petroleum Development Company of Nigeria Ltd.
SSPT	Société Sénégalaise des Phosphates de Thiès
STAMICO	Tanzanian State Mining Corporation
TFC	Tanzania Fertilizer Company
TPDC	Tanzania Petroleum Development Corporation
TVA	Tennessee Valley Authority
U.S.A.	United States of America
UDC	Uganda Development Corporation
UGM	Uganda Gold Mining Ltd.
UN	United Nations
UNDP	United Nations Development Programme
UNIDO	United Nations Industrial Development Organization
UNRFNRE	United Nations Revolving Fund for Natural Resource Exploration
USAID	United States Agency for International Development
USBM	United States Bureau of Mines
USDA	United States Department of Agriculture
USGS	United States Geological Survey
USSR	Union of Soviet Socialist Republic
WAPCO	West Africa Gas Pipeline Company
WRECO	Western Rift Exploration Company
ZIMPHOS	Zimbabwe Phosphate Industriés Limited
ZPA	Zambia Privatization Agency

Acronyms and Abbreviations (Other)

Al	aluminum
AN	Ammonium nitrate
APS	Ammonium phosphate sulfate
AS	Ammonium sulfate
As	Arsenic
BCOG	Break-even cutoff grade
bpd	Barrels per day
BPL	Bone phosphate of lime
BPR	Busumbu phosphate rock
bpy	Barrels per year
Btu	British thermal unit
Ca	calcium
CAN	Calcium ammonium nitrate
Cd	Cadmium
cm	Centimeter
Cr	Chromium
Cu	Copper
DAP	Diammonium phosphate
EPC	Exploration and Production Concession
ESPC	Exploration and Production Contract
F	Fluorine
f.o.b.	Free on board
Fe	Iron
FEED	Front-end engineering design
FPSO	Floating production, storage, and offloading (vessel)
ft^3	Cubic feet
g	Gram
Gcal	Gigacalorie
h	Hour
ha	Hectare
Hg	Mercury
IRR	Internal rate of return
JV	Joint venture
K	Potassium
kcal	Kilocalorie
KCl	Potassium chloride
kg	Kilogram
km	Kilometer
km^2	Square kilometer
L	Liter
LHD	Load-haul-dump
LNG	Liquefied natural gas
LOI	Loss on ignition
LPG	Liquefied petroleum gas

µm	Micron, micrometer
m	Meter
m^2	Square meter
m^3	Cubic meter
Ma	Million years before present
MAP	Monoammonium phosphate
MCP	Monocalcium phosphate
Mg	Magnesium
mg	Milligram
min	Minute
mL	Milliliter
mm	Millimeter
MMBtu	One million British thermal units (Btu)
MMcal	One million calores
MOU	Memorandum of Understanding
MW	Megawatt
N	Nitrogen
Na	Sodium
NAC	Neutral ammonium citrate
ND	Not detected or not determined
NPK	Nitrogen, phosphorus, and potassium
NPV	Net present value
P	Phosphorus
PAPR	Partially acidulated phosphate rock
Pb	Lead
ppm	Parts per million
PR	Phosphate rock
PSA	Production-sharing agreement
PSC	Production sharing contract
Ra	Radium
RAE	Relative agronomic effectiveness
REE	Rare earth elements
Rn	Radon
ROI	Return on investment
ROM	Run-of-mine
ROP	Run-of-pile
s	Second
S	Sulfur
Se	Selenium
SEM	Scanning electron microscope
SSP	Single superphosphate
Th	Thorium
tpd	Tons per day
tph	Tons per hour
TPR	Tilemsi phosphate rock
tpy	Tons per year

TSP	Triple superphosphate
U	Uranium
UAN	Urea-ammonium nitrate
URPAC	Upper Ruvubu Plutonic Alkaline Complex (Burundi)
V	Vanadium
VCR	Value-cost ratio
WPA	Wet-process phosphoric acid
XRD	X-ray diffraction
XRF	X-ray fluorescence
Zn	Zinc

Table of Contents

Fertilizer Raw Material Resources of Africa

CHAPTER I.
INTRODUCTION TO FERTILIZERS AND THE FERTILIZER INDUSTRY

For centuries, farmers have realized the need to maintain soil fertility to sustain or improve crop yields. By accident or by trial and error, it was found that applications of various organic wastes or naturally occurring mineral substances, such as manure, compost, fish remains, ashes, saltpeter, and other materials, would sometimes increase crop yields or apparently restore the fertility of the land.

The history of the production and use of inorganic fertilizer can be traced back to the nineteenth century when Justus von Liebig established the theoretical foundations of agricultural science and when John Bennett Lawes began producing fertilizers containing phosphorus (Smil, 1997). As the science of chemistry progressed and more and more chemical elements were discovered, the relative importance of various elements for plant growth and yield was identified. The German scientist Liebig recognized the value of elements derived from the soil in plant nutrition and correctly deduced the necessity of replacing those elements in the soil to maintain soil fertility. Liebig is usually credited with initiating the fertilizer industry. In 1840 Liebig published a recommendation that pulverized animal bones be treated with sulfuric acid to make the phosphate more readily available to plants. This practice was accepted, and production of fertilizers by chemical processing began in the 1840s.

Fertilizers provide plants with nutrients needed for growth and development. Plants grow and reproduce by utilizing nutrients, water, and carbon dioxide from the air, and energy from the sun. While carbon, hydrogen, and oxygen, which collectively make up 90%–95% of the dry matter of all plants, are provided by the atmosphere, other essential nutrients are derived from the soil. These nutrients are classified as primary nutrients (nitrogen, phosphorus, and potassium) and secondary nutrients (calcium, magnesium, and sulfur). Plants also need micronutrients (boron, chlorine, copper, iron, manganese, molybdenum, and zinc) in much smaller amounts.

Nutrients taken up by crops must be replenished to maintain soil fertility and productivity and prevent land degradation. The use of fertilizer to replenish these nutrients results in many benefits to man and the environment, including:

- Increased agricultural outputs (mainly food and fiber).
- Increased water-holding capacity.
- Biological nitrogen fixation.
- Improved soil erosion control.
- Less extensive land use.
- Reserving lands marginally suitable for agriculture for other uses.

Commercial fertilizers usually contain at least one of the primary plant nutrients in a form that is assimilable or “available” to plants. This includes compounds that are water soluble or soluble in special solutions that are used to estimate availability to plants such as citric acid, neutral ammonium citrate, or alkaline ammonium citrate. With nitrogen fertilizers, slow release may be very desirable from an environmental and efficiency standpoint.

Fertilizer products are customarily designated by a series of numbers to express the grade of the fertilizer product. Each of the numbers indicates the amount of a nutrient contained in the fertilizer product. This number includes only the amount of nutrient present in a form that is available for plant nutrition. The content of each nutrient is the guaranteed minimum rather than actual amount, which is usually slightly higher. Three numbers are usually used when expressing the grade of a fertilizer product. These numbers always refer in order to the content of the primary nutrients: nitrogen, phosphorus, and potassium. If any other nutrient is present, an additional number is given, followed by the chemical symbol of the nutrient it represents. Most countries indicate the content of phosphorus and potassium in oxide forms, P_2O_5 and K_2O. Therefore, a fertilizer product with a grade of 12-6-22-2MgO is guaranteed by the manufacturer to contain a minimum of 12% N, 6% P_2O_5, 22% K_2O, and 2% MgO. Some common fertilizers and common grades are given in the following table.

Diammonium phosphate (DAP)	18-46-0
Monoammonium phosphate (MAP)	10-50-0
Potassium chloride (KCl)	0-0-60
Single superphosphate (SSP)	0-18-0
Triple superphosphate (TSP)	0-46-0
Urea	46-0-0
Ammonium nitrate (AN)	34-0-0

Fertilizer is an integral part of the technological trinity—seed, water, and fertilizer—responsible for bringing about the “Green Revolution” that helped many countries, including India, China, and Indonesia, avert predicted disasters and achieve food self-sufficiency in a short span of 20–25 years. Since the 1960s, global cereal production has more than doubled, increasing from 877 million tons[1] in 1961 to nearly 2,300 million tons in 2004, with developing countries accounting for nearly 70% of the increase (Figure I.1). It is estimated that fertilizers accounted for 56% of the rise in average yields per hectare and about 30% of the total increase in production. Cereal production closely parallels fertilizer use in developing countries (Figure I.2).

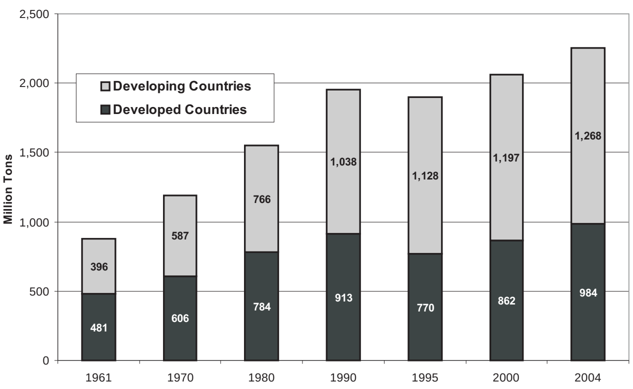

Figure I.1. Cereal Production in Developed and Developing Countries, 1961–2004

Growth in the future demand for food will be influenced mainly by growth in population, income levels and economic development, and changes in the food preferences of consumers. Projections of medium population growth indicate that during the next 20 years approximately 75 million people will be added to the world’s population each year, increasing the population from about 6.2 billion in 2005 to over 8 billion by 2025. A significant amount of this increase will probably occur in the cities of the developing world, which will account for most of the increased demand for food, including meat products that require significant amounts of grain to feed livestock and poultry. Increased demand will require farmers worldwide to produce 50% more cereals in 2025 (Roy, 2003).

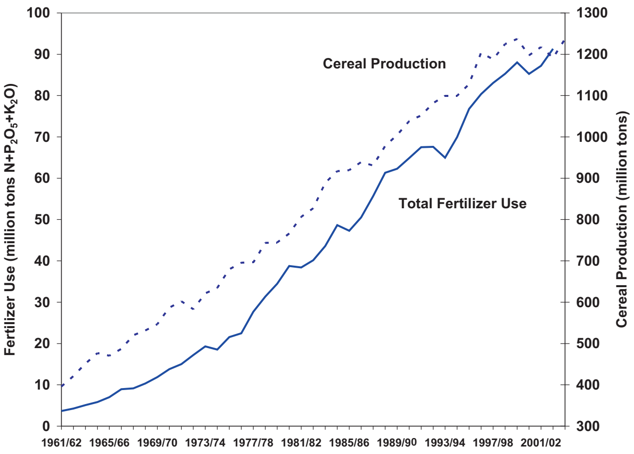

Figure I.2. Developing Countries: Total Cereal Production and Total Fertilizer Use, 1961/62–2002/03

Due to the need to preserve the forests and wildlife habitat, much of the increase in cereal production will have to come from the existing land under cultivation. This can be achieved only through increasing crop yields. Historically the use of fertilizer has been very successful in increasing yields while limiting land use (Figure I.3). Increased

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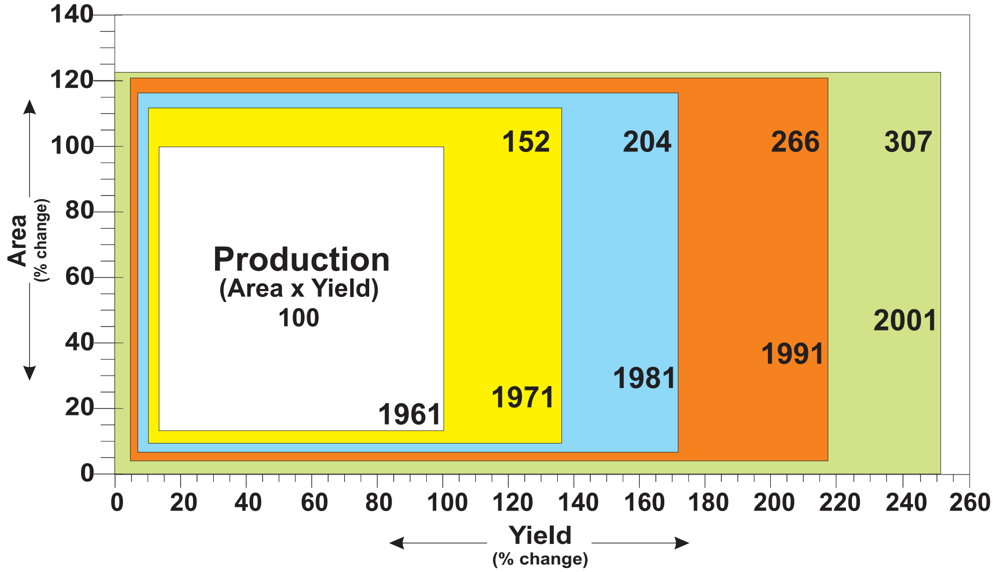
[1] All tons in this paper are metric tons.



Source: Derived from FAOSTAT data, FAO Statistical Database, December 6, 2005 <http://FAOSTAT.fao.org>

Figure I.3. Land Use Versus Cereal Production in Developing Countries, 1961–2001

fertilizer use has to be balanced against the environmental and human health concerns stemming from intensive agriculture, particularly in environmentally sensitive areas.

Prior to the middle of the twentieth century, natural organic materials, natural minerals, and various chemical byproducts represented a large proportion of the total world fertilizer supply. Dependence shifted almost entirely to synthesized or chemically processed materials after the 1950s. Increasing populations, increased farm acreage, and improved crop varieties fueled the need for high-analysis fertilizers. Systems using natural products simply could not provide the volumes of nutrients needed to meet the demand or match the efficiency of other aspects of production agriculture. World agriculture rapidly embraced the use of chemical fertilizers. As Parish (1993) concluded, after 30 to 40 years of growth in the use of chemical fertilizers, the elimination or even the reduction of fertilizer use in developing countries would result not only in the starvation and malnutrition of millions but also in increased degradation of the environment through deforestation, soil erosion, and desertification.

Today the scientific aspects of fertilizer use involve many disciplines, tens of thousands of individuals, and numerous organizations worldwide. The development and introduction of “high-yielding” varieties of wheat, rice, and other plants required more nutrients and improved fertilizers. Worldwide, many organizations and companies have carried out extensive research and development on improving fertilizer production, developing new products, and increasing efficiency of usage. Some of the most notable among these organizations include the U.S. Department of Agriculture (USDA), the Tennessee Valley Authority (TVA), IFDC, and the Rothamsted Experiment Station in England.

The world fertilizer industry can be characterized as a large-volume producer, which has developed in response to global demand. Figure I.4 shows the yearly global consumption of primary plant nutrients (N, P_2O_5, and K_2O) from 1970/71 to 2002/03. For 2002/03 the total world consumption of N, P_2O_5, and K_2O was 152.5 million tons (as nutrients). China, the United States, and India consumed 39.6 million tons, 19.3 million tons, and 16.1 million tons, respectively; collectively, these three countries accounted for about 50% of the world consumption. At an assumed average nutrient content of 40%, some 358 million tons of fertilizers was produced and handled by the industry during 2002/03.

The structure of the world fertilizer industry has evolved over time. The industry includes large-

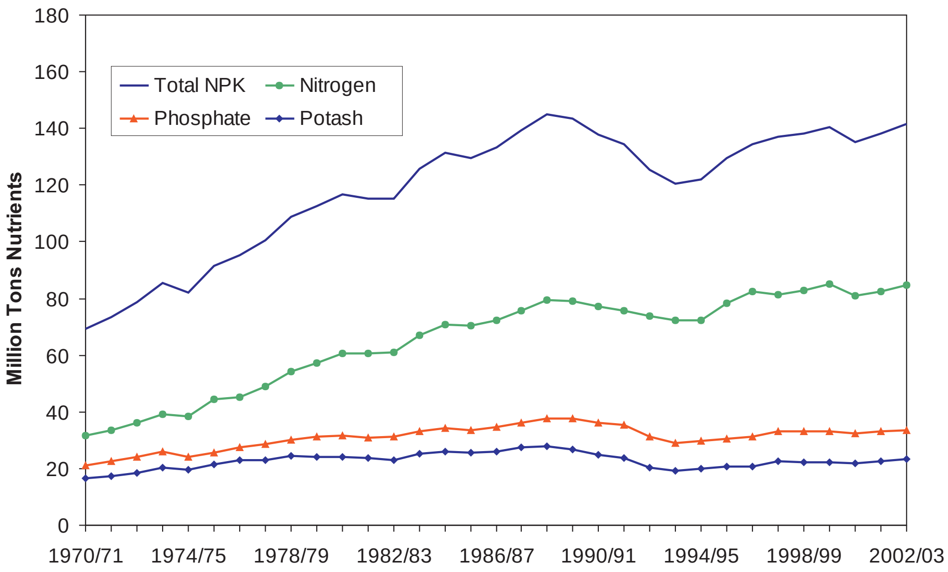


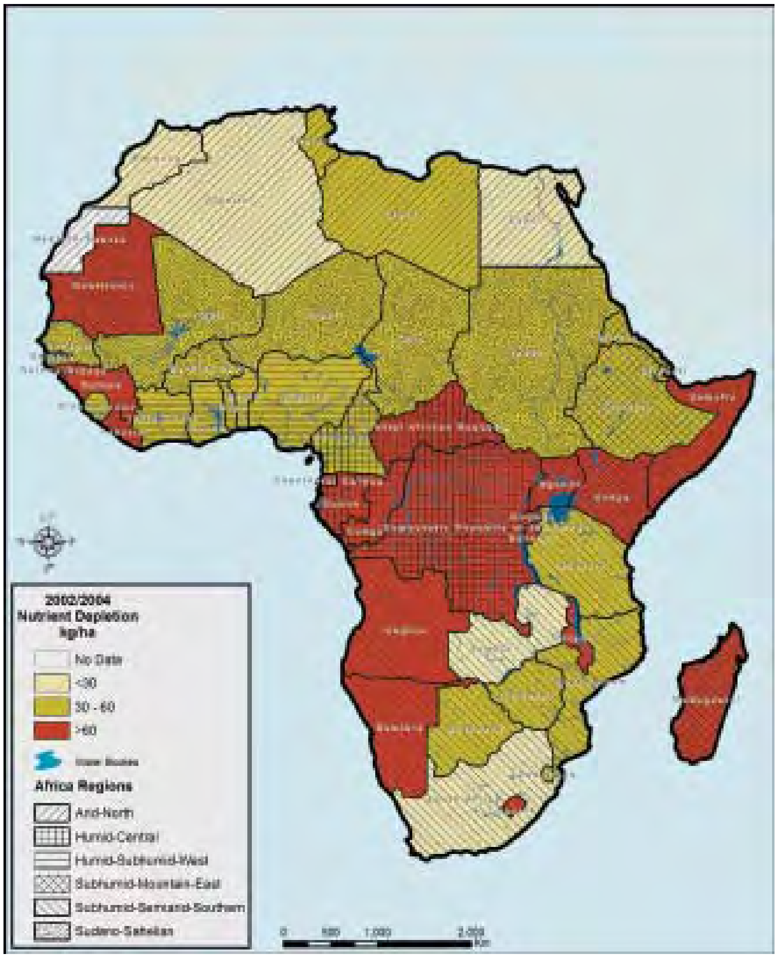
Figure I.4. World: Nitrogen, Phosphate, Potash, and Total NPK Consumption, 1970/71–2002/03

scale “basic producers,” which typically concentrate on producing large amounts of single-nutrient or high-analysis fertilizer products, usually at locations near raw material sources such as phosphate rock or natural gas. Other components of the industry are located closer to distribution points or farmers to provide fertilizer or to perform various secondary processing operations, such as granulation, blending, or conversion to fluids, and then to distribute the materials to farmers. The fertilizer industry has become very sophisticated in both the manufacture of fertilizers and environmental control. Procuring and handling of raw materials and the distribution and marketing of products involve the latest technology.

In the future, the only certainty is that the fertilizer industry will continue to evolve as sources of raw materials change, as processes change and/or are refined, and in response to consumers’ needs. Considering projected world population growth, the demand for fertilizers can only increase.

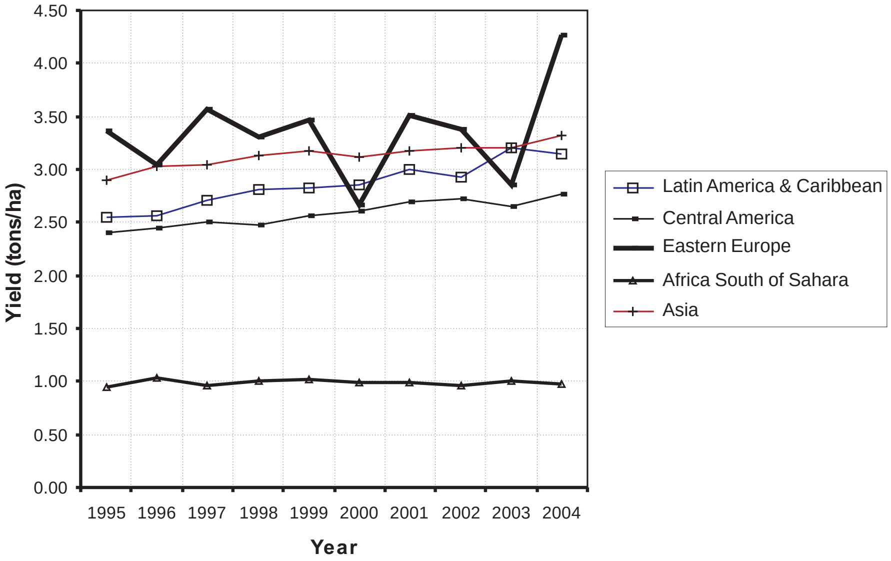
Fertilizer use is of critical importance in Africa, where the soils are suffering serious levels of nutrient depletion (Figure I.5). As a consequence of natural factors, population pressure, and lack of replenishment of the nutrients in the soil, cereal yields in sub-Saharan Africa are among the lowest in the world (Figure I.6). Fertilizer use must increase in Africa if yields are to be increased, or even maintained.

Africa is endowed with many natural resources. Among these resources are deposits of phosphate rock (Figure I.7), accumulations of hydrocarbons and deposits of coal that can be used to produce nitrogen, and potash deposits (Figure I.8). Data from the United States Geological Survey (USGS) indicate that six countries in Africa control approximately 41.5% of the world’s currently producible phosphate rock reserves and approximately 50.2% of the total global phosphate rock reserve base that may be producible in the future. Data in the Morocco section of this volume indicate that Morocco may possess substantially more resources than the USGS data would indicate. Development of indigenous fertilizer raw material resources and the establishment of local or regional fertilizer production facilities are alternatives to supply the nutrients that African farmers must have to feed growing populations.



Source: Henao and Baanante (2006).

Figure I.5. Nutrient Depletion in Africa



Source: Henao and Baanante (2006).

Figure I.6. Yields of Cereals in Selected Developing Regions

Figure I.7. Significant Phosphate Rock Deposits of Africa

Figure I.8. Significant Potential Nitrogen and Potash Resources of Africa

CHAPTER II.
OVERVIEW OF FERTILIZER PRODUCTION ALTERNATIVES

Nitrogen Fertilizers

The production of nitrogen fertilizers is a highly technical and capital-intensive endeavor. The only naturally occurring sources of nitrogen for agriculture are various manures, guanos, and the nitrates found in the Atacama Desert of Chile. These sources can supply only a small portion of the world's nitrogen needs.

Ammonia

Ammonia is the basic building block of the world nitrogen industry. Although significant quantities of ammonia are directly applied to the soil as fertilizer in some countries, on a worldwide basis, ammonia is generally processed into a variety of liquid and dry fertilizer products before application to the soil. The main downstream products include urea, ammonium nitrate, liquid urea ammonium nitrate (UAN), ammonium sulfate (AS), ammonium phosphates, and ammonium polyphosphate as a liquid.

Ammonia is a colorless gas at ambient pressure and temperature, and it is lighter than air. It is a strong alkali and has a powerful corrosive effect on human tissue. For storage at sea-level atmospheric pressure, ammonia must be cooled to –33ºC. In the usual temperature range of 0º–40ºC, the range of vapor pressure is about 4–15 atmospheres; without refrigeration, ammonia must be stored in pressure vessels.

Almost all ammonia is produced in the anhydrous form (free of water) by catalytic reaction, under high temperature and pressure, between atmospheric nitrogen and hydrogen from a hydrocarbon source. Air is directly or indirectly the source of nitrogen in all processes. The process used is mainly determined by the hydrocarbon source.

Two-step steam reforming is used to generate hydrogen feeds from natural gas, naphtha, and light gasoline fractions. The most common feedstock is natural gas, which is primarily methane. Steam reforming is the least expensive and most popular method of producing hydrogen for ammonia synthesis. The first step in the process is desulfurization of the hydrocarbon feedstock because the reforming catalysts are highly sensitive to sulfur poisoning. The desulfurized feed is fed to a primary reformer where it is reacted with steam. The gases pass to a secondary reformer where air is introduced to produce raw synthesis gas with a 3:1 hydrogen/nitrogen mole ratio. Methane in the gas is reduced to a very low value in this step.

Partial oxidation processes are used to produce synthesis gas from coke-oven gas, crude oils, and coals. The hydrogen sources are partially oxidized in a converter/gasifier. Some processes use a catalyst, but most do not.

Hydrogen-rich refinery gases or coke-oven off-gases can be used as feedstock. Synthesis gas for ammonia production can be produced from coke by a water-gas reaction. A few plants may still produce hydrogen for small-volume production by electrolysis of water.

Whatever the source, raw synthesis gas must be purified before ammonia synthesis. The shift conversion step removes most of the carbon monoxide from the synthesis gas and produces more hydrogen. Synthesis gas with steam is passed over catalysts in two steps to convert carbon monoxide and water to carbon dioxide and hydrogen. The synthesis gas is then scrubbed with solutions to remove most of the carbon dioxide. The gas is further treated by a variety of methods to remove residual quantities of carbon monoxide and carbon dioxide. The purified synthesis gas is compressed and sent to the converter where the contained hydrogen and nitrogen combine into ammonia over a catalyst at high temperature and pressure. A wide variety of ammonia synthesis designs are available and are described in the literature.

As a result of many developments in process technology, large 1,500- to 2,000-tpd ammonia plants based on natural gas are the industry standard. Single plants as large as 2,200 tpd are operating, and a 3,000-tpd plant was under construction with startup scheduled in 2006. Over the last 30 years, numerous improvements have been made in energy efficiency, recovery, computer control, mechanical equipment, designs and construction, and catalysts.

Urea

Urea (46% N) is produced from ammonia and CO_2, a byproduct of ammonia production, and all urea plants are located adjacent to or very close to an ammonia plant. On a worldwide basis, urea is the most popular solid nitrogen fertilizer. Most of the world production is in a solid form (prills or granular) although a growing volume is used for liquid fertilizers.

Ammonia and carbon dioxide are fed to a high-pressure reactor where they react to form urea (NH_2CONH_2), water, and ammonium carbamate (NH_2COONH_4). The reactions are reversible and do not go to completion. Output from the reactor includes unreacted ammonia, ammonium carbamate, and carbon dioxide. Production processes are classified according to how the unreacted ammonia, ammonium carbamate, and carbon dioxide are utilized.

In a once-through process, unreacted ammonia and ammonia recovered from ammonium carbamate decomposition are used as feed in the production of other nitrogen products such as ammonium nitrate. Typically, the manufacture of small amounts of urea by a once-through process is integrated with UAN solution plants.

In a partial-recovery process, excess ammonia and a part of the unreacted ammonium carbamate are recovered and recycled to the reactor. The remaining unconverted ammonium carbamate is decomposed to ammonia and carbon dioxide, and the ammonia is used in the manufacture of other nitrogen products.

The vast majority of the world's solid urea capacity is based on total recycle process variations. Excess ammonia feed is recovered and recycled to the reactor. Ammonia and carbon dioxide released from ammonium carbamate decomposition are recovered in carbamate absorbers and recycled to the reactor as an ammonium carbamate solution. Process variations use different feed ratios, methods of ammonium carbamate decomposition and recovery, and operating conditions.

The resulting aqueous urea liquor is evaporated to an essentially anhydrous melt and converted to a solid by prilling, granulation, or crystallization. In prilling, anhydrous melt is sprayed at the top of a tower. The falling droplets air cool to form prills. The size of the prills is a function of the spray equipment, pumping rate, tower height, and air temperature. When larger urea particles are desired, granulation is the next option. Several urea-granulation processes have been developed. Larger urea particles are needed for size compatibility in bulk-blended products.

Crystallization of urea from urea solution yields a product with minimum biuret content. Crystallized urea is not generally used for fertilizer.

Solid urea products are usually conditioned to reduce consolidation or caking in storage. The urea may be coated with anticaking agents such as clays, or various additives may be added in the melts prior to granulation or prilling.

Urea in water solution from the synthesis unit may be used in liquid fertilizer. The most popular use is to make UAN solutions.

Ammonium Nitrate

Ammonium nitrate (NH_4NO_3) is derived from the reaction between ammonia and nitric acid. Half of the nitrogen (33.5%–34.0%) is in the nitrate form (which is readily assimilated by plants), and half is in the ammonia form. Similar to urea, AN can be produced as prills or granular material. Ammonium nitrate plants are generally associated with ammonia plants although the ammonia may be purchased. Some of the ammonia is used to produce nitric acid by oxidizing the ammonia over a catalyst. The nitric acid is subsequently used to react with ammonia to produce ammonium nitrate solution. The heat of reaction between the ammonia and nitric acid is sufficient to partly concentrate the ammonium nitrate solution. Finally, the solution must be concentrated to various levels (over 90%) depending on the final product desired (granular, low-density prills, or high-density prills).

Calcium ammonium nitrate (CAN) can be produced using ammonium nitrate and calcium carbonate. Ammonium nitrate sulfate products can be manufactured by ammoniating mixtures of nitric and sulfuric acid.

Ammonium Sulfate

Ammonium sulfate (NH_3SO_4) is valued as an important source of nutrient sulfur as well as nitrogen; it contains 24% S and 21% N. It can be produced as a primary product from the direct reaction between ammonia and sulfuric acid. However, most world production is recovered as byproduct or coproduct from (1) organic monomer synthesis (principally caprolactam generated during nylon production), (2) the stripping of sulfur from stack gases at coke ovens, (3) some metallurgical operations, and (4) coal gasification and/or electrical generation plants. Almost all byproduct AS is used as fertilizer.

Nitrogen Solutions

Nitrogen solutions are generally composed of water, ammonia, urea, and ammonium nitrate or mixtures of these materials. They are often produced from off-specification material within industrial complexes. Some nitrogen solutions are also produced by blending urea solutions and AN solutions to form UAN solutions.

Phosphate Fertilizers

At the present time, nearly all phosphate fertilizers are manufactured from naturally occurring phosphorus-containing minerals. Bone meal, guano, and other natural organic phosphate sources are of only minor commercial importance today because of the higher cost per unit of nutrient. Also, the potential supply is only a tiny fraction of the amount of the raw material needed to produce the quantity of fertilizers used in world agriculture.

Some phosphate rocks may be suitable for direct application. However, the phosphorus content of most phosphate rocks, in the form of the mineral apatite, is not readily available to plants. In order to convert the phosphorus to water-soluble or plant-available forms, various methods are used to process phosphate rock. The most important methods are described in the following sections. Figure II.1 illustrates the general relationship between phosphate rock and the various fertilizers.

Direct-Application Phosphate Rock

Ground phosphate rock is not classified as a fertilizer in many countries and is not included in fertilizer consumption statistics reported in most countries. Considerable differences of opinion exist

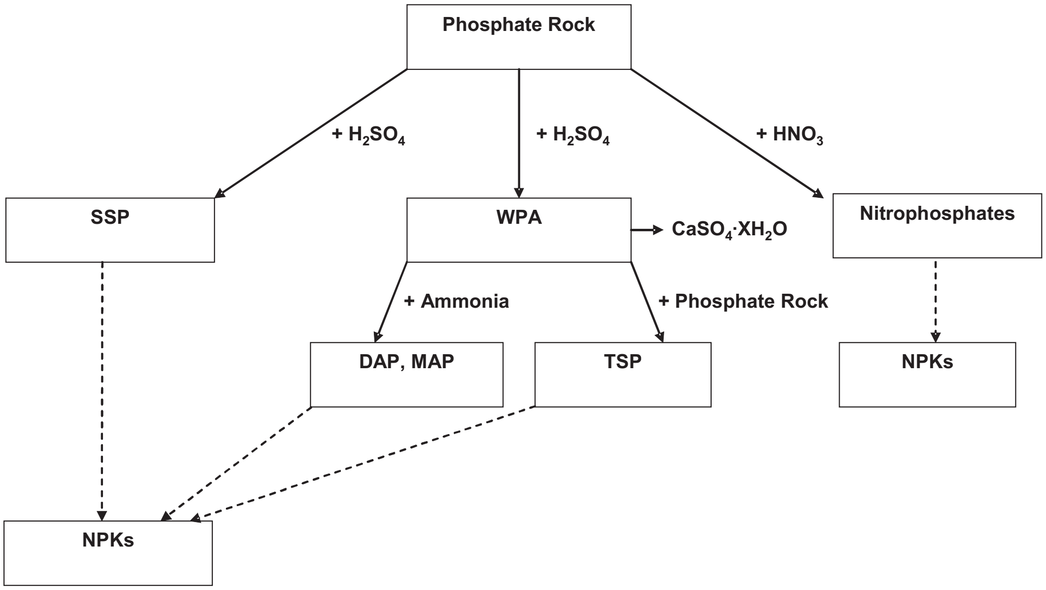


Figure II.1. Relationship of Phosphate Rock and Phosphate Fertilizers

as to the merits of ground phosphate rock as a fertilizer. In many cases, industry or government authorities have promoted its use. The main purpose of such a policy is to enable less costly sources of phosphate to be brought into use. This is often perceived as a desirable alternative in countries with reserves of phosphate rock but with inadequate financial resources to invest in the development of industrial production of phosphoric acid, TSP, and ammonium phosphates, or where sufficient markets for these fertilizers do not exist.

The following are some of the factors that contribute to the difficulty of making an impartial appraisal of the merits of direct application of ground phosphate rock:

1. Phosphate rocks vary widely in their reactivity; hence, their agronomic value varies.
2. The agronomic response to phosphate rock strongly depends on the type of soil and crop and climatic factors.
3. The response depends on timing, method of application, and particle size.
4. The residual value of a single application or the cumulative value of repeated applications is important with all phosphate fertilizers, but this is not easily evaluated. Ground phosphate rock often has a more favorable long-term than short-term effect.
5. Agronomic and economic studies of long-term use on food crops are not extensive.

The principal potential advantage of ground phosphate rock is its low cost. There are other potential advantages as well:

1. A relatively low capital investment is required for processing.
2. Advanced technical skills for mining and processing may not be required.
3. The energy requirements for processing are lower.
4. There are fewer losses during processing.
5. Rocks unsuitable for chemical processing are, in some cases, suitable for direct application.
6. Rock-grinding facilities can be established in a short time period.
7. Ground phosphate rock has a liming value on acid soils.

The main disadvantages are uncertainty as to agroeconomic value, inconvenience of handling and applying the fine, dusty material, and relatively low P_2O_5 content compared with TSP or ammonium phosphates.

It is generally agreed that ground phosphate rock is effective only on acid soils (pH 6 or less). Phosphate rocks are also more effective in warmer climates, in moist soils, and on crops that have fairly long-term growing patterns.

Phosphate rock should be finely ground when used as a direct-application fertilizer. However, there is some difference of opinion as to the usefulness of very fine grinding. The majority opinion seems to be that there is little to be gained by grinding to a finer size than about 90% through 100-mesh (0.147 mm), although there are some who claim that very fine grinding such as 80% through 320-mesh (0.043 mm) is worthwhile.

Ground rock that has been granulated after grinding has given rather poor first-crop results even when the granules disintegrate in the soil, presumably because granulation reduces the area of contact with the soil. However, in most of the tests, the granules were in the 1- to 4-mm range.

Phosphate rock that consists mainly of hydrated aluminum phosphate minerals may be useful for direct application after being calcined at a controlled temperature. The calcining may be done in a rotary kiln or in a fluidized bed calciner. By removing the combined water, calcining enhances the grade and destroys the crystallinity of the phosphate minerals, thereby improving the reactivity of the phosphate.

At present, only two aluminum phosphate rocks are known to be used for direct application after calcining. One of these occurs in Senegal near Thies. The ore, as mined, contains about 29% P_2O_5 on a dry basis; after calcination it contains over 34% P_2O_5. After calcination, the ore is ground to about 95% minus 100-mesh and marketed for direct application under the trade name “Phos-Pal.” About 75% of the P_2O_5 is soluble in alkaline ammonium citrate.

Single Superphosphate

SSP, also called simple, ordinary, or normal superphosphate, is the simplest and oldest of manufactured phosphate fertilizers. Ground phosphate rock is treated with sulfuric acid in a comparatively simple plant to produce a product usually containing about 18% P_2O_5. Most of the phosphate is converted to a water-soluble form. If phosphate rock below about 32% P_2O_5 is used, the total P_2O_5 content will be correspondingly lower. SSP can be used for direct application, bulk blending, or in the production of mixed fertilizers. If the product is to be used for bulk blending, it should be granulated. For use in the production of granular fertilizers, run-of-pile (ROP), or nongranular, material is preferred.

The main equipment used to produce SSP usually consists of a mixer, a den to allow the mixture to set and, if granulation is used, some suitable type of equipment for granulation with steam or water. The dens can be either batch type or continuous, which employs an enclosed conveyor-type den system.

Although SSP is a relatively low-analysis fertilizer, it is an excellent source of phosphate and also contains sulfur, an important secondary nutrient. SSP is often used as a primary component in the preparation of NPK fertilizers and is particularly well suited for use in the granulation of NPK fertilizers. SSP has steadily declined in importance, having dropped far behind high-analysis ammonium phosphates and TSP in world production. The steady decline in the use of SSP is primarily due to the comparative cost disadvantage of shipping low-analysis phosphate fertilizers. In some parts of the world (India and Brazil), it is still an important product.

SSP, because of its low analysis, is usually manufactured in small plants near the point of use. Investment in plant facilities and operating costs are relatively low. Production by either the batch or continuous processes is relatively simple. A typical SSP plant will have a mixer where the dry phosphate rock and usually 70% sulfuric acid are mixed. Then the pasty mixture falls onto a conveyor or into a den where the mixture sets into a friable, porous, solid mass that can be readily disintegrated by a mechanical cutter at the end of the den. Fluorine, evolved from the acid/rock reaction, is captured by wet scrubbing of the off-gases. The “green” superphosphate is usually stored in piles for a few weeks to cure and to allow the reaction to go to completion before shipment or use. The finished product is referred to as ROP-SSP.

In a slight variation of the SSP process, which is seldom used, the SSP is made in a granular form. The only difference is the physical appearance of the granular product. Its chemical characteristics are the same as ROP-SSP.

At the present time, sulfuric acid used for fertilizer production is usually guaranteed to be almost free of impurities. As noted by the United Nations Industrial Development Organization (UNIDO) in a discussion of process technologies, elemental sulfur used as raw material in the contact process to produce sulfuric acid is 99.5% pure and free of arsenic, chloride, and fluoride (UNIDO, 1978). If sulfuric acid from zinc or lead sulfide smelting is used for manufacturing SSP or other fertilizers, there is a potential of incorporating heavy metal and other impurities in the process.

Wet-Process Phosphoric Acid

Wet-process phosphoric acid (WPA) became important in fertilizer production in the early 1950s when TSP containing 46% P_2O_5 was established as an effective, economical, high-analysis fertilizer. WPA is usually produced in large complexes often near the phosphate rock deposits. A large part of the acid is used near the sites of rock production to produce nongranular and granular TSP and granular ammonium phosphates. However, substantial amounts of WPA are shipped to local and distant plants around the world.

Uncalcined phosphate rock is ordinarily used for WPA manufacture. Since calcination upgrades the rock and removes organic and carbonate impurities, calcined rock is sometimes used when a clear and green acid is desired for making liquid fertilizers.

The ground phosphate rock is reacted (digested) as a slurry with sulfuric acid in multiple-reaction tanks or in a compartmented single tank. Retention time in the digester ranges from as short as 1.5 h to as long as 12 h. Slurry from the reaction system is filtered to remove the calcium sulfate that is precipitated in the reaction. Conditions during the reaction are controlled to obtain crystals of calcium sulfate that filter at a high rate. The dihydrate WPA process results in the precipitation of byproduct calcium sulfate as the dihydrate form ($CaSO_4•2H_2O$, gypsum). Other WPA processes are operated at higher temperatures, resulting in the precipitation of calcium sulfate in the hemihydrate or the anhydrite form. The filter cake is washed to recover about 95% of the rock P_2O_5 as phosphoric acid at a concentration usually ranging from 28% to 30% P_2O_5 for the dihydrate process or 40%–50% P_2O_5 for the hemihydrate and anhydrite processes.

The filter acid is concentrated by vacuum evaporation to 52%–54% P_2O_5 (merchant grade) for shipping and for use in producing phosphate fertilizers. For ammonium phosphate production at the site, a concentration of about 40%–45% P_2O_5 is sufficient. Wet-process superphosphoric acid, used mainly in preparation of liquid fertilizers, is prepared by concentration to 68%–70% P_2O_5 content. Single-stage and double-stage vacuum evaporators of the forced-circulation type are widely used in concentration of WPA.

The calcium sulfate that is removed from the reaction slurry in production of WPA may be disposed of by storage in huge piles (stacks). Large areas of land are required for storage because there is no significant use for the gypsum at most locations. Gypsum produced in central Florida (United States) must be stacked because the radioactivity of the material exceeds 10 picocuries/g, which is the United States Environmental Protection Agency (EPA) limit for gypsum. Gypsum exhibiting radioactivity above these levels cannot be used for agricultural or other purposes. In other locations, gypsum is disposed of by dumping into rivers or the ocean. Substantial quantities of gypsum are used as a soil amendment. In Japan and several other locations, the calcium sulfate hemihydrate is processed to the dihydrate form and used in the production of wallboard and other similar building materials.

Composition of WPA varies considerably, depending on impurities in the phosphate rock, process efficiency, and the procedures used for clarification of the product acid. Since the late 1970s, producers in Florida and other locations have faced significant problems due to the increasing impurity content (Fe, Mg, Al) and decreasing grade of phosphate rock available for use in the production of WPA. Processing problems are encountered, recovery of P_2O_5 is lower, and it is difficult to maintain the grade and quality of products made with WPA.

Depending on the process used and the intended end use of the phosphoric acid, the acid may or may not be clarified and concentrated. Clarification may remove significant amounts of impurities as sludge. Phosphoric acid from the gypsum filter (26%–30% P_2O_5) contains some suspended solids. Small crystal particles pass through the filter cloth, and there may be holes in the cloth that allow solids to pass through. Suspended solids, usually in the size range of a few micrometers, generally amount to up to 2 wt % of the acid (Becker, 1983). When the acid begins to cool, the filtrate becomes saturated and more solids precipitate. Further cooling occurs in the storage tanks, where the acid filtrate can be considered supersaturated and more precipitation takes place. The amount of further precipitation is related to the cooling rate of the acid in the tank and the time spent in the tank. The sludge composition depends on the purity of rock used to produce the acid and the grade of the acid ultimately produced.

Triple Superphosphate

TSP is made by acidulation of phosphate rock with phosphoric acid. TSP (45%–46% P_2O_5) did not appear on the world market in any appreciable quantity until WPA was produced commercially in large volumes. Competition from higher analysis phosphate products on the world market forced producers of phosphate rock in many countries to produce WPA and TSP in that the costs of transportation and handling favor the production of the higher analysis TSP (46% P_2O_5) compared with SSP (20% P_2O_5).

The TVA cone mixer is used throughout the world in production of nongranular ROP-TSP. The “set time” is usually only 14–20 minutes for TSP, compared with the general 40–50 minutes for SSP. Therefore, a simpler cupped conveyor belt is usually used to hold the acidulate until the TSP solidifies instead of the contained dens typically used for SSP. The rock is usually ground to about 90% minus 150 μm and 70% minus 75 μm. The TSP usually is cured 4–6 weeks prior to shipment or for use at the site.

Granular TSP is produced in large quantities for direct application and in bulk blends. In some processes, cured TSP is granulated in a rotary drum or pan granulator using steam and water to promote granulation. In some countries, TSP is granulated in a pan or drum as it comes from the den. A slurry process is a widely used method in many countries. Pulverized phosphate rock is treated with WPA in a two-stage slurry reaction system, and the slurry is sprayed into a pug mill or rotary drum for layering on recycle at a typical ratio of 10–12 kg of recycle per kilogram of product. Product granules (45% P_2O_5) are usually quite spherical and dense; they have a high crushing strength. For production rates higher than about 25 tph, a rotary drum is normally used rather than a pug mill.

Partially Acidulated Phosphate Rock

Partially acidulated phosphate rock (PAPR) processes depend on treating ground phosphate rock with only a portion of the stoichiometric requirement of the acid needed to fully acidulate the rock. For example, 50% PAPR is acidulated with 50% of the acid calculated to fully acidulate the phosphate rock. Varying degrees of acidulation are possible (30%, 40%, 50%, etc.), and the amount of water-soluble phosphate, plant-available phosphate, and unreacted phosphate rock in the product varies according to the composition of the original rock, the type of acid used, the process used, and the degree of acidulation.

Sulfuric and phosphoric acids are the acids most commonly used for partial acidulation. Three processes are possibilities: (1) a conventional run-of-pile process followed by granulation, (2) single-step acidulation and granulation, and (3) a slurry-granulation TSP-type process. The lowest cost option is the use of sulfuric acid and a run-of-pile process.

Ammonium Phosphates

Ammonium phosphates were first produced in significant quantities during the early 1960s. Ammonium phosphate became the leading form of phosphate fertilizer in the United States in 1971 and in the world by 1977. Almost all new phosphate fertilizer complexes built in recent years are designed for the production of ammonium phosphates as the primary product. The main ammonium phosphate fertilizers are DAP, MAP, and ammonium phosphate sulfate (APS).

Granular DAP—DAP is produced by reacting WPA and ammonia. WPA of about 40%–45% P_2O_5 content (or a mixture of 54% P_2O_5 concentrated acid and filter-grade acid from the phosphoric acid plant of 28%–30% P_2O_5 content) is fed to a preneutralizer. Anhydrous ammonia is sparged through open-end pipes to neutralize the acid in the preneutralizer to an NH_3:H_3PO_4 mole ratio of about 1.4. This is in one of the ranges of maximum solubility of ammonium phosphate and ensures high fluidity of the slurry. The heat of reaction evaporates considerable water, and the water content of the slurry in the preneutralizer is typically 16%–20%. The temperature of the slurry in the preneutralizer is held at 110°–115°C or slightly higher. The slurry is pumped at a controlled rate and distributed on the bed of a rotary drum ammoniator-granulator. Anhydrous ammonia is sparged beneath the bed in the rotary drum to continue ammoniating the slurry; the usual finishing NH_3:H_3PO_4 mole ratio is 1.85 to 1.9, which is near enough to the point of minimum solubility of ammonium phosphate (mole ratio of 2) to allow operation with a comparatively low recycle ratio.

Material discharged from the granulator is dried with moderate heat. Most DAP/MAP plants screen hot material and cool only the product fraction since the material is not very sticky. Rotary coolers or those of the efficient and compact fluidized-bed type are used. The product, with moisture content of about 1.5%–2%, may not require a conditioner.

The standard DAP grade for international trade is 18-46-0. High impurity contents in the phosphoric acid can lead to the formation of impurity-phosphate compounds in the process so that the phosphate is not completely available for reaction with ammonia. Therefore, clarification/purification of phosphoric acid may be required to achieve the standard N grade.

Granular MAP—Substantial interest in the use of granular MAP fertilizers has developed, particularly in areas where soils are mainly alkaline. Also, where the primary interest is in producing and shipping phosphate, the 11-52-0 to 10-54-0 grades are particularly attractive because they provide about a 15% higher phosphate payload than DAP. MAP is produced in a variety of grades. Unlike DAP there is no standard for international trade. A substantial amount of the phosphate in the finished product may not be water soluble, but it will be plant available.

Production of MAP can be very similar to that of DAP. There are basically two methods to produce MAP: (1) the preneutralizer slurry is ammoniated only to an NH_3:H_3PO_4 mole ratio of about 0.6 (high solubility) and then to about 1.0 in the ammoniator-granulator drum (forward titration) and (2) the preneutralizer slurry is ammoniated to about 1.4, as with DAP, and then additional phosphoric acid is distributed onto the bed in the granulator to adjust the MAP mole ratio back to 1.0 (back titration). The essential factor is that final adjustment in the granulator must be near the point of minimum solubility at a NH_3:H_3PO_4 mole ratio of 1.0. A third method can be used to produce MAP by using a pipe reactor discharging directly into the granulator.

Nongranular MAP—Simple processes have been developed for the production of nongranular MAP, sometimes called “powder” MAP. In one of the most common methods used to produce nongranular MAP, WPA is ammoniated in a reactor and the slurry sprayed into a fabric-enclosed tower. The slurry droplets solidify as they fall downward through an upward airflow in the tower and form very small prill-like particles. In another similar process, a pipe reactor is used for the chemical reaction. Other processes use an atmospheric preneutralizer to produce slurry at a mole ratio of about 1.4. Then, the slurry is fed into a pug mill-type unit, and additional acid is sprayed into the material to adjust back to a mole ratio of about 1.0. There is also a process that uses a spray tower for ammoniation of the acid and solidification of the product. Storage and handling properties of nongranular MAP are generally good. This product may be shipped to other plants where it is used as a main component in production of NPK granular fertilizers.

APS—Ammonium phosphate sulfate is essentially a mixture of MAP and AS formed by the reaction of ammonia, phosphoric acid, and sulfuric acid, although solid AS can be used in place of sulfuric acid. The best known grade is 16-20-0. APS is produced in North America and Europe using slurry processes or by pipe reactor processes.

In manufacturing ammonium phosphates, metal impurities precipitate upon ammoniation of WPA. The compositional form and relative abundance of these metal salts depend upon both acid composition and operative parameters during ammoniation and granulation. The various types of precipitates depend on the pH, temperature, and retention time during ammoniation. The solubility properties of the DAP and MAP fertilizers depend on the total content of impurity solids and their specific compositional forms.

Divalent metals are thought to precipitate as $M^{2+}NH_4PO_4^{2-}$ compounds. These compounds are generally expressed as anhydrous compounds. Although each of several divalent elements may be relatively insignificant in quantity, their collective effect, particularly in acids from the western United States, is to bind a significant quantity of phosphoric acid in the form of compounds with low nitrogen content.

Sludge can be utilized during MAP and APS production as is similarly done with TSP. MAP and APS production does not require that the sludge be separated from the acid, and all the sludge is fed into the neutralization system.

NPK Fertilizers

NPKs can be produced by numerous methods, including bulk blending, steam granulation, chemical granulation in conjunction with nitrophosphate and APS production, or by other processing schemes. The phosphate products listed in the previous sections are used as raw materials in the production of NPKs by steam granulation, chemical granulation, and with APS production. It should be noted that NPK facilities are generally designed to operate as zero effluent/zero solid waste facilities; that is, liquid effluents, solid spillage, and other wastes are integrated with production to eliminate the need for waste disposal. Some particulate matter may be carried from such sites, but the amount of this material is minimal.

Nitrophosphates are produced using several process variations; the most common is the Odda Process. Basically, phosphate rock is dissolved with nitric acid. The resulting phosphoric acid intermediate is generally utilized internally within the fertilizer complex to produce a number of multinutrient granular products. Calcium is removed from the system as calcium carbonate, CAN, or calcium nitrate. The level of calcium removal from the nitric/phosphoric acid solution controls the water solubility of the phosphate in the finished product. Insolubles (silica sand, etc.) are removed from the system and may be sold as construction materials.

In nitrophosphate processes, the iron and aluminum oxides present in the phosphate rock feed present no special problem within the range of occurrence in commercial phosphate rocks. These oxides usually are dissolved and reprecipitated during ammoniation as citrate-soluble phosphates. One of the main selling points to promote the nitrophosphate process over the years has been the fact that phosphate rocks with high impurity contents can be utilized.

A positive characteristic of nitrophosphate plants is that there is no byproduct gypsum to deal with. In most nitrophosphate plants, no waste is generated; that is, all the raw materials and associated trace elements are processed and contained in some type of product or marketable byproduct.

Potassium Fertilizers

Potassium salts produced and used as fertilizer are commonly referred to as potash, a term derived from the leaching of wood ashes in large iron pots. Because potash can refer to many compounds, the potassium content is usually expressed in terms of K_2O content.

Potassium chloride (KCl or muriate of potash, the mineral name is sylvite) is the most abundant and least expensive water-soluble potassium fertilizer. It is the most common and generally preferred potash source for fertilizer use. Commercial KCl grades contain about 60% K_2O and are usually 95%–96% pure. KCl is also used as an intermediate to produce potassium sulfate and potassium nitrate.

Several grades of KCl are marketed, depending mainly on the particle size and purity. It is a natural material occurring in a wide range of sizes; the most desirable are the larger sizes that are suitable for bulk blends. Material produced by crystallization from brines is the finest material, but it is also the purest material, commanding higher prices for chemical applications or fluid fertilizers.

Potassium sulfate (K_2SO_4, sulfate of potash) is derived directly from brines or is synthesized from other potassium salts. Commercial grades typically contain about 50% K_2O. Potassium sulfate is used for chloride-sensitive crops such as potatoes. Similar to KCl, it is graded by size.

Potassium magnesium sulfate (sulfate of potash magnesia) is generally a double salt containing both magnesium and potassium sulfates; commercial products produced from langbeinite ore ($K_2SO_4 \bullet 2MgSO_4$) typically analyze 22% K_2O, 11% Mg, and 22% S. It is also used for chloride-sensitive crops and where magnesium and sulfur are needed. As with other potash products, it is graded by analysis and size.

Potassium nitrate (KNO_3, nitro, saltpeter) is a white crystalline salt. Recovery of naturally occurring materials from caliche beds in the Atacama Desert of Chile has been ongoing since the 1800s. The analysis of fertilizer-grade material is about 13%–14% N and 44% K_2O. It is used on chlorine-sensitive crops.

As indicated, a common feature of many of the potash products is that they are graded on size. This is due to the fact that they are produced from minerals that occur naturally in a range of sizes or that break down during processing to a range of sizes, or they are produced from brines by crystallization. Larger sizes command premium prices because they are the least abundant fractions and are suitable for blending. Many of these potash products are subjected to compaction processes to produce larger size material. Some products such as potassium magnesium sulfate are also produced by drum granulation.

CHAPTER III.
FERTILIZER RAW MATERIAL CHARACTERISTICS AND PRODUCTION

Nitrogen Fertilizer Raw Materials

The primary raw materials for nitrogen fertilizers are natural gas, naphtha, fuel oil, and coal. Natural gas, naphtha, and fuel oil are substances or mixtures to which clearly definable specifications can be applied. Variations in composition will usually be minor regardless of where they are obtained or produced. Coal can have significant variations in composition and contained energy.

Ammonia is a basic building block for most nitrogen fertilizers with the exception of some naturally occurring nitrates. In ammonia manufacture, nitrogen is fixed from the earth’s atmosphere. Nitrogen (at about 78%) is the most common gas in the earth’s atmosphere. The amount of nitrogen in the earth’s atmosphere is not considered a limiting factor in nitrogen fertilizer production.

Hydrocarbon and coal feedstocks for ammonia manufacture perform a dual role as sources of both hydrogen and energy. The relative amounts of hydrogen and energy that are actually supplied for the manufacture of ammonia depend on the type of feedstock and type and efficiency of a process. An average figure for the contribution of the feedstock to each category may be 60% hydrogen and 40% energy. Water also contributes a portion of the hydrogen needed for ammonia manufacture.

Origins of Hydrocarbons and Coal

Natural gas, oil, and coal are associated with sedimentary rocks. Natural gas and oil are produced from sedimentary rocks ranging in age from Precambrian (+600 million years) to Cenozoic (60 million years to the present).

It is widely accepted that plankton living in ocean waters were the sources of nearly all petroleum. Fine-grained muds rich in planktonic remains are deposited offshore in low-energy, oxygen-poor environments. Slow decomposition by anaerobic bacteria turns the planktonic remains into an amorphous material called sapropel. As the muds are buried and form shales and mudstones, the sapropel is converted to petroleum compounds by biological, chemical, and physical processes, which are not fully understood. Young petroleum tends to have compounds of higher molecular weight and produces heavy crudes. With deeper burial, increased temperature and pressure break down the organic structures into lighter and simpler hydrocarbon compounds. At great depth, methane may be the only remaining hydrocarbon.

Several criteria must be met before petroleum hydrocarbons can accumulate to form a field:

1. Sapropelic source beds must be formed.
2. With burial, heat and pressure conditions must exist to bring the source beds to maturity and generate petroleum compounds.
3. Migration from source beds to reservoir rocks must be possible.
4. Suitable porous reservoir beds must exist.
5. Traps (stratigraphic and structural) must exist so that accumulations can form.
6. A suitable seal or cap rock must exist to prevent the oil and gas from escaping.

Perhaps 60% of the world’s petroleum reserves are associated with sandstones, whereas about 40% are associated with limestones. Gas migrates updip of (above) the liquid petroleum fraction, may form separate fields, or may cap the oil zone.

Significant oil and gas fields are mainly associated with large basins located on continental margins, on former continental margins, or in intercontinental basins where significant sediment accumulations have occurred. These accumulations may be currently located onshore or offshore. Areas devoid of petroleum accumulations include areas of igneous rocks or sedimentary rocks that have been subjected to very high levels of heat and pressure.

Crude oils are separated into components such as gasoline, naphtha, and fuel oils by distillation. Higher weight petroleum compounds may be broken down to lighter fractions by heat in a process called thermal cracking or under the influence of catalysts (catalytic cracking). Lighter fractions may be processed to higher weight hydrocarbons by a process called reforming. Sulfur is generally removed from natural gas near the wellhead, and sulfur is removed in the process of refining crude oils.

Liquid petroleum fractions are more easily transported and stored than gases, which require high-pressure compression and transportation in special vessels. In areas where there is no market for petroleum gas or developed infrastructure to transport natural gas, the use of natural gas to produce ammonia and solid nitrogen fertilizers may be the only and/or most lucrative option for development.

Coals are formed in swamps under warm climatic conditions that promote rapid vegetative growth. Coal deposits are generally associated with mountain-building events and deltaic environments. Coals can be traced to the Devonian period, when woody plants first evolved, about 370 million years ago.

To be preserved, vegetative matter must accumulate quickly in an anaerobic environment. After deposition, anaerobic bacteria cause biochemical changes that slowly transform the vegetative matter into peat. As the peat deposits become buried beneath increasing thicknesses of younger sediments, the peat is subjected to increases in temperature and pressure. Water and volatile compounds are expulsed, and crosslinking occurs between carbon atoms.

Under the effects of increasing temperature and pressure, peat acquires the solidity, color, and chemical composition of coal. These changes are the basis for a progressive increase in the rank of coal. Coal is characterized or ranked by four groups although the boundaries between groups are arbitrary. Peat is more or less spongy, decomposed plant debris with a high water content. Brown coals and lignite have high water content and contain about 40%–55% volatile components. Bituminous coals are the best known coals. Those with 30%–45% volatiles are widely used for steam-raising and general combustion, while those with 20%–30% volatiles may be suitable for coking. Anthracites or hard coals contain up to 95% carbon and less than 5% volatiles.

Commercial coals contain impurities such as clays and sulfur in a general range of 0.5 wt % to 3.0 wt %, which lead to varying amounts of ash and clinker. As coals increase in rank, calorific values increase to the anthracite level at which, due to expulsion of most volatiles, calorific values may decrease somewhat. The calorific content and impurity content of coals dictate the design of coal-burning or gasifying facilities and associated pollution control equipment.

Naturally occurring commercial coal beds are generally extensive and thick, have minimal partings (thin beds of shale), and have acceptable calorific contents. Coal is mined by both opencast and underground methods. If the coal is mined underground, suitable roof rock conditions must exist. The thickness and character of overburden and other site-specific conditions determine the use of opencast methods. Opencast methods are by far the most cost-effective methods to mine coal.

Power generation and/or fertilizer production units using coal require significant amounts of water and coal. Coal-fired power generation units and/or fertilizer production units are often located near the mine site.

World Ammonia Production and Feedstock Reserves

Table III.1 presents a forecast of ammonia production for fertilizer through the year 2010. Feedstock requirements may be met by natural gas, oil, naphtha, or coal depending on the regions of the world where the ammonia will be produced. The various feedstocks contain varying amounts of energy. Thus, varying quantities are required per ton of ammonia produced, as shown in Table III.2. Liquefied natural gas (LNG) and liquefied petroleum gas (LPG) are used as feedstocks in some regions that produce little oil or natural gas. Table III.3 shows the production of natural gas and petroleum for the year 2004 and the reserves at the end of 2004.

The cost of feedstocks will vary from region to region depending on supply, reserves, and other

Table III.1. Forecast of Ammonia Production for Fertilizer

Region	Nitrogen x 1,000 tons				
	2005/06	2006/07	2007/08	2008/09	2009/10
Africa	3,110	3,408	4,007	4,321	5,226
America – North	6,396	5,200	4,998	4,796	4,596
America – Latin	6,807	6,922	7,011	6,986	6,967
Asia – East	32,985	34,644	36,351	36,595	36,582
Asia – South	13,963	14,064	14,429	14,908	14,979
Asia – West	7,085	9,294	10,043	11,430	12,392
Europe – Central	4,042	4,026	4,009	4,018	4,001
Europe – West	6,561	6,508	6,454	6,396	6,338
East Europe and Central Asia	14,938	14,990	15,313	15,591	15,628
Oceania	574	927	959	962	944
Total	**96,461**	**99,983**	**103,574**	**106,003**	**107,653**
Ammonia equivalent	117,135	121,412	125,773	128,722	130,726

Source: IFDC unpublished data.

Table III.2. Energy Requirements Per Ton of Ammonia

Feedstock and Fuel	Assumed Heating Value	Quantity	Gcal
Natural gas	8,015 kcal/m^3	873 m^3	7.0
Naphtha	10,556 kcal/kg	0.72 ton	7.6
Fuel oil	9,722 kcal/kg	0.87 ton	8.5
Coal	6,333 kcal/kg	1.54 ton	9.8

Source: UNIDO/IFDC (1998).

factors. In the past, there has been some credibility to pricing natural gas, naphtha, oil, and coal on an energy-content basis. In recent times, extensive pipeline construction in developed countries has given the end user more options in obtaining supplies of feedstock so that price is driven more by competition than energy content. This principle also applies to refinery capacity, i.e., the region that has the most excess capacity will normally have the lowest cost oil and naphtha. Coal has generally been priced much lower than natural gas or liquid feedstocks on an energy-content basis.

Competition from other users has dramatically increased costs for natural gas in recent years in the United States. As a result of these high prices, approximately one-third of the North American ammonia capacity was shut down during 2000–2006. Demand for ammonia and other nitrogen products was met by increased imports.

Feedstocks in developing countries will vary depending not only on availability but also on the ability to move the feedstock to the plant site. Coal is used as a feedstock where natural gas is not readily

Table III.3. World Production and Reserves of Natural Gas and Petroleum

Region	Natural Gas		Petroleum	
	Production 2004	Reserves 2004 End	Production 2004	Reserves 2004 End
	(10^9 m^3)		(10^9 bpd[a])	(10^9 barrels)
Africa	145.1	14,060	9.26	112,200
Asia Pacific	323.2	14,210	7.88	41,000
North America	762.8	7,320	14.15	61,000
South and Central America	129.1	7,100	6.76	101,200
Middle East	279.9	72,830	24.57	733,900
Europe and Eurasia	1,051.5	64,020	17.58	139,200
World Total	**2,691.6**	**179,540**	**80.20**	**1,188,500**
Energy equivalent (MMBtu x 10^9)	95.04	6,190	489.59	7,250,460
Energy equivalent (Gcal x 10^9)	23.95	1,561	123.37	1,827,003

a. barrels per day.

Source: *BP Statistical Review of World Energy*, June 2005, <www.bp.com/statisticalreview>.

Notes:
1. Energy content of natural gas assumed at 8.9 MMcal/m^3 (35,310 Btu/m^3).
2. Energy content of petroleum assumed at 1.54 Gcal/barrels (6.1 MMBtu/barrels).
3. 3.9685 MMBtu equivalent to 1 Gcal.

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available. Table III.4 shows world production and reserves of coal for 2003.

While reliable data are not readily available on feedstock use by type (natural gas, oil, naphtha, and coal), an analysis of world reserves of natural gas, oil, and coal by region indicates that natural gas will be the dominant feedstock. Of course, the lowest cost natural gas sources will be the most favorable for development. The lowest cost natural gas sources for fertilizer will be located in areas where there is abundant natural gas, where there is little or no competition for its use, and where gas is produced as a byproduct of petroleum production. Oil and naphtha will continue to be used as feedstocks primarily in those regions or areas that do not have natural gas reserves and are unable to receive natural gas by pipeline. Coal will be used when there are no other economically feasible options. Review of reserve data covering all feedstocks indicates no shortage of feedstock material in the short-term future.

Table III.4. World Production and Reserves of Coal, 2003

Region	Production	Reserves
	(million ton oil equivalent)	(million tons coal)
Africa	137.5	55,367
Asia Pacific	1,317.7	292,471
North America	589.6	257,783
South and Central America	39.2	21,752
Middle East	0.6	1,710
Europe and Eurasia	434.0	355,370
World Total	**2,518.6**	**984,453**
Energy equivalent (MMBtu x 10^9)	110.6	29,238
Energy equivalent (Gcal x 10^9)	27.87	7,367

Source: Data from *BP Statistical Review of World Energy*, June 2005.

Notes:
1. Energy content of oil assumed at 6.1 MMBtu/barrels.
2. Energy content of coal assumed at 29.7 MMBtu/ton.
3. 3.9685 MMBtu equivalent to 1 Gcal.
4. 7.2 barrels of oil/ton.
5. Includes anthracite, bituminous, and lignite coals.

Phosphate Rock

"Phosphate rock" is an imprecise term that includes both unprocessed rocks and beneficiated concentrates. Practically all production of phosphate fertilizers is based on phosphate rocks containing some form of the mineral apatite.

Geological Origin and Characteristics of Phosphate Rock

There are two main types of phosphate rock deposits—sedimentary and igneous. Sedimentary phosphate deposits are exploited to produce more than 80% of the total world production of phosphate rock.

Igneous phosphate deposits are often associated with carbonatites and/or alkalic (silica deficient) intrusions. Igneous phosphate ores are often low in grade (less than 5% P_2O_5) but can be upgraded to high-grade products (from about 35% to over 40% P_2O_5).

Sedimentary phosphate rocks occur throughout the geological time scale. They exhibit a wide range of chemical compositions and great variations in physical form. The most favorable deposits to exploit usually occur as one or more thick high-grade beds that are unconsolidated and have a uniform granular texture and composition, shallow overburden, and a minimum of structural deformation.

Insular deposits are a type of sedimentary deposit associated with oceanic islands. Insular deposits have been an important source of phosphate rock for more than 100 years. However, intensive exploitation has caused several deposits to be totally depleted or to have short projected lifetimes, e.g., Ocean Island, Christmas Island, and Nauru, to name a few.

Depending on their origin (igneous or sedimentary), phosphate rocks have widely differing mineralogic, textural, and chemical characteristics. Furthermore, entire deposits or portions of deposits have been influenced by near-surface conditions that alter their original mineralogic, textural, and chemical characteristics. Many igneous apatite deposits are composed of loose residual materials. In these deposits the apatite has survived weathering and has become concentrated because it is more resistant to chemical and physical breakdown than are associated minerals. Many important sedimentary phosphate deposits owe their present character to surface or near-surface processes.

While each general type of phosphate deposit (sedimentary and igneous) would seem to have its own general set of characteristics, widely differing characteristics are found within sedimentary and igneous deposits as groups. Some igneous phosphate deposits, such as the Kola deposit in Russia, are hard-rock deposits. Apatite crystals are found within a hard crystalline fabric of other igneous minerals. With intense weathering, the fabric of igneous phosphate rocks can be destroyed; soft, soil-like residual deposits, such as those found at Sukulu Hills, Uganda, are produced. The character of such soil-like material is more like an unconsolidated sedimentary rock than a hard-rock igneous deposit. Weathering of igneous deposits may also be at an intermediate stage, between an unaltered hard rock and soft soils.

Sedimentary phosphate rocks can range from loose, unconsolidated materials, to weakly cemented materials, to highly indurated rocks. In general, younger sedimentary phosphate rocks that have not been subjected to deep burial and that contain significant amounts of phosphate particles, sands, and clays tend to be in the unconsolidated category. Phosphate rocks of varying ages have been deposited simultaneously with carbonates. Such carbonate-containing phosphate rocks can range from weakly indurated to highly indurated, depending on the geologic history and degree of carbonate cementation. As previously mentioned, exposure to near-surface conditions may result in the leaching of carbonates from the rock.

When sedimentary phosphate rocks have been subjected to varying levels of burial and heat, profound mineralogical and textural changes can occur. In general, the rock becomes less porous, more compact, and more highly indurated. Sedimentary phosphate rocks that have been subjected to extremely deep burial (high pressure and perhaps shearing forces and/or heat) may be further categorized as a third type of phosphate rocks known as metamorphic phosphate rocks. Igneous rocks may also be subjected to heat and pressure to form metamorphic phosphate rocks. Metamorphic phosphate rocks will not be dealt with separately in this section except to state that metamorphic examples of both sedimentary and igneous phosphate deposits can be found and their significance is limited.

Phosphate Rock Mineralogy—Phosphate rock mineralogy can be highly variable. Sedimentary apatites are formed near the surface of the earth under low temperature and pressure in a variety of environments that can range from freshwater to marine to hypersaline conditions. Igneous apatites, on the other hand, are formed under very high temperature and pressure. Although these apatites have similar formulas and crystal structures, they are distinctly different.

Minerals associated with the various types of phosphate rocks are fairly distinctive. High-temperature igneous minerals are associated with hard-rock and mildly weathered igneous phosphate deposits. Clastic sedimentary minerals such as quartz and clays or biological or chemical precipitates such as carbonates are associated with sedimentary phosphate rocks.

Under conditions near the surface of the earth, a wide spectrum of secondary minerals can form that may be common to both igneous and sedimentary phosphate rocks. These minerals include iron and aluminum phosphates, clays, and iron oxides.

Sedimentary Apatites—Most sedimentary deposits contain varieties of carbonate-fluorapatite that are collectively called francolite. Francolite is defined as an apatite that contains significant CO_2 with >1% fluorine (McConnell, 1938). In establishing a series of systematic relationships among francolites, McClellan and Lehr (1969) and McClellan (1980) used X-ray diffraction (XRD), chemical analysis, and statistical methods to show that the contents of Ca, Na, Mg, P, CO_2, and F can adequately describe most francolites (Table III.5). McClellan and Van Kauwenbergh (1990a) and Van Kauwenbergh (1995), using similar methods, reconfirmed earlier findings and included SO_4 as a minor component in the francolite structure. Studies of francolite in commercial phosphate rock concentrates show that the replacement of Ca^{2+} by Na^+ and Mg^{2+} is systematic although limited. Thus, at least a part of the Na^+ and Mg^{2+} in a commercial concentrate can be substituted within the francolite structure and cannot be removed by beneficiation. Most importantly, carbonate substitutes for phosphate in a 1:1 ratio. The maximum amount of substitution is between 6% and 7% CO_2. Net charge imbalances are compensated by both cation and anion substitutions (primarily Na^{+1} and F^{-1}). The incorporation of CO_2 into the francolite structure is accompanied by increased fluorine contents. In this document, these carbonate apatites are referred to as excess-fluorine francolites.

One of the most important results of these studies was the recognition that francolite compositions and properties can be estimated by X-ray and optical measurements. In excess-fluorine francolites, the unit-cell a dimension (a-value) decreases from 9.369 ± 0.001Å to approximately 9.320 ± 0.001Å

Table III.5. Varieties of Apatite and Selected Crystallographic and Optical Properties

Variety	Formula	Unit-Cell a-Value (Å)	Refractive Index (N_D^{25})
Francolite[a]	$Ca_{10-x-y}Na_xMg_y(PO_4)_{6-z}(CO_3)_zF_2F_{0.4z}$	9.320–9.369	1.595–1.633
Francolite[b]	$Ca_{10-a-b}Na_bMg_b(PO_4)_{6-c}(CO_3)_cF_2F_{0.185c}$	9.318–9.369	1.597–1.633
Carbonate-hydroxylapatite	$Ca_{10}(PO_4,CO_3)_6OH_2$	9.420	1.630
Fluorapatite	$Ca_{10}(PO_4)_6F_2$	9.370	1.629–1.633
Hydroxylapatite	$Ca_{10}(PO_4)_6OH_2$	9.420	1.651
Chlorapatite	$Ca_{10}(PO_4)_6Cl_2$	9.640	1.667

a. McClellan and Lehr (1969), McClellan (1980).
b. Van Kauwenbergh (1995).

with maximum carbonate substitution. The index of refraction also decreases with increasing carbonate substitution, as shown in Table III.5.

Sedimentary phosphate rocks that are obtained from insular and cave deposits often contain carbonate apatites that have a lower F content than that of stoichiometric fluorapatite and, according to calculations, contain significant amounts of hydroxyl in their structures. Although some of these carbonate apatites may meet the francolite definition, they have crystallographic, chemical, and other physical properties that differ substantially from those of francolites that contain excess fluorine (McClellan and Van Kauwenbergh, 1990b,c). These carbonate apatites form a series, with end members that contain almost no fluorine (carbonate-hydroxylapatite) and end members that are very close in composition to pure fluorapatite and to francolites that have almost no carbonate substitution (Table III.5). Members of this series are referred to as hydroxyl-fluor-carbonate apatites in this section. Table III.6 shows the unit cell a-values of some phosphate rocks containing hydroxyl-fluor-carbonate apatites in this series.

Some carbonate apatites do not fit well within either the excess-fluorine francolite series or the hydroxyl-fluor-carbonate apatite series and perhaps belong in an intermediate class; see Table III.6.

Table III.6. Unit-Cell a-Dimension of Some Hydroxyl-Containing Carbonate Apatites in Some Sedimentary Phosphate Rocks

PR Source	Length of a-axis (Å)
Naura Island[a]	9.375
Christmas Island[a]	9.389
Lumphun, Thailand[a]	9.434
Mejillones, Chile[b]	9.332
Sechura, Peru[b]	9.337

a. Samples from insular or cave deposits. These apatites are part of a hydroxyl-fluor-carbonate apatite series.
b. Calculations indicate these samples are fluorine-deficient and may contain significant hydroxyl. Unit-cell a-dimensions are similar to those of excess-fluorine francolites, but other properties vary.

Phosphate rocks from the deposits in Sechura, Peru, and Mejillones, Chile, might be placed in this category. The carbonate apatites in these rocks have unit-cell a-dimensions that fall plainly into the range of the francolite series (≅9.320–9.370Å). However, samples from these deposits, which have been extracted for free carbonates, exhibit higher carbonate contents and chemical reactivities than calculations based on excess-fluorine francolite models would indicate. Calculations indicate that the carbonate apatites from these deposits have lower fluorine contents than expected and may contain significant hydroxyl substitution.

Phosphate rocks from the same sedimentary deposit may contain apatites with widely differing properties due to geologic conditions and postdepositional alterations (Van Kauwenbergh and McClellan, 1990a). Francolites are metastable with respect to fluorapatite and can be systematically altered through the combined effects of weathering, metamorphism, and time (McClellan, 1980). Older sedimentary rocks generally contain francolites with a limited amount of carbonate substitution, whereas younger sedimentary phosphate rocks may have compositions that span the francolite model as seen in Figure III.1 (McClellan and Van Kauwenbergh, 1991).

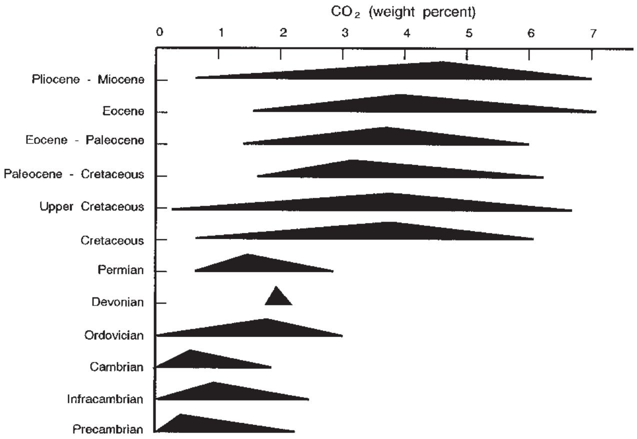


Figure III.1. Variation in CO_2 Contents in "Excess-Fluorine" Francolites of Varying Geologic Ages (472 Samples, 165 Deposits; Peak of Triangle Represents Average CO_2 Content)

The determination of the type and amount of apatite in a phosphate rock is very important. Sedimentary phosphate rocks containing the most highly carbonate-substituted apatites can only be beneficiated to maximum grades of 33–34 wt % P_2O_5. Depending on the amount of carbonate substitution, the grade can increase to a maximum of about 42 wt % P_2O_5 for sedimentary apatites with essentially no substitution. In order to reach comparable concentrate grades, increasing amounts of gangue minerals must be removed from sedimentary phosphate rocks containing highly carbonate-substituted apatites (Table III.7). For more details concerning apatite mineralogy, see the United Nations Industrial Development Organization (UNIDO)/IFDC *Fertilizer Manual* (1998).

Igneous Apatites—The apatite associated with igneous source rocks may be of a primary magmatic, hydrothermal, or secondary origin. Primary igneous apatite crystals are generally well formed and found in association with high-temperature minerals or the weathering products of high-temperature minerals. Apatite may also form in the last stages of hydrothermal alteration of phosphate-bearing igneous bodies. Evidence from phosphatic pegmatites (Fransolet et al., 1986) suggests that apatite may form at temperatures as low as 50°–100°C. Secondary apatite is common in the weathered and supergene-enriched zones of igneous deposits. Such apatites are generally microcrystalline and may have some degree of carbonate substitution.

Primary apatite from igneous sources may be of fluorapatite, hydroxylapatite, or chlorapatite varieties, as shown in Table III.5. A continuous series exists between the fluorapatite and hydroxylapatite end members. Examples of fluorapatite and hydroxylapatite mixing with chlorapatite are limited. Statistical models have been established to equate the wide range of crystallographic, chemical, and physical properties of sedimentary apatites; however, models equating these properties in igneous apatites are generally lacking although optical and crystallographic properties do vary (Table III.8). Perhaps the most clearly recognized effect of anion substitution in igneous apatites is that of the variation of the average refractive index (N_D^{25}) (Deer et al., 1982; Taborszky, 1972) (Figure III.2). Pure apatites from igneous deposits contain slightly over 42% P_2O_5.

Table III.7. Mineral Composition of Selected Sedimentary Phosphate Rocks

Source	Apatite[a]	Gangue Minerals
	(wt %)	
Western U.S.A.	79.8	20.2
Tennessee, U.S.A.	82.7	17.3
Sechura, Peru	86.4	13.6
Florida, U.S.A.	86.3	13.7
Morocco	88.2	11.8
North Carolina, U.S.A.	90.7	9.3
Tunisia	92.2	7.8

a. Wt % apatite = actual P_2O_5/theoretical P_2O_5 (100% apatite). Assumes all samples contain 32% P_2O_5.

Table III.8. Common Secondary Phosphate Minerals Formed During the Weathering of Phosphate Deposits

Crandallite Series	
Crandallite	$CaAl_3(PO_4)_2(OH)_5{\bullet}H_2O$
Goyazite	$(Sr,Ca)Al_3(PO_4)_2(OH)_5{\bullet}H_2O$
Gorceixite	$(Ba,Ca)Al_3(PO_4)_2(OH)_5{\bullet}H_2O$
Wavellite	$Al_3(PO_4)_2(OH)_3{\bullet}5H_2O$
Varisite	$AlPO_4{\bullet}2H_2O$
Strengite	$FePO_4{\bullet}2H_2O$
Dufrenite	$Fe^{+2}Fe^{+3}(PO_4)_3(OH)_5{\bullet}2H_2O$
Beraunite	$Fe^{+2}Fe_5^{+3}(PO_4)_4(OH)_5{\bullet}4H_2O$

Aluminum and Iron Phosphates—Total P_2O_5 analysis of a potential ore is not a dependable criterion for evaluation of a phosphate deposit. With the weathering of apatitic phosphates and associated minerals, a suite of other secondary phosphate minerals may form (Table III.8). These minerals are most commonly aluminum- and iron-containing phosphates, and they cannot be processed by the

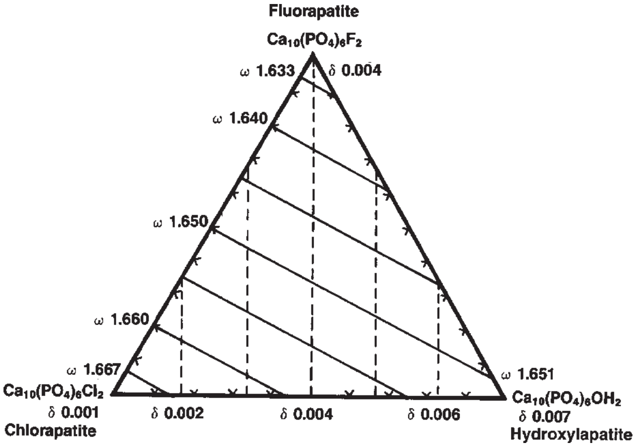


Figure III.2. Optical Properties of Fluor-, Chlor- and Hydroxylapatites (Adapted From Deer et al., 1982)

methods used to beneficiate apatitic calcium phosphates. Aluminum and iron phosphate minerals may form in both sedimentary and igneous deposits.

Probably the most common secondary phosphate minerals produced by weathering are members of the crandallite series. Wavellite is also a common aluminophosphate weathering mineral. Iron phosphates such as dufrenite, strengite, or beraunite may also form. The list in Table III.8 provides only the most common phosphates found in these deposits. There are over 300 currently valid names for species of phosphate minerals (Nriagu and Moore, 1984).

Other Minerals in Phosphate Rocks—The most common nonphosphatic accessory minerals associated with sedimentary phosphate rocks are quartz, clays, and two carbonates: dolomite ($CaMg(CO_3)_2$) and calcite ($CaCO_3$). Carbonate-cemented phosphate rocks are particularly noteworthy because of their abundance. McClellan and Gremillion (1980) estimated that there is 3 tons of carbonate-cemented phosphate rock for every ton of ore that could be handled by conventional milling and flotation processes (quartz- and clay-containing phosphate rocks).

Quartz can occur as detrital grains or as chalcedony cement. Chalcedony cement or particles in samples can be particularly difficult to detect using optical microscopy because the material is anisotropic in nature and similar in appearance to microcrystalline francolite. Quartz can also occur as opaline varieties in sedimentary phosphate rocks.

Other tectosilicates found in sedimentary phosphate rocks include the various feldspars; orthoclase is probably the most common feldspar variety. The high-temperature potassium feldspar, sanadine, has even been detected in sedimentary phosphate rocks from geologic provinces where volcanic activity was occurring during deposition. Micas (biotite and muscovite) can also be found in sedimentary phosphate rocks.

Clays (aluminosilicates) found in sedimentary phosphate rocks include illite, kaolinite, smectites, and magnesium-rich clays such as palygorskite and sepiolite. Kaolinite, smectites, and magnesium-rich clays often appear to occur in zones within phosphate deposits. This zonation may be related to weathering and the general alteration of deposits under surface or near-surface conditions (Van Kauwenbergh et al., 1990; McClellan and Van Kauwenbergh, 1990c).

Apatite of igneous origin is preferentially associated with alkaline intrusions and carbonatites. Common minerals associated with apatite-bearing alkaline igneous intrusions include nepheline, alkali feldspars, micas, pyroxenes, and amphiboles. Commonly the pyroxenes and amphiboles are Mg- or Fe-rich varieties, and the micas are biotite or phlogopite. Carbonatites may or may not be associated with alkaline igneous complexes. Calcite and/or dolomite can be present in these carbonatites. Magnetite is very commonly associated with igneous apatite in carbonatite deposits. Weathering leaches and removes the more soluble carbonates and silicates, leaving resistant minerals such as apatite, magnetite and other iron oxides, pyrochlore, and zircon in the residuum over igneous deposits; a wide variety of secondary phosphate minerals and clays may form. These phosphate minerals and clays include all the minerals previously mentioned in conjunction with sedimentary deposits. The residuum over such deposits is typically very rich in iron and contains significant proportions of hematite and goethite.

Apatite Reactivity—Several methods can be used to measure apatite reactivity. All these methods are based on standardized procedures and specific extraction media. Common extraction media include neutral ammonium citrate (NAC), 2% citric acid, and formic acid. It is not the purpose of this section to discuss the relative merits or disadvantages of different methods. A discussion of these methods can be found in McClellan and Van Kauwenbergh (1990b). Most of the discussion in this section is based on extraction with NAC (Association of Official Analytical Chemists [AOAC] fertilizer method).

Lehr and McClellan (1972) studied a suite of sedimentary phosphate rocks and an igneous phosphate rock concentrate and concluded that carbonate substitution in apatite was the dominant factor influencing reactivity measurements. This study also concluded that reactivity measurements with NAC resulted in the highest correlations with physical and chemical properties of various apatites. McClellan and Van Kauwenbergh (1990b) and Van Kauwenbergh and McClellan (1990b) have further characterized sedimentary phosphate rock reactivity according to the separation of excess-fluorine francolites and insular or guano-derived apatites (hydroxyl-fluor-carbonate apatites). Excess-fluorine francolites have NAC solubilities ranging from about 1.3% P_2O_5 at 0% carbonate substitution to about 7% P_2O_5 at 6–9 wt % CO_2 substitution (Figure III.3).

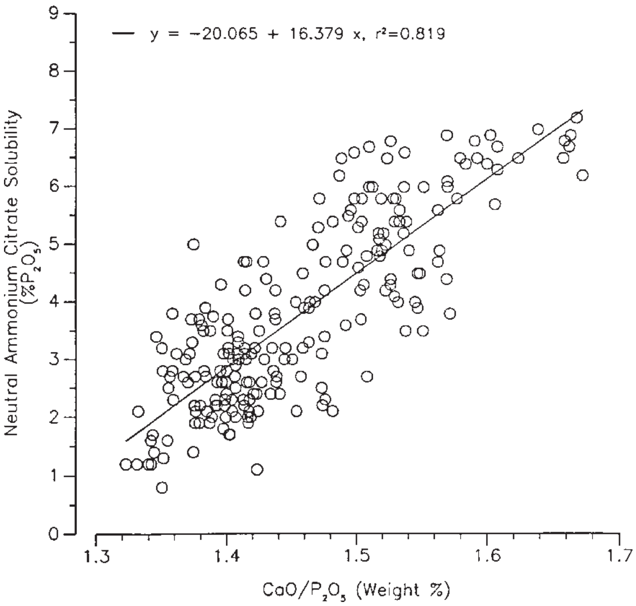


Figure III.3. **Relationship of CaO/P_2O_5 Weight % Ratio to Neutral Ammonium Citrate Soluble P_2O_5, "Excess-Fluorine" Francolites**

Apatites from insular or guano-derived deposits exhibit NAC solubilities that range from about 3.5% to 7% P_2O_5. Although the CO_2 content of hydroxyl-fluor-carbonate apatites cannot be correlated with unit cell a-values, the unit cell a-values of these apatites do appear to be related to the NAC solubility and the fluorine content clearly can be related to solubility (Figure III.4).

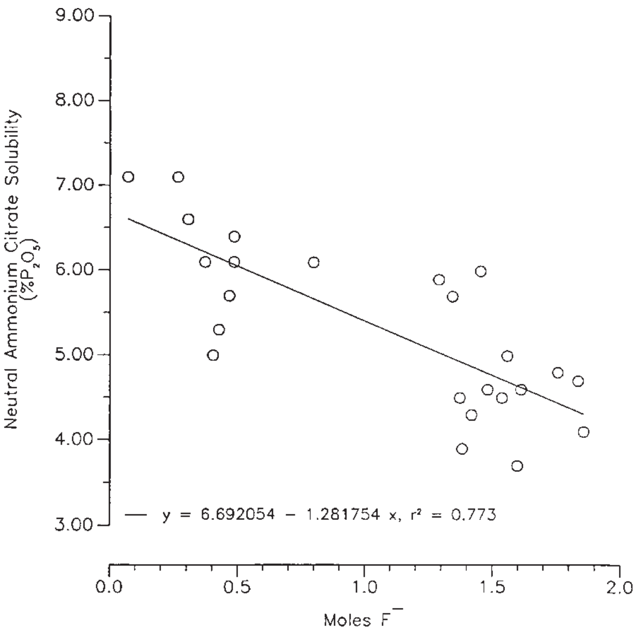


Figure III.4. **Relationship of the Fluorine Content of Hydroxyl-Fluor-Carbonate Apatites to Neutral Ammonium Citrate Solubility**

Igneous apatites have essentially no carbonate in their structures although at times traces of CO_2 are picked up in chemical analyses of igneous apatite crystals. As shown in Table III.9, the reactivities of igneous apatites as measured with NAC are very low, corresponding to values obtained from excess-fluorine francolites with essentially no carbonate substitution.

As previously mentioned in the discussion of excess-fluorine francolites, samples from the same deposits can have widely varying francolite a-values, CO_2 contents, and compositions. Samples from all

Table III.9. Neutral Ammonium Citrate Solubility (AOAC Method) of Some Igneous Apatite Concentrates

Deposit, Country	Total P_2O_5	NAC P_2O_5
	(wt %)	(% P_2O_5)
Palabora, S. Africa	36–41	0.4–1.5
Dorowa, Zimbabwe	33.1	0.8
Tapira, Brazil	35.4	0.8
Matongo, Burundi	39.6	1.3
Araxa, Brazil	36.1	1.4
Martison, Canada	37.8	1.5
Sukulu Hills, Uganda	41.0	1.6

types of sedimentary deposits, including those from the same deposits or from deposits within the same country, exhibit widely varying NAC solubilities due to compositional differences (Figure III.5).

The type of apatite and/or degree of carbonate substitution largely determines the reactivity as independently measured by reactivity tests and the suitability for direct application. The most highly carbonate-substituted sedimentary apatites have the highest reactivity and highest potential. Reactivity of sedimentary apatites decreases with decreasing carbonate substitution to a level where reactivities are essentially the same as those of igneous apatites. Igneous apatites have the lowest potential for direct application of all the apatites.

Aluminophosphate-containing phosphate rocks with high P_2O_5 contents can be calcined at low temperatures (550° to 600°C) to remove waters of hydration and alter the crystallinity of the aluminophosphate minerals. This treatment results in marked improvements in the availability of P_2O_5 as measured by common extraction procedures.

In Senegal, a product called Phos-Pal is produced by calcination of aluminophosphate ores. The Phos-Pal product contains 34% P_2O_5, and 26%–27% P_2O_5 is soluble in ammonium citrate (Joulie test).

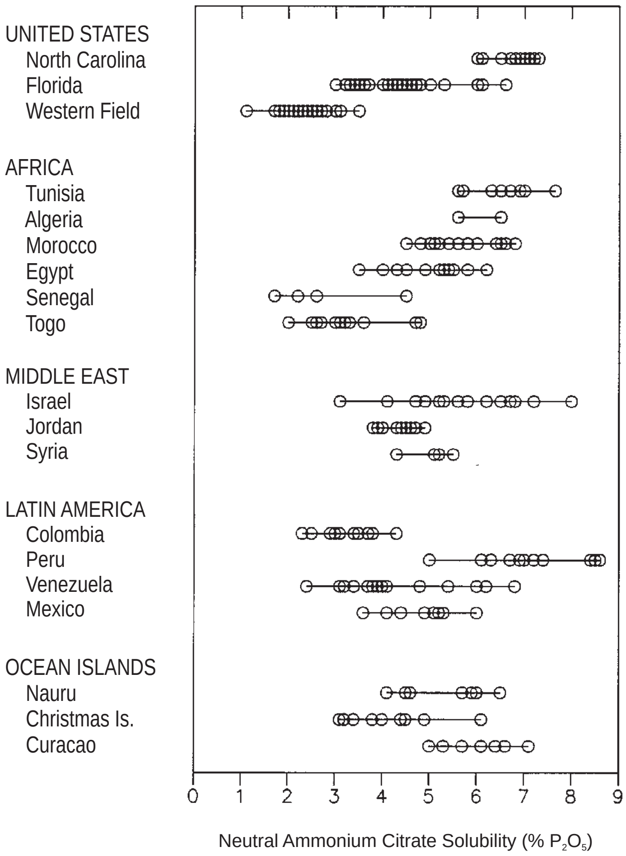


Figure III.5. Neutral Ammonium Citrate Solubilities of Sedimentary Phosphate Rocks From Various Countries

Two calcined aluminophosphate products, Calciphos (coarse product) and Citraphos (fine product), were produced by calcining Christmas Island C grade ore. The products had a total minimum P_2O_5 content of 30%; a minimum of 20% P_2O_5 was soluble in neutral ammonium citrate, and approximately 10% P_2O_5 was soluble in 2% citric acid or 2% formic acid. These products are not currently being produced.

Although determination of the type of apatite and reactivity of a phosphate rock may indicate the potential for direct application, many other factors are involved. These factors include type of crop (long or short term), soil pH and other soil characteristics, and climatic factors. Agronomic test work is needed to determine the potential for direct application under specific conditions or a range of conditions. Tables III.10 and III.11 list two classification

Table III.10. Proposed Classification by Diamond (1978) for Phosphate Rock for Direct Application Based Upon Solubility and Expected Initial Response

Rock Potential	Solubility (% P_2O_5)		
	Neutral Ammonium Citrate	Citric Acid	Formic Acid
High	>5.4	>9.4	>13.0
Medium	3.2–4.5	6.7–8.4	7.0–10.8
Low	<2.7	<6.0	<5.8

Table III.11. Ranking System by Hammond and Leon (1983) for Some South American Phosphate Rocks According to Their Solubility and Relative Agronomic Effectiveness (RAE)[a]

Soluble P_2O_5 in Neutral Ammonium Citrate	RAE	Solubility Ranking
(% P_2O_5)	(%)	
>5.9	>90	High
3.4–5.9	90–70	Medium
1.1–3.4	70–30	Low
<1.1	<30	Very low

a. $RAE\ \% = \frac{(yield\ of\ ground\ PR) = (yield\ of\ check)}{(yield\ of\ TSP) = (yield\ of\ check)}\ x\ 100$

systems for phosphate rocks based on NAC, citric acid, and formic acid solubilities.

Effect of Phosphate Rock Texture and Mineralogy on Further Processing—The texture and mineralogic contents of phosphate rocks can have a profound effect on the possibilities for beneficiation. Phosphate rocks that contain large well-defined apatite crystals or phosphate grains that break cleanly from enclosing crystals or cements usually have good liberation characteristics and typically can be further processed. Phosphate rocks containing small apatite crystals or grains that may be well-intergrown with enclosing crystals or cements require finer grinding for liberation; further processing of such rocks usually results in high phosphate losses and lower grade concentrates.

Sedimentary phosphate rocks containing phosphate grains or a microcrystalline phosphate matrix with significant amounts of occluded gangue are typically very difficult to beneficiate to levels suitable for fertilizer processing. Fine clays or Fe and Al phosphates in unconsolidated sedimentary phosphate rocks can often be removed by simple water washing and size-classification methods (screening or hydrocyclones). Plate-like micas can also be removed by hydraulic methods. For weathered igneous phosphate rocks, attrition scrubbing may be required to remove Fe and Al phosphates and fine iron oxides from the surface of apatite grains. Magnetic or paramagnetic minerals can be removed by magnetic fields.

Chemical ratios and the level of certain chemical constituents can be important considerations in deposit assessment, beneficiation, and processing for use as fertilizers. One of the most useful criteria in the mineralogical and metallurgical evaluation of phosphate deposits is the CaO/P_2O_5 ratio. The CaO/P_2O_5 ratio of pure igneous apatite is approximately 1.32. For excess-fluorine francolite, CaO/P_2O_5 ratios can range from 1.66 to 1.32. In an unbeneficiated phosphate rock sample, this ratio may be influenced by the presence of other phosphate and nonphosphate minerals. The presence of calcium-aluminum, aluminum, and iron phosphates decreases the CaO/P_2O_5 ratio below that of the apatite that is present. Crandallite minerals have a CaO/P_2O_5 ratio of approximately 0.39. Wavellite and many iron phosphates contain no calcium ($CaO/P_2O_5 = 0$). If the CaO/P_2O_5 ratio of a phosphate rock is below the ratio predicted for the variety of apatite present, significant amounts of nonapatite phosphates may be present. Based on CaO/P_2O_5 ratios, mineralogic determinations, and beneficiation testwork, portions of or entire phosphate deposits may be deemed unsuitable for further processing.

Carbonate substitution in the apatite lattice increases the CaO/P_2O_5 ratio. The presence of other calcium-bearing minerals will also raise the CaO/P_2O_5 ratio above 1.32. In both sedimentary and igneous phosphate deposits, these calcium-bearing minerals often are calcite and dolomite. Calcium-bearing silicates such as augite, feldspars, and clays also may raise the ratio.

Many fertilizer-processing calculations are based on CaO levels and/or CaO/P_2O_5 ratios. Acid consumption in acid attack processing is primarily related to CaO contents, and the relative yield of P_2O_5 is closely related to the CaO/P_2O_5 ratio. The presence of carbonates results in the increased consumption of costly acids. Ca-bearing silicates may be highly resistant to acid attack and are relatively inert.

The characteristics of potential ores from a deposit are critical in the evaluation of the deposit. For instance, low CaO/P_2O_5 ratios and elevated Fe_2O_3 and Al_2O_3 contents may be indicative of undesirable ore zones. Knowledge of these factors can guide further planning and exploration. Chemical analysis (and expenses for analyses) can be limited to those analyses that are actually needed to adequately define potential ore zones. Portions of deposits with unsuitable ore types may be eliminated from resource/reserve calculations. Portions of deposits may be determined to have slightly different characteristics and may require different processing methods. The first evaluation of a phosphate deposit should probably include some type or level of characterization studies. Many aspects of phosphate characterization that initially may seem minor to nonspecialists may be critical at some point in later studies.

Phosphate Rock Mining

The most successful phosphate mining operations in the world generally involve high-volume removal of waste and ore, low or reasonable costs for upgrading, ore suitable for upgrading to prevailing market-grade specifications, and large annual concentrate output. Successful export-oriented mining operations are also generally located within 200 km of the coast and a port, or where there is a well-developed transportation network to a port or markets.

A wide variety of techniques and many types of equipment are used to mine and process phosphate rock. Phosphate rock is mined by both surface (open cast or strip mining) and underground methods.

Surface Methods—Surface mining can take many forms, from manual methods employing picks and shovels to highly mechanized operations. Surface mining is by far the most utilized method for mining phosphate deposits. Surface mining methods are typically less costly and are always the preferred method when deposit geometry and other factors are favorable.

In very small mines, hand labor may be used to excavate phosphate rock from the surface; front-end loaders may be used to load the rock into trucks. Small power shovels, bulldozers, front-end loaders, and dump trucks may be used to strip overburden and mine soft phosphate beds or zones. Dozer/rippers may be used to strip overburden and mine the beds.

If the ore bodies are irregular, small diesel draglines and power shovels may be used to mine soft phosphate deposits at the surface. Small dump trucks may be used for transport. If sedimentary ores are very soft and dip at high angles, bulldozers with vertical scraper blades may peel off layers of ore; then earthmovers may be used to scrape up the ore and move it to storage piles.

In very large-scale operations, bucket-wheel excavators or large electric walking draglines are used to both strip soft overburden and mine essentially flat-lying soft phosphate beds. Typical bucket sizes may range from 40 m^3 to 70 m^3. The draglines must have a relatively flat and stable surface to work from and walk on. Bulldozers, dump trucks, graders, earthmovers, power shovels, and various other equipment are used for site preparation. This type of equipment is also used for land reclamation once an area is mined-out.

From the mine the ore may be transported to the beneficiation plant by several methods. At the mine face, flexibility is required, and the ore may be transported by truck or conveyor belt. If rail transport is used, there generally must be a secondary loading site. If the availability of fresh water is not an issue, ores may be slurried and transported by pipeline.

Underground Methods—There are several underground phosphate rock mining operations in the world and, just as with surface mining, the methods used range from labor intensive to highly mechanized.

With highly dipping beds and hard phosphate rock, methods such as block caving, inclined room and pillar, shrinkage stoping, and sublevel caving may be employed. For moderately well-cemented, relatively flat-lying sedimentary beds, room and pillar methods can be used. Such a mine might use continuous miners or long-wall techniques. Conveyors are generally used to move the rock to a beneficiation plant stockpile.

Beneficiation of Phosphate Rock

Increasing world fertilizer demand in the 1960s and 1970s and the need for phosphate feedstocks stimulated efforts to develop techniques to upgrade low-grade ores and remove impurities. Among the common impurities (gangue minerals) associated with phosphate ores are:

- Clays (kaolinite, illite, smectites, and attapulgite).
- Quartz and other silicates (usually feldspars).
- Carbonates (mainly calcite and dolomite).
- Secondary phosphates (iron- and aluminum-bearing phosphates).
- Iron oxides (goethite, hematite, and magnetite).

It is highly desirable, for both economic and technical reasons, to remove as much of these impurities as possible and thus to increase the apatite content and the grade of phosphate feedstocks and improve the chemical quality. Phosphate ores can be beneficiated by many methods, and usually a combination of methods is used.

Beneficiation Techniques—In phosphate rock beneficiation, the availability of water is of prime importance and may dictate the process or processes used. The total lack of water or lack of availability of freshwater may exclude deposits from development or restrict capacity. In areas where water availability is severely restricted, dry screening may be an effective way to produce preconcentrates or concentrates if ore characteristics are suitable. Seawater or brackish water may be used for washing and size classification. Seawater may also be used for flotation. Where seawater or brackish water is used for beneficiation, a freshwater final rinse is needed to remove as much chloride as possible from the final concentrate. Even in areas of the world where freshwater availability is not as restricted, water is usually carefully managed, and most of the water may be recycled.

Clays, fine-grained iron-aluminum phosphates, and fine-grained iron oxides can often be fairly simply removed from phosphate ores by using combinations of comminution, scrubbing, water washing, screening, and/or hydrocyclones. The disposal of fine ore constituents can be problematic.

The beneficiation technique of froth flotation is widely used within the world phosphate industry. Froth flotation is generally employed with silicious ores when other less expensive or less complicated techniques fail to produce phosphate concentrates suitable for chemical processing.

The removal of carbonates from phosphate rock has been the focus of significant research efforts for several reasons. Many countries have large deposits of phosphate rock that contain significant amounts of calcite ($CaCO_3$) and dolomite ($CaMg[CO_3]_2$). Many of these deposits are not exploitable using existing beneficiation technology. It is desirable to reduce the free carbonate contents of phosphate ores and concentrates as much as possible.

Several treatments have been proposed for the removal of free carbonates from phosphate ores including:

- Flotation (Lawendy and McClellan, 1993; Lawendy et al., 1987).
- Acid washing (Abu-Eishah, et al., 1991).
- Calcination (Doheim et al., 1978).
- Magnetic separation (Unkelbach and Wasmuth, 1991).
- Heavy media separation (Lawendy and McClellan, 1993).

Heavy media separation can be utilized when the phosphate grains are liberated from the associated gangue minerals at relatively coarse sizes. Magnetic separation may be possible when the carbonates are contaminated with iron oxides. Calcination of phosphate ores to remove carbonates is expensive because of the high costs of energy used to attain the temperatures necessary to thermally disassociate carbonates (approximately 780° to 835°C).

Flotation of calcareous and dolomitic phosphate ores seems to be the most economically viable technical alternative. However, selective flotation of carbonates from phosphate is rather difficult due to the similarity in the physico-chemical properties of carbonate and phosphate minerals. Carbonate/phosphate separation by flotation is commercially used in Finland and Brazil to treat igneous phosphate ores. Both direct and reverse phosphate and carbonate flotation techniques have been tested for effectiveness in upgrading sedimentary phosphate ores with high carbonate contents. Flotation is used in China and India to treat dolomite-containing sedimentary phosphate ores.

Various methods have been developed for the removal of iron gangue minerals from phosphate rocks, including scrubbing and size classification (IFDC, 1990), magnetic separation (Russel, 1992), and flotation (Lawendy and Van Kauwenbergh, 1993). Quite often combinations of two of these methods are used to reduce the iron content of concentrates to acceptable levels.

The design of the beneficiation processes can vary widely depending on the characteristics of the ores being processed. For soft sedimentary phosphate ores, beneficiation flowsheets can be as simple as washing and size classification. Beneficiation flowsheets can also be very complicated when several size-classification steps, several stages of flotation, or other processing steps are used. For further details concerning beneficiation, see UNIDO/IFDC (1998).

Factors Affecting Quality of Phosphate Rock

The wide variety of geologic settings in which phosphate rocks occur results in textures, accessory mineral assemblages, and chemical compositions that range from simple to very complex. Variations in quality from a single phosphate rock source can arise because continuous mining removes beds or ore zones that have internal variations, and beneficiation processes may deviate from normal practices for various technical or economic reasons. Impurity contents and compositional differences not only contribute to processing difficulties that have an indirect effect on product quality but also can directly contribute to variations in fertilizer product compositions.

The principal market specification relating to the P_2O_5 content (grade) of phosphate rock is not a reliable indicator of the potential quality of phosphate fertilizer produced by a particular process, nor is it an indicator of the similarity of equivalent grade phosphate rocks from different sources. In general, lower P_2O_5 means higher impurity contents. Lower P_2O_5 content results in lower yields, and high impurity contents result in more processing problems and higher costs. Variability in phosphate rock composition contributes to the quality factors (physical and chemical) summarized in Table III.12 (Lehr, 1980). The effects of impurities are not all negative. The presence of some impurities has a positive effect during processing and/or on the physical properties of products (McClellan and Lehr, 1982; Smith, 1991).

Physical Factors—Processing of commercial phosphate rock concentrates depends to a large extent upon their texture. In general, a phosphate rock concentrate has the ideal texture for processing when it is disaggregated and contains relatively soft

Table III.12. Quality Factors for Commercial Phosphate Rocks

Physical Factors
Texture: hardness, porosity, cementing, or coating phases
Phosphate particle size: coarse to cryptocrystalline
Degree of crystallinity of the apatite
Effect of physical treatments: natural or calcined state

Chemical Factors
P content of phosphate rock (BPL grade)
F content of the apatite
Carbonate content of the apatite
Free carbonate content
CaO/P_2O_5 weight ratio (phosphate and accessory mineral sources)
Fe and Al content (combined R_2O_3)
Mg content (phosphate and accessory mineral sources)
Content of inert mineral gangue (insoluble oxides and silicates)
Na and K (phosphate and accessory mineral sources)
Organic matter (native types + beneficiation reagents)
Chlorides (from evaporite salts, phosphate substitution, process water)
Heavy metals (Cd, Pb, Zn, Hg)
Potentially toxic elements (Se, As, Cr, V)
Radionucleides (U, Th, Ra, Rn) from phosphate minerals

but competent porous, sand-sized sedimentary phosphate particles that are easily handled and metered mechanically. Grinding of these phosphates to a particle size range required for phosphate fertilizer manufacture usually presents no major problems. Concentrates with porous phosphate particles that occur naturally in a suitable size range can be used for phosphoric acid manufacture without grinding. Many of these desired textural properties are common to many sedimentary phosphate concentrates, but not to concentrates produced from igneous or metamorphic phosphate deposits (McClellan and Gremillion, 1980).

Sedimentary phosphate rocks with compact, indurated, coarse particles or concentrates containing coarse apatite crystals such as those of igneous or metamorphic origin are often slowly reactive in acidulation processes. Reaction/retention times may become long, and phosphate losses may become unacceptable due to blinding of phosphate particle surfaces. These types of concentrates may require fine grinding to an acceptable particle size. A common grind for relatively unreactive phosphate rocks is 70% minus 200-mesh (Tyler). Calcined phosphate rocks may have low reactivity because of agglomeration, loss of porosity, and thermally induced crystal growth of the apatite. When francolites are treated with heat, carbonate is expulsed and the apatite recrystallizes, producing apatites similar in composition and reactivity to igneous apatites.

Chemical Factors—In spite of the known physical, mineralogical, and chemical differences that exist among various types of phosphate rocks, grade is typically the primary criterion used to differentiate phosphate rocks and is often expressed in terms of tricalcium phosphate [$Ca_3(PO_4)_2$]. The trade name for tricalcium phosphate is “bone phosphate of lime” or BPL. Early workers believed that tricalcium phosphate was the chief constituent of commercial phosphate rock. Because these commercial terms are widely used, the following conversion factors are included for reference purposes:

$$\begin{aligned} P_2O_5 &= 0.4576 \times \text{BPL} \\ \text{BPL} &= 2.1852 \times P_2O_5 \\ P &= 0.1997 \times \text{BPL} \end{aligned}$$

Commercial phosphate rocks vary in grade from about 80 BPL to about 60 BPL. Most international trade involves the higher grade phosphate rock, and lower grade rock is often used at local processing facilities.

*Phosphorus Content***—**A somewhat ill-defined terminology may be used to indicate processing quality according to grade although no absolute marketing specifications presently exist. Each producer will have its own specifications. Trade organizations have established grade categories for record-keeping purposes. For example, the International Fertilizer Industry Association (IFA), Paris, France, uses five grade categories at the present time:

- 65 BPL and under.
- 66–68 BPL.
- 69–72 BPL.
- 73–77 BPL.
- 78 BPL and over.

Premium-grade phosphate rock concentrates were considered by Lehr (1980) to contain at least 31% P_2O_5 (over 68% BPL). Lehr (1980) considered phosphate concentrates to be nonpremium grades when the P_2O_5 content was below 31% and the concentrations of accessory mineral impurities were correspondingly higher. Regardless of grade, marginal phosphate rocks were considered by Lehr to be raw materials with high contents of accessory mineral impurities that render them marginal or unsuitable for chemical processing. Robinson (1978) indicated that in Europe phosphate rocks were generally considered high grade if they had P_2O_5 contents in the 33%–39% range (over 72 BPL). Phosphate rocks were considered low grade if their P_2O_5 content was in the 28%–33% range.

Phosphate rocks from both igneous and sedimentary sources are generally lumped together by grade in statistical tabulations. There are very few sedimentary phosphate deposits from which most of the concentrate production is entirely over 33% P_2O_5. For several major sedimentary deposits, some of the production is over 33% P_2O_5 but most is below 33% P_2O_5. In contrast, concentrates produced from igneous phosphate rocks are almost invariably over 33% P_2O_5 and are usually over 35%–36% P_2O_5 (~78 BPL).

It is not important that phosphate rocks be placed in categories according to grade. It is important to realize that higher P_2O_5 contents translate to lower impurity contents. Increased P_2O_5 contents in concentrates result in increased yields per ton of material shipped, handled, and processed. Lower impurity contents generally result in increased reaction efficiencies, fewer processing problems, and less waste. In general, higher P_2O_5 concentrates command higher prices. Processing of phosphate rocks containing less P_2O_5 and more impurities results in lower product yields, higher processing costs, and less potential profit. Correspondingly, phosphate rocks with lower P_2O_5 content are priced lower.

Carbonates—Carbonate, to varying degrees, is part of the crystal structure of sedimentary apatite (francolite). It is desirable that the free carbonate contents of phosphate ores and concentrate be as low as possible. The carbonate content of internationally traded phosphate rock is usually minimal and generally confined to the apatite component. Carbonates cause foaming in the production of phosphoric acid and consume valuable acid in any acid attack processing scheme. A benefit of the carbonate content of the francolite in phosphate rock is seen in the manufacturing of SSP and TSP by the den process. Phosphate rocks that contain carbonate produce a porous, friable den product that is more easily cut and handled.

Iron and Aluminum—High iron and aluminum contents are not desirable in commercial phosphate concentrates. High R_2O_3 ($Al_2O_3 + Fe_2O_3$) contents can lead to poor physical properties in superphosphates, fertilizer intermediates that are difficult to handle, and phosphoric acid-based products that are difficult to dry and that may cake in storage. When concentrations of R_2O_3 exceed about 3%, problems resulting from precipitation of iron and aluminum phosphate compounds can be expected during concentration, cooling, and storage of phosphoric acid. Fertilizers produced from phosphate rocks and phosphoric acid containing high amounts of R_2O_3 also contain less water-soluble P_2O_5 as a percentage of total P_2O_5 due to the formation of water-insoluble iron and aluminum compounds. Furthermore, the presence of high iron and aluminum contents can lead to reversion of water-soluble P_2O_5 compounds to insoluble compounds over the passage of time in storage. An acceptable level of the R_2O_3/P_2O_5 weight ratio in phosphate rock feedstocks for processing to fertilizers is about 0.1 or less (McClellan and Lehr, 1982).

The presence of impurities in phosphate rock is not entirely negative. Low aluminum contents (<0.1%–0.2%) in phosphate rock concentrates can lead to needle-like gypsum crystal formation in phosphoric acid manufacture, low filtration rates, low wash efficiency, and unacceptable P_2O_5 recovery. Low Al_2O_3 and perhaps low Fe_2O_3 content in phosphoric acid used to produce ammonium phosphates results in products that tend to cake easily. During the granulation of SSP and TSP produced from high-purity phosphate rock and phosphoric acid, iron-rich high-aluminum clays (kaolinites) have been added to promote granulation and assist in the formation of strong granules.

Magnesium—High magnesium contents in concert with high R_2O_3 contents result in similar processing and product problems. High magnesium contents can result in the formation of compounds that increase the viscosity of phosphoric acid upon concentration, even when the R_2O_3 contents are low. The presence of magnesium leads to the precipitation of insoluble phosphate compounds in the manufacture of liquid ammonium phosphate fertilizers.

Fluorine Content—Phosphate concentrates with high fluorine contents and low silica contents yield phosphoric acid that is high in fluorine. In the production of phosphoric acid, excess free fluorine ions result in long, thin, needle-like phosphogypsum crystals, which are difficult to filter and have a low washing efficiency and a high final cake moisture. When a phosphate rock has excess fluorine, the addition of active silica is beneficial to improve the crystal shape (Smith, 1991). Free aluminum and magnesium may react with fluorine to lower the free fluorine content. High fluorine contents in phosphoric acid have a marked influence on the kinds and amounts of insoluble precipitates that form in the ammoniation products, and the concentration of the residual fluorine in liquid fertilizers is especially critical (Lehr, 1968).

Silica and Silicates—Silica present as crystalline quartz is generally unreactive in any acid attack scheme and mainly acts as a diluent. Crystalline quartz increases the erosion rate for beneficiation and fertilizer processing equipment. Fine crystalline quartz can hamper filtration by filling the pores of the cake and plugging the filter cloth. Active silica has a positive effect on the reduction of corrosion, as it complexes with the free fluorine ions and influences the crystallization of phosphogypsum (Smith, 1991). During phosphoric acid manufacture, blinding of the filter cloth can occur when colloidal silica is formed in the reaction medium.

Sodium and Potassium—The quantity of sodium or potassium in the phosphate rock has an impact on the scaling tendency during phosphoric acid production. If sufficient fluorine and dissolved silica are present in the acid, the formation of Na_2SiF_6 and K_2SiF_6 is expected to increase scaling in the filter circuit. These compounds are water insoluble and act as diluents in MAP, DAP, and nitrophosphates.

Strontium—Strontium sulfate ($SrSO_4$) has a minimum solubility in 40% phosphoric acid. $SrSO_4$ forms a scale in the heat exchangers of phosphoric acid concentrators. An extremely thin film of this precipitate causes pronounced reductions in the capacities of such units (Smith, 1991).

Organic Matter—Some forms of organic compounds give rise to persistent foams that require the use of antifoaming agents. The presence of organic matter may result in NO_x release in nitrophosphate manufacture. During processing, the presence of organic matter may result in odors that may persist and be objectionable to the population near a fertilizer plant. Organic matter may be a benefit if the phosphate rock is processed by the electric furnace method where the organic matter burns and reduces fuel and energy requirements.

Sulfides—During acidulation, sulfides can release H_2S, which is a toxic gas. Sulfides produce reducing conditions, increase corrosion rates in phosphoric acid manufacture, and give NO_x release in nitrophosphate manufacture.

Chlorides—The usual sources of chloride ions in phosphate concentrates are the naturally occurring salts found in some sedimentary ores or from seawater or brackish water that might have been used in beneficiation. Chlorides sharply increase the corrosion rates of stainless steel equipment during acidulation. In general, chloride contents higher than 200–300 ppm cannot be tolerated because corrosion rates for common stainless steels then become excessive (McClellan and Lehr, 1982). With special steels, use of plastics, and special concrete construction, higher Cl contents can be tolerated.

Heavy Metals—Heavy metals do not appear to have any adverse effect on fertilizer manufacture but may be potentially hazardous. In particular, cadmium (Cd) is a cause of concern. Some countries have imposed limits on the cadmium contents of fertilizers.

There is no known process that is capable of economically removing Cd from phosphate ores at minimal cost. At the present time very low cadmium contents in fertilizers can only be reached economically by using phosphate rocks with low cadmium contents.

Cadmium content may be especially high in some sedimentary deposits (Van Kauwenbergh, 1997). Legislation enacted, particularly in Europe, or pending legislation may preclude the direct use of phosphate rocks from many sedimentary deposits for fertilizer products. For a review of the issue of cadmium in phosphate rock and fertilizer products, see Van Kauwenbergh (2001a; 2001b).

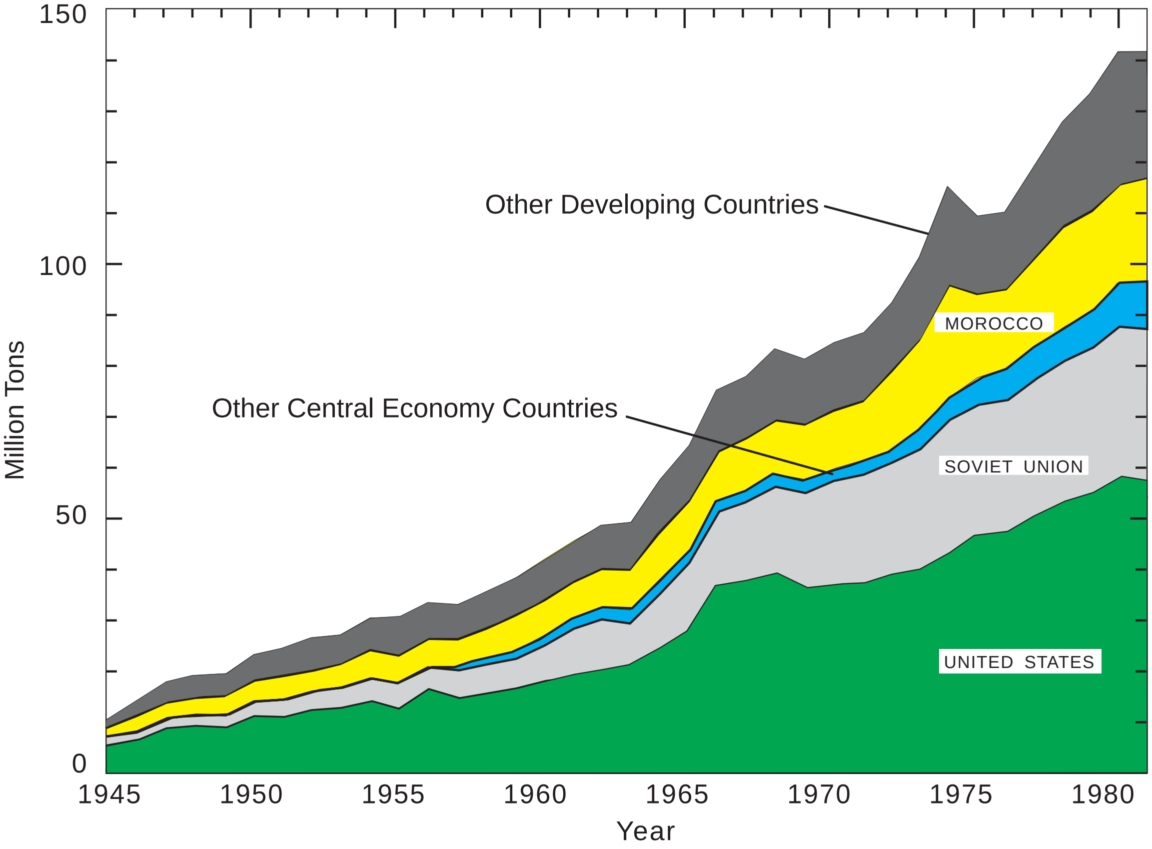
Radionuclides—Radioactivity of the commercial phosphate rocks typically does not interfere with fertilizer manufacture but must be considered because of potential health hazards. Recent interest has been focused on uranium (U) and radium (Ra), regarding both recovery and potential health hazards in manufacturing and in handling byproducts and final products.

Measuring and Estimating the Impact of Factors Affecting Phosphate Rock Quality—The quality of phosphate rock influences the design, capital costs, and operating costs of processing facilities. If a phosphate rock source has been used for many years, a wealth of engineering data and expertise has probably been developed concerning its use. However, when new or different sources of phosphate feedstock are to be used, the effects of physical and chemical factors can often be determined only by laboratory and pilot plant-scale testwork. In comparative studies, unknowns are compared with phosphate rocks or intermediates with known processing characteristics and specified processing conditions. The data from such tests can be used in designing or modifying processing plants. It should be stressed that such tests should simulate industrial processes as closely as possible, and be of sufficient scale and duration to provide reliable data for design purposes.

World Phosphate Rock Production and Quality

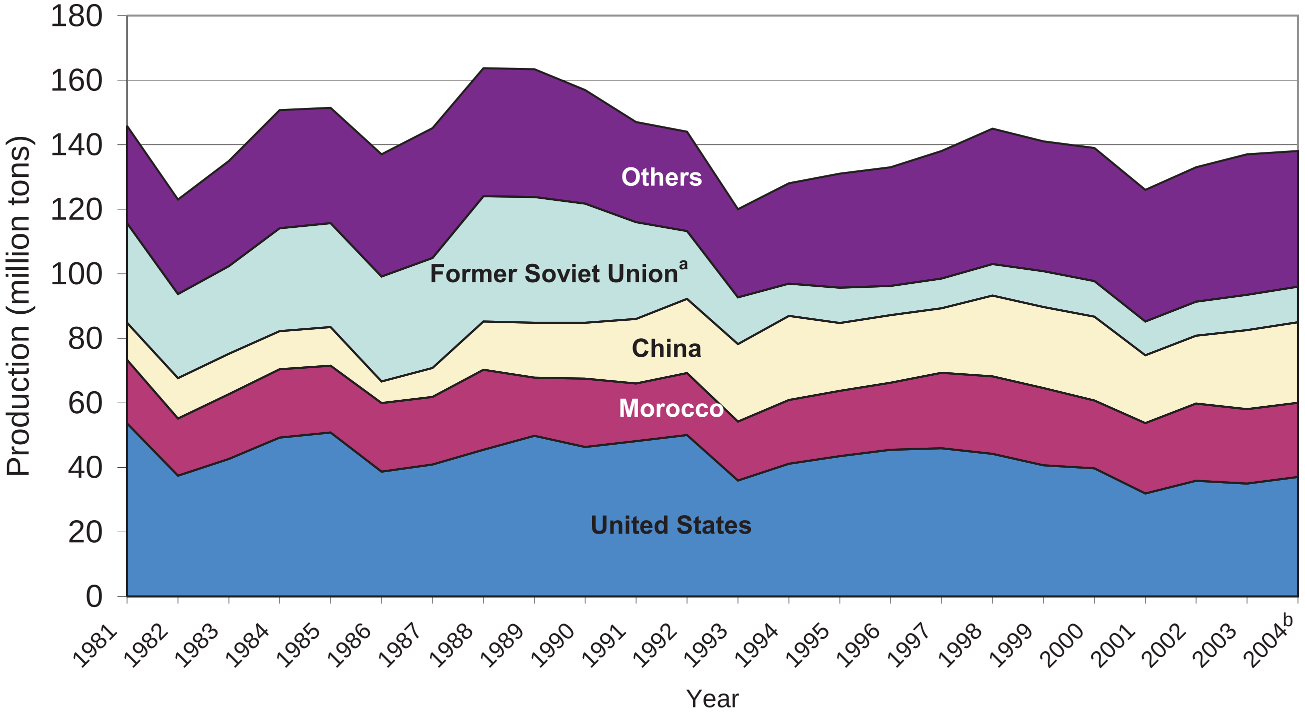
Commercial production of phosphate rock for the manufacture of fertilizers began in the mid-19th century. In 1847, about 500 tons of phosphate rock was mined in Suffolk, England (Gray, 1930). World production increased to 5,000 tons in 1850, 10,000 tons in 1853, over 100,000 tons in 1865, over 1 million tons in 1885, over 10 million tons in 1928, and over 100 million tons in 1974. In the mid-1970s, one estimate indicated that phosphate rock production would be about 300 million tons by the year 2000 (Anonymous, 1976).

Such estimates proved to be overly optimistic. Figure III.6 shows the growth in production between 1945 and 1981. In 1945 total world concentrate tonnage was just over 10 million tons. Growth in phosphate concentrate production seems to have increased linearly to about the mid-1960s, reaching a level of about 50 million tons. An abrupt increase in the growth rate then occurred. In the 1980s and into the early 1990s, phosphate rock production growth stagnated (Figure III.7) and seemed to have leveled off at a world production rate of around 150–160 million tons prior to the breakup of the Soviet Union (1990/91).



Source: Krauss et al. (1984).

Figure III.6. World Mine Production of Phosphate Concentrate, 1945–1981



a. 1992–1997 FSU data include Kazakhstan, Uzbekistan, and Russia data. 1998–2004 FSU data include Russia only.
b. Year 2004 Estimated.

Source: Compiled from USGS (1984–2005).

Figure III.7. World Phosphate Rock Production, 1981–2004

World phosphate rock production figures for 1988 are given in Table III.13. The figures for 1988 were chosen for illustrative purposes; the Soviet Union was still intact, and the world phosphate market was relatively stable at this time. Based on 1988 data, four countries—the United States, the Former Soviet Union (FSU), Morocco (including Western Sahara), and China—collectively produced about 75% of the world's phosphate rock. The top 12 countries produced about 95% of the world's total phosphate rock.

Trade conflicts in the world phosphate market in 1989 did not prove to deter phosphate rock production, and world production remained at approximately 163 million tons, according to the United States Geological Survey (USGS, 1984–2005). In 1990 world production fell to about 154 million tons. The U.S. production decreased about 4 million tons, and perhaps the first changes were occurring in the FSU where production was down about 4 million tons.

With the advent of significant social changes in the FSU and associated economic disruption, FSU production slumped from about 35 million tons of phosphate rock in 1990 to about 29 million tons in 1991. Overall world production dropped further to about 147 million tons in 1991 (USGS, 1984–2005). Due mainly to further decreases in production from the FSU and slightly reduced production in the United States, world phosphate rock production fell to about 144 million tons in 1992. World production reached a low point in 1993, mainly due to reduced production from the FSU but also due to reduced production from the United States.

For comparison with 1988 data (Table III.13), one set of world phosphate rock production estimates for 2003 is given in Table III.14, the last year for which firm figures are available. Although the data may not be strictly comparable because they were obtained from different sources (IFDC unpublished data; Mew, 2004; USGS, 1984–2005), it is interesting to note that several producers have changed

Table III.13. World Phosphate Rock Production, 1988

	Thousand Tons of Product	% of World Total
United States	45,389	28.0
Former Soviet Union	34,400	21.2
Morocco and Western Sahara	25,015	15.4
China	16,600	10.2
Subtotal Top Four	**121,404**	**74.8**
Jordan	6,611	4.1
Tunisia	6,103	3.7
Brazil	4,672	2.9
Israel	3,479	2.1
Togo	3,464	2.1
Republic of South Africa	2,850	1.7
Syria	2,342	1.4
Senegal	2,326	1.4
Subtotal Top Twelve	**153,251**	**94.6**
Nauru	1,540	0.8
Algeria	1,332	0.8
Iraq	1,273	0.8
Egypt	1,146	0.7
Mexico	835	0.7
India	739	0.4
Finland	584	0.3
North Korea	500	0.3
Vietnam	330	0.2
Sweden	142	0.1
Zimbabwe	125	0.1
Turkey	74	<0.1
Colombia	35	<0.1
Pakistan	35	<0.1
Sri Lanka	23	<0.1
Tanzania	15	<0.1
Australia	13	<0.1
Peru	13	<0.1
Mali	10	<0.1
Chile	9	<0.1
Thailand	8	<0.1
Philippines	8	<0.1
Indonesia	1	<0.1
Venezuela[a]	–	–
World Total	**162,041**	**100.0**[b]

a. No Venezuela production reported for 1988, 99,000 tons reported for 1987, and 237,000 tons reported for 1989.

b. Totals may not add to 100% due to rounding.

Source: Stowasser (1990).

Table III.14. Estimated World Phosphate Rock Production, 2003[a]

	Thousand Tons of Product	% of World Total
China[b]	42,120	27.0
United States	35,000	22.5
Morocco	23,340	15.0
Russia	11,000	7.1
Subtotal Top Four	**111,460**	**71.6**
Tunisia	7,890	5.1
Jordan	6,760	4.3
Brazil	5,600	3.6
Israel	3,210	2.1
Republic of South Africa	2,920	1.9
Syria	2,430	1.6
Australia	2,290	1.5
Egypt	2,180	1.4
Subtotal Top Twelve	**144,740**	**92.9**
Senegal	1,760	1.1
Togo	1,480	0.9
Kazakhstan	1,300	0.8
India	1,180	0.7
Canada	1,000	0.6
Algeria	898	0.6
Vietnam	820	0.5
Finland	800	0.5
Christmas Island	590	0.4
Uzbekistan	430	0.3
Venezuela	400	0.3
Nauru	147	0.1
North Korea	100	<0.1
Colombia	44	<0.1
Peru	43	<0.1
Zimbabwe	31	<0.1
Sri Lanka	14	<0.1
World Total	**155,777**	**100.0**

a. Subtotals and totals may not add to 100% due to rounding.

b. Includes unofficial production.

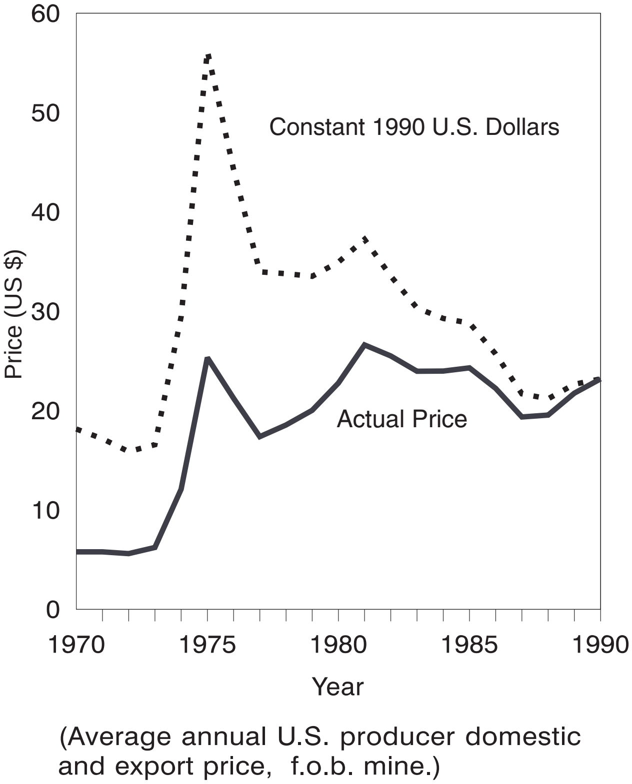
Sources: Mew (2004); USGS (1984–2005); IFDC unpublished data.

positions in their ranking. In 2003 China was the leading producer of phosphate rock in the world (using unofficial production figures). Total FSU (Russia, Uzbekistan, and Kazakhstan) production was approximately 37% of 1988 levels. Overall production was down 6.3 million tons from 1988 to 2003. The data indicate, however, that the top four producing countries still produced over 70% of the world's phosphate rock and the top 12 producing countries still produced over 90% of the world's phosphate rock.

Phosphate rock is a relatively low-cost bulk commodity. The average cost of phosphate rock in the United States was $27.01/ton in 2003. Since the so-called phosphate rock shortage of 1975, the price of U.S. phosphate rock in constant dollars steadily declined, with some minor recovery in 1980 and

1981 and in 1990 and 1991 (Figure III.8); however, prices dropped in 1993 and 1994 (Figure III.9). In general, world phosphate rock prices have behaved similarly to U.S. phosphate rock prices. In 1993 and 1994 world phosphate rock prices dropped to 20-year lows (Mew, 1994; Anonymous, 1994a).

World phosphate rock production capacity was estimated as 195.5 million tpy in 1990 (Stowasser, 1990). At 150 million tpy, world capacity utilization was about 77%. At 120 million tpy, world capacity utilization was about 61%. Perhaps most significant in this scenario were the production capacities of the two primary players in the export market—the United States (55 million tpy) and Morocco and Western Sahara (32 million tpy). Competition, together with the overcapacity of the major players and of the world as a whole, is one of the prime reasons that world phosphate rock prices continued to decrease until 1994/95.



Source: Stowasser (1991).

Figure III.8. Time-Price Relationships for Phosphate Rock, 1970–1990

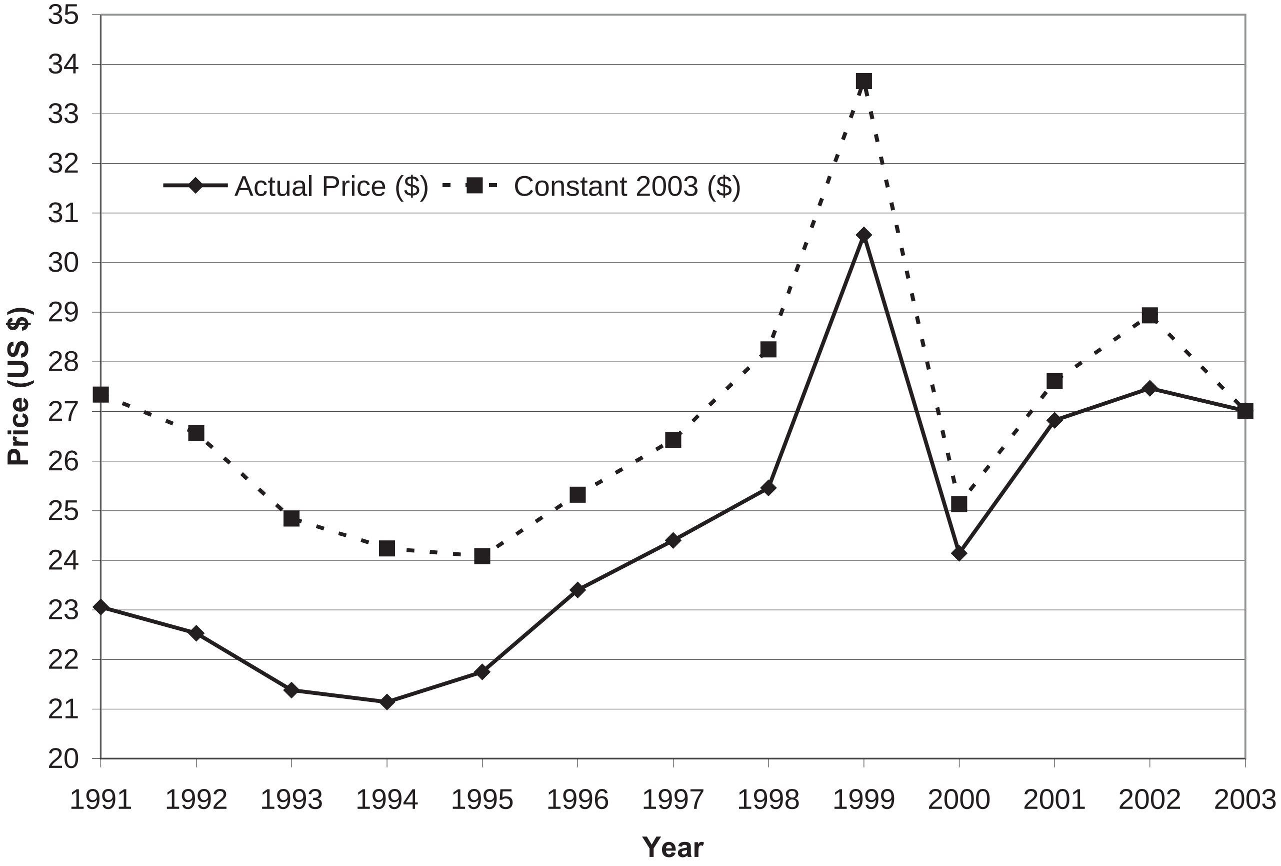
From 1994/95 to 1999 the price of U.S. phosphate rock steadily increased in terms of both actual price and constant 1999 dollars. In 2000 U.S. phosphate rock prices dropped over $8.00/ton; some recovery was seen in 2001, and prices remained relatively constant in 2002/03. In general, similar to the U.S. phosphate rock prices, world phosphate rock prices have increased over the last 5–6 years.

It has been widely suggested for many years that, in general, there has been a continuous decrease in world phosphate rock quality as reserves of high-quality rock are being depleted (McClellan and Gremillion, 1980; Anonymous, 1992). Perhaps it would be more appropriate to say that high-grade concentrates from some sources are becoming depleted (principally Florida) and, in general, the quality of phosphate rock that is utilized on a world-wide basis is lower.

Table III.15 shows a breakdown of world phosphate rock production by grade as percentages of total production from 1971 to 2004. This breakdown of world production includes data from countries with centrally planned economies. Since 1971 a vast amount of growth occurred in the world phosphate rock and fertilizer industries, and most of the increased demand was satisfied by increased production of lower grade (–68 BPL) phosphate rock from sedimentary sources. Production of the very highest grade listed, principally from igneous sources, declined with the economic disruption in the FSU but appears to have stabilized at 16%–17% of total world production.

High-grade phosphate rock is available from several sedimentary and igneous sources, i.e., Togo, Senegal, Morocco, and South Africa. Because of the increase in demand and the generally lower quality of additional available phosphate rock, phosphate fertilizer process engineers have modified technologies and continually explore new technologies to cope with lower grade rocks containing higher levels of impurities. At the present time, phosphoric acid producers are utilizing phosphate rocks with P_2O_5 contents below 24%.

One factor that may have negatively influenced the fortunes of several producers of phosphate rock in the last decade is the presence of high levels of cadmium and other potentially hazardous elements in



Conversion to constant 2003 ($) based on Producer Price Index, *International Financial Statistics Yearbook*, 2004.

Source: USGS (1984–2005) for actual prices. Average annual U.S. producer domestic and export prices, f.o.b. mine.

Figure III.9. Time-Price Relationships for Phosphate Rock, 1991–2003

Table III.15. World Production of Phosphate Rock by Grade, 1971 to 2004

Time Period	Grade (BPL)			
	–68	69–72	73–77	78+
	(% of total production)			
2001–04	64.4	11.5	5.1	17.0
1996–2000	65.0	12.1	6.9	16.0
1991–95	58.7	17.5	7.6	16.2
1986–90	50.0	20.6	7.6	21.8
1981–85	48.9	21.1	8.2	21.8
1976–80	41.6	25.8	10.6	21.9
1971–75	39.5	18.4	23.8	23.8

Source: IFDC unpublished data.

the rock or fertilizer products produced from the rock. On the other hand, production or sale of products produced from sedimentary and igneous sources with low contents of potentially hazardous elements has apparently been stimulated.

World Phosphate Rock Reserves and Resources

There is no system accepted worldwide for classifying phosphate rock reserves and resources. In the best cases, facts and figures used to compile world phosphate rock reserves and resource estimates are derived from deposit-specific reports and generally available scientific papers. Both the reliability of information on most phosphate deposits concerning the extent of exploration and the criteria used to determine the economics of production or the potential for economic development are highly variable.

Reserves are defined as “identified resources of mineral- or fuel-bearing rock from which the mineral or fuel can be extracted profitably with existing technology and under present economic conditions” (Brobst and Pratt, 1973). The use of the term “reserves” usually indicates that enough exploration or development work has been done to define the extent and grade of a deposit with a reasonable degree of accuracy. It also indicates that the deposit could be mined and processed to recover a marketable product at the time of the study or under a specified economic scenario. This terminology and this type of highly detailed reserve/resource classification system have been developed by the United States Bureau of Mines (USBM) and the USGS (USGS, 1982). Many international authors may use this terminology. However, adherence to the definitions for certain terms can be highly variable.

Reserve estimates may be stated in terms of the total amount of ore and percentage of P_2O_5, or the estimates may be stated as the amount and grade of recoverable product. Estimates of the amount of product potentially available from a deposit require extensive detailed information. When this detailed information is not available, assumptions must be made concerning the amount of the original P_2O_5 that can be recovered in the product and the eventual grade of the product.

Resources are defined as “reserves plus all other mineral deposits that may eventually become available—either known deposits that are not economically or technologically recoverable at present, or unknown deposits, rich or lean, that may be inferred to exist but have not yet been discovered” (Brobst and Pratt, 1973). Use of the term “resources” implies that the extent and quality of a phosphate deposit cannot be definitively estimated because of insufficient information. Use of the term resources also implies that the deposit or a portion of a deposit cannot be economically exploited under current conditions.

Most reserve/resource estimates are subjective; they depend on the standards assumed by the author or organization in determining the circumstances that may render a deposit economically useful. Substantial differences in reserve and/or resource estimates and other data may exist depending on the sources.

Phosphate deposits are widespread throughout the world (Figure III.10), occurring on all continents with the possible exception of Antarctica. Figure III.10 includes only those deposits that are currently worked, have been worked in the past, or have been shown in detailed studies to be potentially economically viable under certain conditions. The figure includes several very small deposits that are or have been worked for direct-application phosphate rock. The figure does not include every occurrence that might be termed a deposit. By definition, a deposit is “earth material of any type either consolidated or unconsolidated that has accumulated by some natural process or agent” (Bates and Jackson, 1980). The term “deposit” does not imply that phosphate exists in a form, quantity, or quality that is technically or economically feasible to produce. The average abundance of P_2O_5 in the earth’s crust is 0.22 wt % (Carmichael, 1982). A concentration of 1.0 wt % P_2O_5 is certainly anomalous and therefore can be termed a deposit.

Table III.16 illustrates world phosphate reserves and reserve base data (USGS, 1984–2005) for the top 16 producing countries. In this context, reserve base can be considered synonymous with resources. From these data, it is evident that the 16 listed countries possess about 94% of the world’s phosphate reserves. The reserve base data indicate that about 96% of all the phosphate resources of the world are found within these countries.

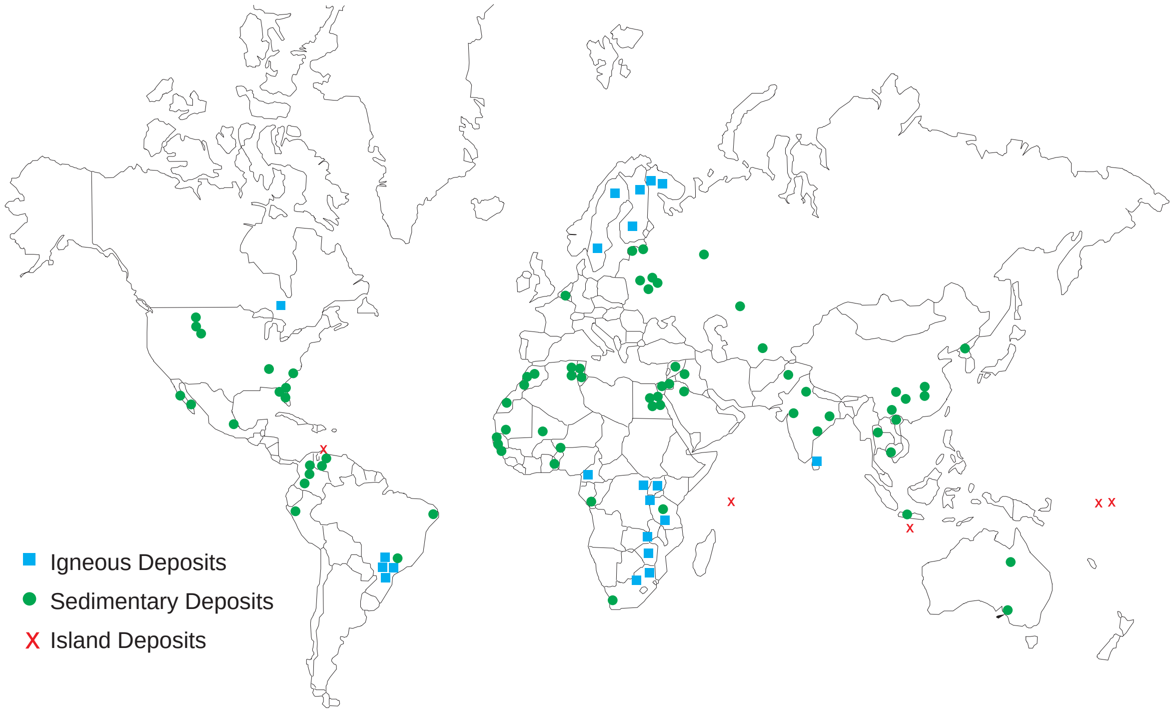


Figure III.10. Economic and Potentially Economic Phosphate Deposits of the World

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Table III.16. World Phosphate Rock Reserves and Reserve Base

	Reserves[a]	Reserve Base[b]
	(thousand tons)	
Australia	77,000	1,200,000
Brazil	260,000	370,000
Canada	25,000	200,000
China	6,600,000	13,000,000
Egypt	100,000	760,000
India	90,000	160,000
Israel	180,000	800,000
Jordan	900,000	1,700,000
Morocco and Western Sahara	5,700,000	21,000,000
Russia	200,000	1,000,000
Senegal	50,000	160,000
South Africa	1,500,000	2,500,000
Syria	100,000	800,000
Togo	30,000	60,000
Tunisia	100,000	600,000
United States	1,400,000	4,000,000
Other countries	1,000,000	2,000,000
World Total	**18,312,000**	**50,310,000**

a. Cost less than US $40/ton. Cost includes capital, operating expenses, taxes, royalties, and a 15% return on investment f.o.b. mine.

b. Criteria for reserve base established by a joint U.S. Bureau of Mines and U.S. Geological Survey working group.

Source: USGS (1984–2005).

Herring and Fantel (1993) modeled depletion of world phosphate rock reserves based on demand created by population growth. Various scenarios of unconstrained growth with no future additions to reserves were considered based on USBM world reserve data and a base year of 1990. The results of this study indicated that world reserves will be depleted in about 50 years from 1990, and additional resources (termed a modified reserve base), which may or may not be economically minable, would be depleted in perhaps another 50 years.

The United States and other countries will not, however, simply run out of phosphate rock at some predetermined date in the future. For example, Table III.17 indicates the amount of phosphate reserves available from various mining areas in the United States in terms of cost per ton. Most of the current reserve figures assume a maximum cost of $40/ton for estimates. If the cost of phosphate rock reaches $60/ton, the U.S. reserve base more than doubles to 2.8 billion (1 billion = 1 x 10^9) tons. These types of detailed data are not available for most other world producers although Fantel et al., (1985) have estimated the production costs from deposits in market economy countries, the United States, North Africa, and the Middle East (Figure III.11). It is reasonable to assume that a similar situation governs the reserve/resource situation in other countries around the world. If phosphate rock prices eventually rise worldwide, a portion of the phosphate rock now classified as resources in many countries will be reclassified as reserves.

Future Trends in World Phosphate Rock Production

Prior to the situation of the mid-1990s, World Bank estimates indicated that the stagnant phosphate rock market of the 1980s would continue until the end of the century (Constant and Sheldrick, 1990). By the year 2000, European imports might decline by 3–4 million tons, whereas Asian imports might increase by 2–3 million tons; overall there might be a decrease in total production. One source (Mew, 1990) indicated that the need for capital investment in new mines was expected to keep phosphate rock prices slowly increasing in the early 1990s. If investments in new mines were not forthcoming, depletion of reserves would cause a tight market in the mid-1990s and prices might rise sharply. Prices have increased slightly from the mid-1990s to the present.

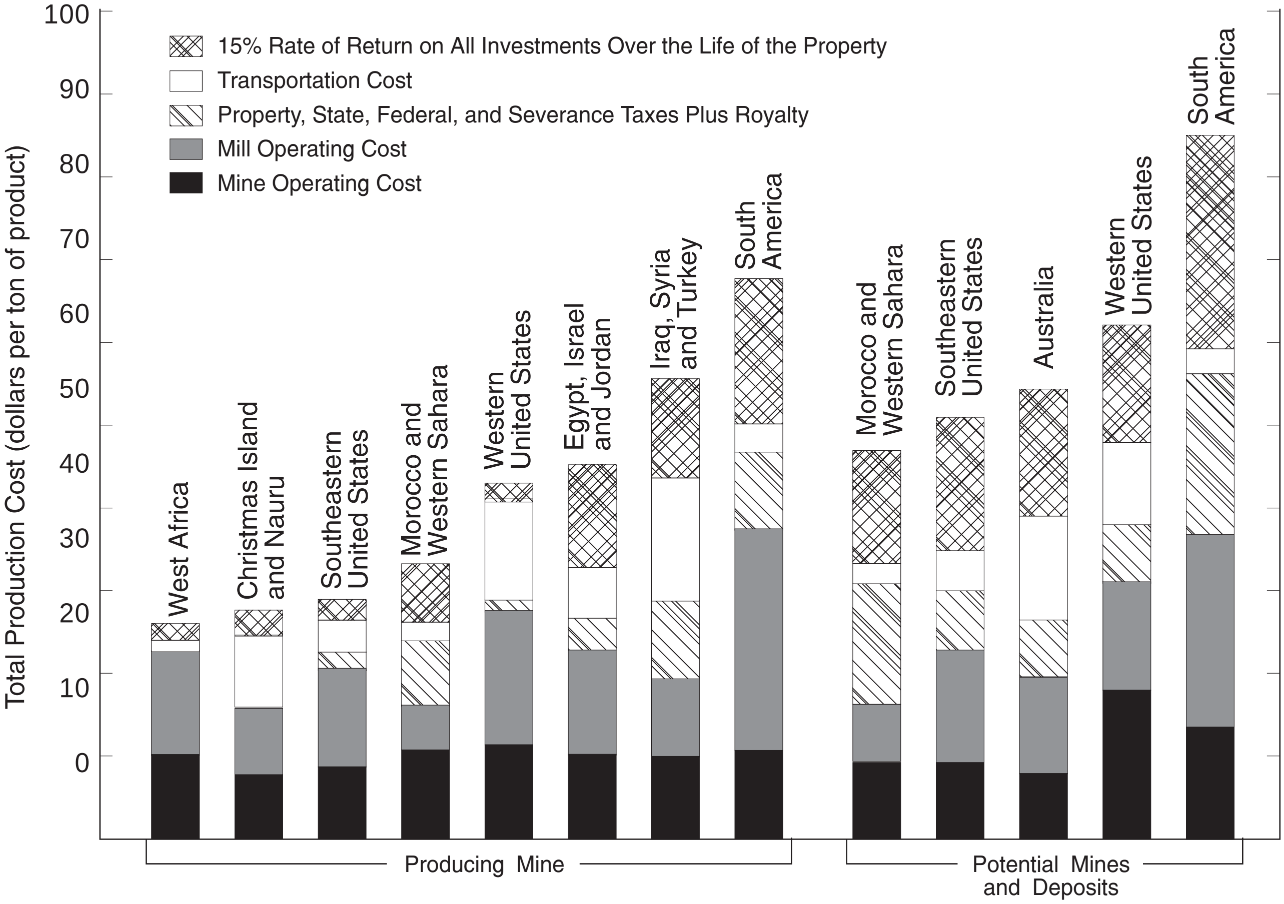
Beyond the year 2000, production from the southeastern United States was predicted by Stowasser (1991, 1992) to fall sharply (Table III.18) to about 31.2 million tons between the years 2000 and 2005 and to about 24.5 million tons by the year 2015. A projection to the year 2040 indicated that total U.S. phosphate rock production may be as low as 17.4 million tons (Stowasser, 1991). Several factors probably contributed to these analyses. Based on Stowasser's analyses (1991, 1992), U.S. production eventually would decrease and would not be able to meet U.S. agrochemical industry demands.

Table III.17. U.S. Phosphate Rock Reserve Base in Terms of Cost[a]

	Cost (1989, US $/ton)						
	<20	20–30	30–40	40–60	60–80	80–100	Total
	(million tons)						
Florida	224	263	258	1,101	520	173	2,539
North Carolina		392		339			731
Western United States		73	14	70	762	177	1,096
Tennessee	2	3		8			13
Total	**226**	**731**	**272**	**1,518**	**1,282**	**350**	**4,379**

a. Tons available at indicated cost.

Source: Stowasser (1991).



Source: Fantel et al. (1985).

Figure III.11. Estimated Production Costs for Selected World Phosphate Surface Mines and Deposits

Table III.18. Projected U.S. Phosphate Concentrate Production

	1995	2000	2005	2010	2015
	(million tons)				
Florida and North Carolina	39.2	48.1	31.2	24.5	24.5
Western United States	6.8	5.8	5.8	5.8	5.8
Total United States	**46.0**	**53.9**	**37.0**	**30.3**	**30.3**

Source: Stowasser (1991).

For many years, the Florida phosphate industry dominated world production. During the late 1980s and 1990s and into the new millennium, the Florida phosphate rock industry underwent considerable rationalization; several companies acquired mining lands, often through the acquisition of preexisting mining operations. At the present time, the three remaining companies that are mining phosphate rock in Florida are Mosaic, PCS Phosphates Co., and C.F. Industries. At present also, three and possibly four U.S. companies are purchasing Moroccan phosphate rock to produce phosphoric acid. Although the significant low-cost reserves have been depleted, the United States should be able to maintain a significant production capacity for several decades in the future. If demand is sufficient and/or the price of phosphate rock and phosphate fertilizer increases, it is also possible that additional new mines could be developed in the western United States and new mining techniques such as borehole mining might be used to produce deposits that presently are not economically recoverable.

Ten years ago China was not foreseen to become a significant exporter of phosphate in the future. The overall quality of the deposits is relatively low by world standards. Chinese phosphate rocks may contain high levels of MgO, CO_2, and/or silicate impurities, and the concentrates produced from these deposits are not generally suitable for export. However, in the last 10 years Chinese phosphate rock has been exported to Malaysia for direct application, and Chinese phosphate rock initially formed the basis for production at the Oswal DAP plant in southern India.

The future production status of the countries constituting the FSU is speculative. The sedimentary deposits of the FSU are generally of low grade and quality when compared with concentrates available on the world market. The Kola deposits, operated by P.O. Apatit, formed the core of FSU phosphate rock and fertilizer production capabilities. In 1989, P.O. Apatit produced about 20 million tons of phosphate rock. The production from the Kola mines for 2003 was 9.5 million tons. Due to the drop in demand and to rationalization and privatization, mines and several processing plants have been closed. The downturn of the Kola industry (and Russian economy) is also intimately intertwined with FSU sedimentary phosphate rock production and the fertilizer industry based on this rock. The production of many fertilizer plants in the FSU was based on high-quality phosphoric acid feedstock produced from Kola apatite and locally obtained lower grade sedimentary phosphate rock to produce off-grade TSP and SSP products. Undoubtedly, additional rationalization of the Russian industry will occur, and it is uncertain at what cost Kola rock can be produced and how competitive it will be on the world market.

Among the current top four phosphate rock producing countries, Morocco is certainly in the most advantageous position. Depending exactly on which reserve/resource classification is used, Morocco may possess over 30% of the world's estimated phosphate rock reserves. Morocco has invested heavily in the mining and downstream phosphate processing industry and has tremendous potential to expand both mining and processing activities. As in Florida, lower grade phosphate rock concentrates are used for production of added-value products, and higher grade phosphate rock is generally destined for the export market. Undoubtedly, Moroccan processing costs will increase in the future. However, production costs for new mines should eventually be less than production costs of new mines in the southeastern United States (Figure III.11).

In the future, potential increased production of phosphate rock may also come from Australia, Jordan, Iraq, or South Africa. As previously mentioned, the capacity of the WMC Fertilizer mine in Queensland is about 2.0 million tpy. If a suitable economic source of additional sulfur or sulfuric acid could be secured to support increased DAP production, production could be doubled with the addition of another DAP plant of the same capacity. Production from Jordan was expected to reach about 9 million tons by the year 2000 although this has not been realized. Production at current or declining levels is expected from Tunisia, Togo, Algeria, India, Israel, Senegal, Syria, Brazil, and Nauru. Mine-out on Nauru is expected in the next few years depending on the production rate.

Potentially increased phosphate rock production could come from several new mines, including:

- Sechura, Peru.
- Al-Jalamid, Saudi Arabia.
- Bofal-Loubboira, Mauritania.
- Farim, Guinea-Bissau.
- Sra Ouertane, Tunisia.

Development of the Sechura, Al-Jalamid, and Farim deposits has progressed to the point that the prime stakeholders have actively sought out partners and/or financing for development.

There is also the potential to discover new deposits. However, oil exploration programs have probed most of the coastal sedimentary basins of the world during the past 20–30 years, and any large-scale discoveries of phosphate rock probably would have occurred in conjunction with these activities.

Another source of future phosphate production is offshore deposits. Deposits of this type occur along the southeastern coast of the United States, on the Peru-Chile shelf, offshore Namibia, on the Chatham Rise off New Zealand, and offshore Baja California, Mexico, and the Republic of the Congo. At the present time, none of these offshore deposits are mined, and they probably will not be mined as long as ample reserves exist onshore.

Potassium Fertilizer Raw Materials

The most significant sources of potash in the world are buried deposits of potassium salts initially formed by the evaporation of water in large basins, as well as present-day salt lakes and natural brines.

Because many of these potash deposits are deeply buried, highly technical and capital-intensive mining techniques are required for exploitation. Potash ores or brines may be complex, and beneficiation and other recovery techniques may be technologically complex and energy intensive.

Geology, Mineralogy, and Origin of Potash Deposits

Large, deeply buried potash deposits are mainly associated with marine evaporite sequences and less commonly with nonmarine evaporites throughout the world. Potash deposits occur on every inhabited continent and have been identified in most geologic time periods from the Cambrian to the present.

The most abundant potash mineral in commercial potash deposits is sylvite (KCl). Sylvite and halite (NaCl) form the common potash ore called sylvinite. In most occurrences, fairly pure sylvinite exists with essentially no soluble sulfate or other salts. In other deposits, fairly pure carnallite ($KCl\ MgCl{\bullet}6H_2O$) is also found with halite. In only a limited number of deposits do soluble sulfate salts occur, such as zones of the Zechstein Basin (Europe) where the occurrence of “hartsalz” [sylvite plus halite with kieserite ($MgSO_4{\bullet}H_2O$) and/or anhydrite ($CaSO_4$)] is common. Double salts occur in deposits in Sicily and Ethiopia where kainite ($KCl{\bullet}MgSO_4{\bullet}3H_2O$) is predominant. Double salts also occur in the deposits of the Carlsbad, New Mexico area (United States) and the Carpathian region (Ukraine) where langbeinite ($K_2SO_4{\bullet}2MgSO_4$) occurs extensively. In many deposits, there are also some occurrences, or occasionally large amounts, of the insoluble mineral polyhalite ($K_2SO_4\ MgSO_4\ 2CaSO_4{\bullet}2H_2O$). In three locations around the world, sylvinite occurs with carnallite and tachyhydrite ($CaCl_2\ 2MgCl_2{\bullet}12H_2O$).

On a worldwide basis, there appear to be as many as 100 large buried potash deposits that could produce commercial products and about the same number of significant potash brine deposits. The buried deposits are primarily of marine origin. The exact mode of the formation of many of these large deposits, as well as a smaller number of deposits that are associated with hot springs, is not known and is the subject of considerable speculation.

Sodium and potassium are significant components of seawater. With sufficient evaporation, halite, epsomite, and potash double salts will crystallize. At some point in the geologic history of a potash deposit, this mixture of salts is transformed to either a kainite-epsomite-halite assemblage or more often to a carnallite-kieserite-halite assemblage, depending upon the extent of evaporation. There are no circumstances that will cause sylvite to be formed directly from seawater. It is generally recognized that, after evaporite formations are flooded with weaker brines, carnallite is converted to sylvinite, and kieserite is dissolved (Garrett, 1996). However, the kieserite dissolution part of this theory is controversial, and there is speculation that all or most of the sulfate content of the seawater may be removed before final evaporation, either by sulfate-reducing bacteria or by the intrusion of calcium chloride-bearing waters. Extensive diagenetic changes can and often did occur long after burial of potash deposits, which further complicates the subject.

Buried Potash Deposits—The potash deposits of the world vary widely in their size (ore resources and reserves), grade (minable % K_2O), and factors that impact economics, such as their location and the cost of mining and processing. The feasibility of mining and mining costs depend upon numerous factors:

- Capacity.
- Depth to the ore.
- Thickness and uniformity of the potash bed.
- Dip of the beds.
- Strength and integrity of the overlying strata (to form a strong roof).
- Danger of water intrusion (flooding).
- The attendant cost of penetrating the aquifer zones with shafts and pumping the water.
- Problems with toxic combustible gases or “rock bursts.”
- Amount of insolubles in the ore.
- Ease of “desliming,” the KCl-NaCl liberation size.
- Amount of impurities present.

Location is very important with respect to the deposit’s distance from markets, transportation, infrastructure, and the cost of transportation. Government royalties, taxes or fees, and possible special circumstances in selling the product (protective tariffs, local or controlled markets, reciprocal trade agreements, etc.) have a great impact on economics. Due to the complexity of these factors, those deposits that are the largest and that have the highest grade and potentially lowest production costs in the world may not be fully exploited, nor do they totally dominate the potash market. In order to provide insight into the complexity of buried potash deposits, a condensed review of some of the better known buried potash deposits is presented in the following pages. For more detailed information concerning potash deposits, see the UNIDO/IFDC *Fertilizer Manual* (1998).

Although the Brazil (Sergipe), Congo, and Thailand deposits are widely separated geographically, they are similar because they contain medium to small sylvite-bearing sylvinite formations with similar unusual mineral assemblages. There are commercial quantities of sylvinite, considerably more carnallite, significant amounts of tachyhydrite, and smaller quantities of bischofite ($MgCl_2$•$6H_2O$). All three deposits and their salt beds contain essentially no carbonates (calcite or dolomite) or gypsum (or anhydrite), except at the top of the sequences. The lower sections of the basins are filled with land-derived sediments, and the halite rests directly on these sediments. Potash occurs at the very edges of the basins, instead of in the more common structure of halite and/or anhydrite and dolomite surrounding the potash and covering a much wider area.

It appears that these deposits are of continental and not marine origin. The potash source could have been a high-Ca geothermal brine similar to the brines emitted from the rift zones of the Red Sea or Salton Sea. The coast lines near the Congo and Brazil deposits would have been closely dovetailed before continental drift, and they are of identical age (Lower Cretaceous, Aptian).

The depth of the Sergipe deposit in Brazil varies from 500 to 850 m, and the potash beds are uneven and highly variable in thickness (DeEston and Hennies, 1991). The thickness of the potash zones at Sergipe varies from 2 to 31.3 m and averages about 20.5 m. The sylvinite zones contain some carnallite, have an average grade of 25% K_2O, and are mined in two layers. Each of those layers is up to 11 m thick and separated by 3–6 m of halite. The tachyhydrite in the floor has low mechanical strength and high creep tendencies, and it is very hygroscopic.

The Congo deposit (Holle) contains less sylvinite, about the same amount of carnallite (estimated at 15% of the total salts), and more bischofite than the Sergipe deposit. A “normal” depositional sequence of thin black shales is followed by halite and then carnallite, with some zones converted to sylvinite. In most areas, the uppermost mineralized zones contain tachyhydrite or bischofite.

A much larger basin of this type, also of Cretaceous age, occurs in Thailand and extends into neighboring Laos. The basin is divided by the Phu Phan mountain range into the Khorat Basin to the south and the Sakhon Nakhon Basin in the north. The deposit is composed largely of carnallite. Sylvinite beds appear to occur primarily on the flanks of salt domes or anticlines (Hite, 1986).

The largest and most minable potash reserves in the world occur in Saskatchewan, Canada, extend slightly into Manitoba, and extend substantially but at considerable depth (1,000 m to over 3,500 m) into Montana and North Dakota in the United States. Sylvinite ore occurs in three members of the Prairie Evaporite Formation (Upper Middle Devonian). The lowest potash member is called the Esterhazy. Above the Esterhazy there is a comparatively minor bed, the White Bear (these two beds do not occur in the northwest area of the Evaporite Basin), followed by the Belle Plaine Member. The Patience Lake Member occurs at the top of the sequence. The Patience Lake Member is divided into two main ore zones (upper and lower). The potash beds dip slightly to the west and more strongly to the south at a rate of 3–9 m/km. Potash is difficult and expensive to mine at depths below about 1,100 m, and the conventional shaft mines lie in the shallowest northwest edge of the Patience Lake Member near Saskatoon, or the northeast edge of the Esterhazy Member near the town of Esterhazy. Solution mines are not so depth-limited, and one mine is located west-northwest of Regina where an appreciable thickening of the Belle Plaine Potash Member occurs. Another solution mine is developed on the flooded PCS Patience Lake mine near Saskatoon (Fuzesy, 1982).

The minable zone of the Esterhazy Member is reasonably thick and high in grade, has low insolubles content, and is overlain by comparatively strong strata (“roof” rock). An approximately 2.4-m-thick zone of the Esterhazy Member is mined at three locations. The ore from the Esterhazy Member averages 25% K_2O and 1% insolubles. Some carnallite is present in the ore, varying from less than 1% (normal) to as much as 10%. The sylvite liberation size is unusually large (much of the ore is liberated at plus 3-mesh [Tyler] or plus 6.7 mm).

Other shaft mines in Canada mainly produce from the Patience Lake Member. Most operations mine the top 2.74–3.35 m of the 3.66- to 4.57-m-thick Upper Patience Lake Member. One mine operates on the lower ore zone and recovers nearly all of the 4.57- to 5.79-m-thick potash bed. The ore grade (20%–26% K_2O) recovered in these mines is generally inversely proportional to the thickness mined. The insolubles content typically is 4%–7%, primarily resulting from several thin clay partings located within the potash zone.

One of the world’s larger potash deposits is of Upper Devonian age and is found in the Pripyat Depression of Belarus. The deposit has as many as 30 individual potash beds and four main potash-bearing layers, numbered from the upper bed down. Four mines, Soligorsk 1, 2, 3, and 4, usually mine Bed 2 and the lower section of Bed 3. In the mining area, Bed 2 is at a depth of 350–620 m and is 1.8–4.4 m thick. The sylvinite ore contains an average of 11% K_2O with 5% insolubles over an area of 250 km^2. Bed 2 is nearly horizontal, sloping gently to the east. Bed 3 lies about 160 m below Bed 2. The lower sylvinite zone of Bed 3 (1.5–2.8 m thick) averages 13.4%–16.4% K_2O with 9% insolubles and extends over a 350-km^2 area.

High-sulfate potash deposits occur in the Carpathian area of western Ukraine. Up to 15 discontinuous ore bodies contain predominantly langbeinite and kainite, with varying but substantial quantities of carnallite, sylvite, and polyhalite. Lesser quantities of kieserite, schoenite, leonite, and glaserite are also found in the ore, as well as large amounts of insolubles. The deposits occur in a 170 km by 15 km area in two zones, which range from lower to middle Miocene in age. The main deposits are centered near Kalush and Stebnik, about 70 km apart. There are often two to five potash beds, typically occurring as 1- to 5-m-thick lenses 0.5-1.0 km long and 200–300 m wide. Most of the ore bodies are moderately to steeply inclined at depths of 0–800 m (an open-pit mine is developed on one ore body). The ores average about 10% K_2O with 10%–18% insolubles and are very difficult to process.

The largest potash occurrence mined in Russia, and second in size only to the Saskatchewan deposits in Canada (perhaps smaller than the less extensively explored Russian Siberian deposits), is of Permian age and is located in the Pre-Ural Trough adjacent to the Kama River and the Ural Mountains. Six mines and plants (one mine flooded and was abandoned) are centered about the towns of Solikamsk, Berezniki, and Romanovo. The potash deposit underlies about a 3,000-km^2 area and consists of 13 potentially minable beds. The lower sylvinite horizon is 26–30 m thick and contains the major sylvinite beds. The upper sylvinite-carnallite zone is 70–80 m thick. The Red II is the principal bed worked across the region. The beds that are mined are 1.2–6.1 m thick, and the average interbed thickness of halite is 1.5–2.0 m. The ore averages about 15% K_2O with 3%–5% insolubles. The potash beds generally have very gentle dips of 0º–4º, but there are some gradual uplifts and folds as well as occasional cavities and numerous barren zones. Halite beds with clay partings lie on top of the mined potash, with thicknesses of 0.8–1.2 m, limiting roof spans to 3–16 m. The depth of the deposit varies from 75 to 450 m, and there is a high-pressure aquifer above the deposit.

The Carlsbad, New Mexico (United States) deposit is stratigraphically and mineralogically complex and contains 11 potash beds separated by thick halite and sporadic thin anhydrite or polyhalite layers. The potash ore bodies vary considerably in terms of their area, shape, and location, but they are fairly flat with only moderate undulations, faulting, and folding. The main ore minerals are sylvite and langbeinite. To the east of the commercial potash deposits, there is a massive polyhalite formation. The lowest potash member is known as the first ore zone and consists principally of sylvinite. It has been commercially mined by all Carlsbad operators and has been largely depleted. This ore zone, 3.0 to 4.6 m thick, contains three generally dark red potash beds, each about 0.6–0.9 m thick and containing >20% KCl. The potash beds are separated by 0.1–0.5 m of orange halite. The potash beds that have been commercially exploited are the first, fourth, fifth, seventh, and tenth beds. Langbeinite has been principally produced from the first, fourth, and fifth potash beds (Griswold, 1982).

The Paradox Basin of the United States covers an area of 16,000 km^2. Potash has been found in 18 of the basin’s 29 evaporite cycles, and 11 of the cycles contain potash beds that may be considered of economic importance. Carnallite and sylvite occur in large quantities, and in some beds the K_2O content exceeds 30%. Some of the beds of individual cycles are quite extensive. Within the basin there is a series of parallel northwest-trending anticlines composed of individual diapiric salt structures that have often penetrated the overlying beds. In the anticlines, the thickness of the salt beds may have as much as doubled. The only structure that has been commercially exploited to date is the Cane Creek anticline near Moab, Utah. The fifth potash cycle is produced at a depth of about 1,200 m. The ore zone averaged 3.4 m in thickness over an area of 31 km^2 with 25%–30% K_2O. The mine originally was a shaft mine and room and pillar operation. However, the mine was gassy (contained methane) and hot (up to 35ºC), the sylvinite bed was highly irregular in thickness and dip, and there were many faults. All these factors made mining very difficult and costly. In 1970 the mine was intentionally flooded, and the mine now operates as a solution mine.

Brine and Lake Potash Deposits—In addition to the buried potash deposits, there are brine or surface potash deposits in North America, South America, and Asia/Middle East.

The Chilean nitrate deposits are unique, and the formation of these soluble salt mineral deposits is one of the great mysteries of the world. It is beyond the scope of this section to discuss the various theories concerning the origin of these deposits. The deposits occur in the Atacama Desert region of northern Chile over a north-south range of approximately 700 km and an east-west distance of 10–150 km as an almost continuous deposit of sodium-potassium nitrate and other soluble salts. The Atacama Desert is one of the driest regions in the world with as much as 20 years between rain showers. These deposits are the only substantial concentration of potassium and sodium nitrate, iodate, perchlorate, and chromate salts found anywhere in the world. This deposit contains an estimated 10^9 tons of sodium nitrate, slightly less sodium chloride, and perhaps twice that amount of sodium sulfate. Potassium nitrate, magnesium sulfate, and boric acid may total about 100 million tons each, while the iodine and sodium perchlorate contents are about 5 million tons each. Almost no bromine is present. The ore occurs as a “caliche” and is generally most concentrated from 1 to 5 m below the surface. High-grade zones have been commercially extracted since the 1800s.

There are a number of saline lakes in China that can be considered potential potash deposits. The largest of these lakes occurs in the Qaidam Basin, a 120,000-km^2 area that contains both wet and dry (playa) lakes with a wide variety of mineralization. The Qaidam Basin is located in the north of the Qinghai-Xizang (Tibet) Plateau about 2,800 km west of Peking at an elevation of 2,600–3,200 m. The climate is arid, windy, and very cold in the winters. The largest of the potash-bearing sub-basins are the Qarhan and Dalongtan playas, which contain beds of carnallite as well as potassium-bearing brines. The estimated reserves of Qarhan Lake are 360 million tons K_2O (Sun and Lock, 1990). Commercial exploitation began in 1989, and the Qinghai Potash Fertilizer Factory had an announced initial capacity of 200,000 tpy of KCl. Solar evaporation of lake brine produces carnallite (as at the Dead Sea operations), and the carnallite is harvested and converted into KCl.

The Dead Sea, which lies in both Israel and Jordan, is the lowest point in the long (600 km), narrow (10–20 km) rift valley that extends northward from the Red Sea between Aqaba and beyond the Sea of Galilee. It is the lowest natural lake on earth; the surface is about 396 m below sea level. The Dead Sea is 76 km long and 16 km wide; it has an area of 930 km^2 and a mean depth of 329 m. It contains an estimated 47 x 10^9 tons of salts, of which perhaps 1 x 10^9 tons is KCl. The brine in the Dead Sea has a high $MgCl_2$ and $CaCl_2$ content, and this composition is quite unusual. The brine is processed by first crystallizing out halite in large solar ponds, and then continuing the evaporation of the brine in a second set of ponds to deposit carnallite and halite. The impure carnallite is harvested and fed to the processing plants to produce KCl and other products. Residual brine is returned to the Dead Sea. All phases of both the Israeli and Jordanian operations are very large, and Israel is probably the world’s lowest cost potash producer.

The Great Salt Lake (Utah, United States) is a large, nearly saturated inland saline lake with a brine much like seawater bitterns. The lake extends for 110 km in maximum length and 50 km in width. The Great Salt Lake is quite shallow. The deepest part has varied from 8.1 to 14.2 m during recorded history, and volume has changed more than threefold. The Southern Pacific Railroad built a large semiporous rock-filled causeway (with two large culverts) across the lake in 1955, which resulted in the northern one-third of the lake (about 1,000 km^2) receiving less annual water input and becoming more concentrated. Brine is withdrawn from the northern third of the lake and sent to solar ponds to crystallize mixed potash salts (primarily kainite and NaCl), which are harvested and converted to potassium sulfate.

Searles Valley (United States) lies near the eastern slope of the Sierra Nevada Mountains in south-central California. Searles Lake is a nearly elliptical desert playa about 16 km long and 10 km wide. The water-soluble minerals in the lake sediments are a mixture of many salts, and hanksite ($9Na_2SO_4 \bullet 2Na_2CO_3 \bullet KCl$) is one of the major components. The upper and lower salt (younger) beds are porous and contain the brine that has been used for commercial potash production by evaporation and crystallization since early in the twentieth century.

Potash Mining

There are two basic types of potash mining: (1) conventional mining, which encompasses several standard methods, modified as necessary for specific situations, and (2) solution mining.

Conventional Mining—Each potash deposit has its own characteristics and mining problems that must be handled on an individual basis. However, many standard methods have become widely accepted within the potash mining industry. For potash beds that are relatively flat and uniform in thickness, or for cutting entries, boring machines with two or four cutting arms have proven to be the most effective and economical mining method. For moderately inclined, undulating and/or thickening-thinning potash seams, continuous miners with cutting “drums” mounted on one or two moveable arms are the most effective. For highly variable ore bodies, or ore with potential rock-bursts or other special needs, drilling and blasting are still required.

Most mine configurations are the conventional room and pillar design; “stress relief mining” (multiple entries with outer yield pillars) has proven highly effective for the deeper mines with plastic flow (of the ore) or unstable roof conditions. For thicker or highly inclined potash seams, the open stope (successive horizontal cuts for thick beds) or cut and fill methods allow both a high ore recovery and an easy means of disposing of both waste produced underground and plant tailings.

For those mines without high-pressure aquifers above the potash and with somewhat plastic overlying strata, the long-wall mining method, which allows the roof to descend soon after the ore is cut, can provide very high ore recovery rates and result in high productivity. In the case of long-wall mining, the beds must be fairly uniform and continuous (very minor faulting, etc.) over the width and length of individual mining panels. Although long-wall mining can produce ores at relatively low costs per ton, equipment and development costs can be high and the method is not as flexible as other methods.

Underground ore transport is now accomplished almost entirely by conveyor belts. Conveyor belts may be suspended from the roof or set on the floor. For the highest capacity mines with continuous (borer or drum) mining machines, flexible belt conveyors attached to or directly fed from the mining machines and directly feeding a panel belt have produced considerable savings. Some mines employ either shuttle cars to take the ore from the mining machines to the feeder-breaker at the panel belt, or load-haul-dump (LHD) machines that pick up ore from the floor and then haul it to a feed station. Most mines have considerable underground ore storage capacity to even out the flow, as well as feed bins where the ore is loaded into high-speed “skips” (elevator bins) that take the ore to the surface and dump it, with all aspects of the loading-lifting-dumping cycle being done automatically. A few shallower mines bring the ore to the surface with conveyor belts in long inclined tunnels.

The costs of potash mining by conventional methods can vary tremendously. Mining is the major expense of potash production in operations that require more manpower because of low-grade ore or difficult mining conditions. For ore bodies and situations that allow high-capacity operations, mining can be somewhat less expensive than the processing of potash ores at the surface.

Solution Mining—Three potash plants in Canada and the United States utilize solution mining as their method of operation. The mine near Moose Jaw, Saskatchewan (Canada), was designed as a conventional 3-pipe (pipes to inject water near the top, withdraw brine from the bottom, and pad the upper surface all in one well) solution mining operation to take advantage of a major thickening of the Belle Plaine Member at about 1,650-m depth. Brine from the well field is evaporated in triple-effect evaporators to crystallize dissolved halite, and the brine is then cooled to crystallize the potash salts. The residual brine is recirculated to the evaporators, although in the winter it is first sent to ponds to be further cooled and to precipitate additional potash salts.

The Patience Lake mine uses solution mining for a former conventional mine that had been extensively operated for 22 years and then was accidentally flooded. Due to the tremendous surface area of the previous workings, the operation selectively dissolves only the KCl. Brine is withdrawn from the mine in the winter and sent to a pond, which was formerly used for tailings before being rebuilt as a holding and cooling reservoir. Potash is crystallized, and then the residual brine is returned to the mine. The potash is harvested by floating dredges and sent to the plant for further processing and drying, screening, and compaction.

A similar intentionally flooded mine was operated at the Moab Cane Creek, Utah (United States) plant. The potash brine is solar evaporated to crystallize sylvinite. The sylvinite is dry harvested and sent to a processing plant for conventional flotation.

Beneficiation and Processing of Potash Ores and Brines

The beneficiation of raw potash ore into marketable products, similar to potash mining operations, requires a somewhat different scheme and equipment for each processing plant. For every deposit there are differences in:

- The ore composition (mineralogy).
- Ore grade (K_2O content).
- Liberation size (amount of maximum particle size required to allow separation of the different minerals).
- Type and amount of slimes (insolubles such as clay, anhydrite, dolomite, silica).

These factors may be highly variable within a single deposit. Accordingly, the modern potash processing plant must have an efficient, highly versatile process to accommodate variations in the feed yet still maintain product quality at as low a production cost as possible.

Four basic beneficiation techniques have been applied in the potash industry: flotation, heavy media separation, electrostatic separation, and thermal dissolution-crystallization. Other techniques have also been experimented with. These include ammoniacal leaching and gravity separation using shaking tables. Ammoniacal leaching has proven too costly, and gravity separation can only produce impure concentrates (about 80% KCl). Most potash processing plants practice a combination of beneficiation techniques.

Crushing and Grinding—The first step in the beneficiation of a solid potash ore is to reduce the ore to a size where the potash is liberated from the other ore constituents and can be separated from them. A prime consideration in crushing and grinding is that a minimum amount of fines be produced. Any fines produced by grinding must be processed by more costly methods. Larger and closely sized product is more valuable, and less energy is spent on grinding.

Fine particles, both ore minerals and insolubles, are always removed to the greatest extent possible before the potash separation step. In flotation, fine particles with high surface areas tend to adsorb excessive quantities of flotation reagents. Excessive amounts of fines can significantly raise reagent costs and cause contamination of the product. Fine gangue particles may float or become mechanically entrapped in the product. The ore slurry is first “attrition scrubbed” to liberate and disperse the fines. Most plants deslime by using one or more stages of cyclones and hydroseparators. A liberation size of about 150-mesh has been determined to provide the best cut-off range for flotation of most potash ores. These fine solids are then floated in a fines flotation circuit, and the impure float is usually sent to a hot leach crystallization plant for further processing.

Direct flotation is the most common flotation technique employed in the potash industry. In the case of flotation to treat sylvinite ores, a cationic collector is added to the closely sized and deslimed ore slurry. These collectors are mostly straight-chain aliphatic primary amines derived from natural fats and oils that are neutralized by acetic or hydrochloric acid before use. The salt (NaCl) and other gangue minerals sink in the pulp and are removed from the bottom of the flotation cell.

Frothers are used to help form and stabilize the flotation froth. Generally, these reagents are organic heteropolar compounds. Pine oil, a widely used frother, contains aromatic alcohols. Modifiers or regulators constitute another class of flotation reagents used to control the process. In potash flotation, slimes depressants such as starch, guar gum, dextrine, and synthetic compounds are typically used (Foot et al., 1980).

Potash flotation circuits always have both rougher and cleaner cells. In the rougher cells, an attempt is made to float as much potash as possible, whereas in the cleaner cells the purity of the floated product is the prime consideration.

Electrostatic Separation—Electrostatic separation is a dry technique in which a mixture of minerals may be differentiated according to their electrical conductivity. For potash minerals, which are not naturally conductive, the separation must be preceded by a conditioning step that induces the minerals to carry electrostatic charges of different magnitudes and, if possible, different polarities.

Ground ore is conditioned with one or more reagents; then the mixture is heated in a fluidized bed, and the relative humidity is adjusted to enhance charging of the particles. The ore is then fed into the electrostatic separator to yield three fractions, i.e., product, residue, and middlings. The middlings, after further grinding, may be recycled to the conditioning stage.

Thermal Dissolution-Crystallization—Thermal dissolution-crystallization is possible because potassium chloride is much more soluble in hot water than in cold whereas sodium chloride is only slightly more soluble at 100ºC than at 20ºC. In saturated solutions containing both salts, sodium chloride is actually less soluble at higher temperatures. When a brine that is saturated with both salts at 20ºC is heated to 100ºC, it is capable of dissolving substantial amounts of KCl but not NaCl.

Sylvinite ore is crushed to minus 3-mesh and washed with cold, saturated NaCl-KCl solution. Clays are removed from the solution by desliming, and the clarified solution is then heated and used to dissolve the potash in the washed ore. Undissolved NaCl is discarded as tailings. The brine solution is then cooled under vacuum, and the KCl crystallizes out and is separated, washed, and dried. The remaining brine is recycled.

Beneficiation of Carnallite Ores and Brines—Carnallite ores are the source of only a small percentage of the world's potash supply even though there are large deposits of carnallite-containing ores in many regions. One disadvantage of carnallite ores is their low grade. Pure carnallite (KCl•MgCl•6H_2O) contains only 17% K_2O. Carnallite cannot be used as a direct-application potash fertilizer because it is deliquescent. Dissolution and recrystallization methods must be used to process carnallite ores, and these methods are energy intensive and expensive. A large volume of byproduct magnesium chloride solution is produced in carnallite processing, which is likely to pose a disposal problem. In spite of many disadvantages, however, ores or brines containing carnallite are processed to produce KCl in several countries, including Germany, Israel, Jordan, and Spain, and may be utilized in the future in Thailand, Pakistan, and the Congo.

Carnallite has been mined, beneficiated, and processed in Germany for approximately 130 years. These operations were economically sustainable only as long as the German mines supplied a very significant portion of the world potash market. As a result of international competition based on the production of sylvinite ores, carnallite processing plants in Germany that only produced KCl were forced to close and potash production in Germany was concentrated at mines with significant amounts of sylvinite ores.

The conventional mining and beneficiation sequence for potash recovery from carnallite encompasses the operations of mechanically mining the ore, hoisting ore to the surface, beneficiating the ore to a carnallite concentrate, dissolving the carnallite, recrystallizing potassium chloride, disposing of saline solid wastes, and disposing of saline liquid effluents. Carnallite ore processing methods vary widely and depend upon accessory minerals that are associated with the ore.

There are two general methods of carnallite processing: cold leaching and hot leaching. Cold leaching processes are carried out at 20º–25ºC. The temperature used to decompose the carnallite is not critical but must be below 25ºC to prevent sulfate from remaining in the magnesium chloride liquor. Decomposition of the ore is carried out using unsaturated brine recirculated from a later filtration stage. In order to prevent reprecipitation of carnallite, the decomposition liquor is allowed to reach only 90% saturation in magnesium chloride.

Carnallite ores may also be treated by a hot leach at about 100ºC to dissolve $MgCl_2$, KCl, and any NaCl that may be present. The hot solution is clarified to remove solid impurities and then evaporated and cooled. After the KCl and NaCl crystals are recovered, they are separated by one of several beneficiation techniques.

Processing of the Dead Sea brine by the Arab Potash Company (APC) in Jordan utilizes solar evaporation. The solar ponds are divided into three basic sections: the salt ponds, the precarnallite ponds, and the carnallite ponds. Sodium chloride is precipitated in the salt ponds. The precarnallite ponds are used to regulate the concentration of the brine that is fed to the carnallite ponds as close as possible to the point at which carnallite precipitation begins. Carnallite is recovered with a specially designed floating-track harvesting machine. A screw-type cutterhead harvests the 30- to 50-cm-thick carnallite layer. The carnallite slurry (20%–25% solids) is cycloned to reduce the water content and pumped at 40% solids to the processing plant.

The slurry is first wet screened to separate the large high-grade carnallite crystals, which are fed to cold crystallizers. Undersize slurry from the screens is mixed with brine discharged from the cold crystallizers. Additional carnallite is then crystallized, and the slurry is thickened. The thickener overflow is returned to the evaporation ponds. The underflow is subjected to salt flotation. Floated NaCl slurry is pumped to the tailings area. The carnallite sink fraction is settled in a thickener. Thickener underflow is dewatered in centrifuges. The cake from the thickener underflow is conveyed to the cold crystallizers where carnallite is decomposed by the addition of water and recycle brine. The leach tank discharge slurry is transported to a thickener, then to two stages of dewatering centrifuges, and finally to a rotary dryer. The dried potassium chloride product passes through screens to be separated into two fractions, standard and fines, according to the required size specifications. The products are collected and stored.

Beneficiation of Sulfate Ores—Langbeinite ($K_2SO_4 \cdot 2MgSO_4$) can be separated from sylvite and halite by selective washing, froth flotation, or heavy media separation. Langbeinite may be marketed as fertilizer or animal feed as a source of K, Mg, and S, or it may be converted to other products. Potassium sulfate is produced by reacting one molecule of langbeinite with four molecules of KCl. Potassium magnesium sulfate is produced by refining langbeinite.

Alunite [$K_2 \cdot Al_6(OH)_{12} \cdot (SO_4)_4$] is a potential source of potassium sulfate, alumina, and sulfur dioxide byproduct. The economics of production hinge on the value of the alumina. Processing involves ore comminution, roasting, and leaching to recover potassium sulfate solution. Filtered solids can be processed in a Bayer-type process plant for alumina recovery (Anonymous, 1972).

Complex mixtures of potash ores may contain any or all of the following minerals: anhydrite, epsomite, halite, kainite, kieserite, langbeinite, polyhalite, and sylvite, along with clays. Extraction of potassium salts from such ores becomes quite complicated because the mineralogical forms of the various components can be unstable.

World Potash Production and Reserves

Until the 1990s, world potash production was only partially based upon economic considerations. In the countries of the FSU and in East Germany, the potash operations were entirely government owned and controlled. These centrally planned economy countries had constructive but forced-use internal markets, and capital and operating costs were often not critical factors. Consequently, the potash industry in many of these countries employed significant numbers of workers per ton of potash produced. Often mines with low-grade ores or processing plants using relatively expensive methods were kept open for social rather than economic considerations. Much less extreme but similar operating practices are occurring or have been employed in other government-controlled or partially subsidized potash production operations in Brazil, Canada, Chile, China, Congo, France, West Germany, Israel, Italy, Jordan, and Spain. A second distinguishing feature of the potash industry prior to the 1990s was that, because of generally poor economics in the industry and similarities in mining and processing options, research and development often were not promoted. Therefore, cost reductions and efficiency changes were comparatively infrequent. Under these conditions, increasing maintenance costs and usually much higher mining costs were incurred as potash operations aged and faced dwindling reserves, declining ore grades, longer distances from mining faces, and often thinner or deeper ore zones.

World production of potash for 1994 and 2004 is given in Table III.19. The data for 1994 are given for comparative purposes. World production in 1994 was about 21,640,000 tons K_2O representing an overall capacity utilization of 60% of world potash production capacity (36,000,000 tons of K_2O). Reduced production from the FSU countries during the time period severely influenced world overall production and capacity utilization. Prior to the breakup of the Soviet Union, the combined production of Russia, Belarus, and the Ukraine was about 11,000,000 tons of K_2O. Canadian production over the last several years has steadily been increased due to increased demand and higher prices. Production increases were accomplished using existing capacity. In 2004, production from Russia and Belarus increased substantially from the lows of the early to mid-1990s. However, production has not returned to levels experienced prior to the breakup of the Soviet Union. Domestic demand has been steadily increasing. The German potash industry has rationalized, and output seems to have stabilized. Prior to the reunification of Germany, production reached approximately 6,000,000 tons of K_2O for eastern and western states. Israel and China production has increased significantly.

Estimating the amount of minable potash reserves for the major deposits of the world is

Table III.19. World Potash Production

Country	1994[a]	2004
	(thousand tons K_2O)	
Canada	7,600	9,500
Germany	3,000	3,670
Russia	2,800	5,400
Belarus	2,000	4,650
United States	1,425	1,200
Israel	1,350	1,940
France	950	–
Jordan	820	1,130
Spain	600	600
United Kingdom	560	580
Brazil	255	360
Ukraine	200	60
Chile	55	400
China	25	550
Total	**21,640**	**30,040**

a. Estimated.

Source: USGS (2005).

difficult for a number of reasons. Many of the deposits have been incompletely explored, and exploration data are not made public. The definition of economically minable ore changes with time, technological development, the price of potash, and the owner's interests. Also, few details are published on the areas in mines that must be left because of faults, intrusions, fear of water breakthrough or rock bursts, or very sudden ore body changes. Finally, it is unknown whether solution mining will be considered at the end of conventional mining. Perhaps the most authoritative estimate on world potash reserves has been made by Mayrhofer (1983), but his figures are now somewhat dated, optimistic for the German deposits, and conservative for the others. Table III.20 lists these values, along with those from the USGS (2005).

Sulfur

Sulfur is one of the more common constituents of the earth's crust and can be ranked as the 16th or 17th most abundant element (Carmichael, 1982). The mean sulfur content of the rocks forming the crust of the earth is estimated to be about 400 ppm. Sulfur naturally occurs as elemental sulfur, metal sulfides in coal and mineral ores, sulfates, hydrogen sulfide in natural gas, and complex organic sulfur compounds in crude oil and coal. All of these various forms of sulfur are used as sulfur sources, but the most important sources are elemental sulfur, hydrogen sulfide in natural gas, and iron pyrites.

The uses of sulfur are as varied as its sources, but approximately 80%–85% of the sulfur that is produced is used to manufacture sulfuric acid. Approximately half of this acid is used in fertilizer production, mainly to convert phosphates to water-soluble forms. Sulfur is an important plant nutrient, and elemental or other forms of sulfur are sometimes added or mixed with fertilizers to correct sulfur deficiencies. Elemental sulfur can also be used in agriculture as a pesticide or fungicide.

Sulfur Sources

Native sulfur or brimstone, sulfur naturally occurring in the elemental form, is found in several

Table III.20. Estimates of the World's Potash Reserves

	Mayrhofer, 1983		USGS, 2005	
	Minable	Total	Reserves	Reserve Base
	(million tons K_2O)			
A. Underground Deposits				
Canada (total)			4,400	9,700
Saskatchewan	6,137	507,218	–	–
New Brunswick	70	182	–	–
Russia	2,110	10,822	1,800	2,200
Belarus	100	444	750	1,000
Ukraine	25	129	25	30
Germany (total)			710	850
East	245	730	–	–
West	218	650	–	–
England	60	240	22	30
United States (total)	33	800	90	300
Brazil (total)	25	100	300	600
Spain (total)	21	100	20	35
France	20	217	–	–
Sicily	6	30	–	–
Congo	0	0	–	–
B. Brine or Surface Deposits				
China	–	–	8	450
Chile	–	–	10	50
Dead Sea (Israel, Jordan)	–	–	80	1,160
United States (total)	–	–	200	300
C. Carnallite Deposits				
Congo	–	–	–	100
Thailand, Laos	–	–	–	120
United States, Paradox Basin	–	–	–	800

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geologic environments. During volcanic activity, sulfur may be sublimated directly around volcanic vents. Although sulfur production from volcanic deposits is generally limited, considerable tonnages have been produced in Japan from such deposits.

Native sulfur may be formed from gypsum and anhydrite in evaporite deposits through the movement of saline waters and hydrocarbons and the influence of anaerobic sulfate-reducing bacteria. Notable sulfur deposits associated with salt domes, such as along the U.S. Gulf Coast, and stratified sulfur deposits, such as found in Sicily, Poland, and Iraq, are thought to have been formed by this process.

Deposits of pyrite (FeS_2) or other iron sulfides are found in many countries. Sulfides are found in a broad spectrum of geologic environments from igneous rocks (both volcanic and intrusive) to sedimentary rocks. Iron sulfide deposits can be extremely important for those countries that do not possess other sulfur sources. The importance of iron sulfides has been diminishing to a certain extent due to high production costs, environmental concerns, and the move to a global economy. Iron sulfides are mainly used for the direct production of sulfur dioxide and sulfuric acid.

Many of the non-ferrous metals such as copper, lead, zinc, and nickel are obtained from sulfide ores. One of the final stages of the extraction processes for these metals is the separation or removal of sulfur by roasting. Sulfur is recovered in the off-gases.

Fossil fuels such as coal, crude oil, and natural gas contain sulfur in low but variable quantities; the amount mainly depends upon the geologic origins of the fuels. In the United States, coals from portions of the eastern, midwestern, and southern states are relatively high in sulfur (2%–4% S), while coals from some portions of the eastern states and from the western states may contain less than 1% S. The sulfur content of German lignite is usually 1%–2%. South African coals contain from 0.3% to 2.8% S (Hoddinott, 1994). Occasionally, some of the pyrite that occurs in coals can be mechanically separated. However, fine pyrite and the sulfur that is organically bound in the coal are either very difficult to remove or cannot be removed. When coal is burned to generate heat, sulfur will escape to the atmosphere as sulfur dioxide if the off-gases are not treated. During the coking of coal, most of the sulfur will be converted to hydrogen sulfide, which has to be removed from the gases. This potential pollutant/byproduct is converted to sulfur dioxide, sulfuric acid, and AS.

Crude oil usually contains between 0.1% and 2.8% sulfur. A few individual crudes contain over 3% S (Hager, et al., 1983). Sulfur is largely removed during oil processing, resulting in substantial quantities of byproduct hydrogen sulfide and mercaptans.

The composition of natural gas varies widely. Some natural gases may contain almost no sulfur; in others, the hydrogen sulfide content may be extremely high. Gas originating from southwestern France, for instance, contains 15% H_2S, and some of the natural gases from Canada (Alberta and northeast British Columbia) contain about 30% H_2S. Natural gas and crude oils containing substantial amounts of H_2S are termed “sour.” In general, sour crude oil and sour natural gas are associated with production from carbonate formations.

Among the naturally occurring sulfate ores, only gypsum has ever been of any importance as a raw material for sulfur production, and only in the direct production of sulfur dioxide for sulfuric acid manufacture. Byproduct calcium sulfate from phosphoric acid production (phosphogypsum) has been used to produce sulfuric acid. Elemental sulfur has never been extracted from sulfates on any significant scale because of high energy costs. Experimental work has been done on both chemical (Anonymous, 1980) and microbiological (Conghill, 1971) methods of reducing gypsum to hydrogen sulfide.

Production Methods

Production From Native Sulfur Deposits—Sulfur-containing ores are usually mined by conventional open-pit or underground mining methods. In the deposits around the Gulf of Mexico that are associated with salt domes, and in one or two other places in the world, elemental sulfur is produced directly from deposits by melting with hot water and pumping the molten sulfur to the surface (Frasch process) (Anonymous, 1994c). Many processes have been used or proposed for extracting sulfur from sulfur ores (Bain, 1994); however, only a few processes have gained commercial importance, including flotation, melting out, distillation, and the Frasch process.

Flotation can be used to upgrade sulfur ores (Forbath, 1953). After grinding the ore to the liberation size (the size at which the sulfur particles are free from the associated gangue minerals), sulfur is floated with foaming agents such as pine oil, cresylic acid, or amyl alcohol. When the gangue minerals contain carbonates, certain depressants such as water glass (sodium silicate) are recommended. Flotation results in concentrates containing 70%–90% S. The disadvantages of flotation are that it does not produce pure sulfur, as do most other processes, and that the sulfur concentrate has to be dried.

Producers in Sicily used the melting-out process and had a virtual world monopoly in sulfur production until 1904 (Fischer, 1984). Sulfur melts at 112º–114ºC, but becomes highly viscous at temperatures above 158ºC. Originally sulfur was melted out in moundlike ore piles known as “calcarilli.” Calcarilli were built up on small hearths equipped with drain holes and simply ignited. Approximately one-third of the sulfur was recovered by this method; the other two-thirds was burned and lost to the atmosphere as sulfur dioxide. A substantial improvement in yield was achieved by covering the ore pile with soil, as practiced in charcoal making; sulfur yields increased from 30% to approximately 60%. The melting process was substantially changed by the introduction of chamber furnaces, which improved the yield of sulfur up to 78%. The Sicilian sulfur monopoly effectively ended with the introduction of the Frasch production method and development of deposits in the Gulf Coast region of the United States.

Distillation of sulfur has been practiced in Japan by the “Yakutori Process” (Griffith, 1941). Sulfur-bearing ore is heated by external firing with coal to above 440ºC (the boiling point of sulfur). The process uses small retorts (0.4 m^3) that are made of 13% chromium steel and hold approximately 0.24 ton of ore. Up to 100 retorts can be coupled to form one furnace. To produce one ton of recovered sulfur, 0.41 ton of coal is consumed.

The most effective and economic method of extracting sulfur from native deposits *in situ* under suitable conditions is the Frasch process (Anonymous, 1994c). The process involves injecting hot water directly into the sulfur deposit and then pumping the molten sulfur to the surface. The sulfur is then pumped to storage areas where it solidifies. In this way, blocks of pure sulfur are obtained. Frasch-produced sulfur can be quite pure (99.7%–99.8%) and light yellow in color. If the sulfur is associated with small amounts of bituminous residues, it is brown or blackish. This so-called dark sulfur may contain up to 1% carbon, mainly present as complex organic sulfur. Poland and Iraq practice Frasch sulfur production on a commercial scale, as did Mexico until 1993, and the United States until 2000.

Sulfur Recovery From Gases—Recovered sulfur accounts for over 60% of the total world production of elemental sulfur. Most of the recovered sulfur originates from the processing of fossil hydrocarbons, especially natural gas, oil, and coal. In natural gas, sulfur is mainly in the form of hydrogen sulfide, but in oil and coal it is also present as organic compounds such as mercaptans and as sulfides, disulfides, and heterocyclic compounds.

Hydrogen sulfide cannot be tolerated in natural gas, even in low concentrations, because of its great toxicity. Hydrogen sulfide is also corrosive. Therefore, “sour” natural gas containing hydrogen sulfide is usually desulfurized near the wellhead to very high standards of purity.

In the refining of crude oil, sulfur partly comes off as hydrogen sulfide, but mostly tends to accumulate in the heavy fractions. The practice of using high-sulfur heavy oils containing 3%–4% sulfur as industrial fuels is no longer permissible under the pollution control regulations in force in many parts of the world. Therefore, heavy oils are often treated with hydrogen to reduce the organic sulfur to hydrogen sulfide (Anonymous, 1994b).

There are essentially three types of practical processes for removing hydrogen sulfide from gas streams:

- Sorption on a solid.
- Reversible chemical or physical absorption in a liquid medium.
- Absorption and oxidation in an oxidizing liquid medium (direct conversion).

In the direct conversion processes, hydrogen sulfide is not only removed from the sour gas stream but is also converted into elemental sulfur in the same liquid medium. There are two methods by which this conversion can be achieved. One is the so-called “Wet Claus” process, in which sulfur dioxide is introduced and reacts with the hydrogen sulfide according to the following equation:

$$2\,H_2S + SO_2 \rightarrow 3S + 2H_2O$$

Processes of this type are most frequently used for processing tail gases from Claus sulfur recovery plants, which are operated to contain the correct stoichiometric proportions of hydrogen sulfide and sulfur dioxide (Lagas and Borshoom, 1994). The other type of direct conversion process uses an alkaline solution (often sodium carbonate) containing one or more mild oxidizing agents that oxidize hydrogen sulfide to sulfur and are then themselves regenerated by oxidation with air (Goar, 1994).

Where coal is used as a fuel for industrial and power station boilers, coal processing for the purpose of removing sulfur is too costly, and very large quantities of coal, including the high-sulfur varieties, are still burned directly. Often high- and low-sulfur coals are blended to stay within specified sulfur-emission limits. In the best of cases, both pyritic and organic sulfur in the coal are burned to sulfur dioxide and discharged with the combustion gases. Where emission standards must be met, some method of removing at least a portion of the sulfur dioxide from the off-gases must be used. However, although the technology exists, it is seldom economically justifiable to recover sulfur or any other useful sulfur product under these conditions.

Sulfur Production From Sulfide Ores and Sulfates—Non-ferrous metal ores such as copper, zinc, lead, and cobalt are found mainly in the sulfide form. A typical copper ore concentrate composition is 27% Cu, 28% Fe, and 32% S. In the roasting stage, the sulfide components are broken down under the influence of heat to cuprous sulfide and elemental sulfur (Habashi, 1978).

Various methods have been used or have been proposed for the production of elemental sulfur from sulfide ores. Methods of treating sulfide ores fall generally into several groups. Thermal decomposition of pyrites occurs at about 600ºC; in the absence of air, pyrite decomposes and sulfur gases can be recovered from the off-gases by condensation (Anonymous, 1956). Roasting and/or smelting sulfides under reducing conditions with coal, coke, or a reducing gas produces a gas mixture containing hydrogen sulfide and sulfur dioxide. These compounds can be converted to sulfur in a Claus plant (Goar, 1994). Reacting pyrite with sulfur dioxide can produce elemental sulfur and magnetite:

$$3FeS_2 + 2SO_2 \rightarrow Fe_3O_4 + 8S$$

Sulfide ores can be treated with chlorine or hydrogen chloride. Wet chemical or biological/chemical extraction methods can also be used to produce sulfur from sulfide ores.

Although off-gases from smelting operations are somewhat more concentrated than gases from the burning of coal, the economics are generally not in favor of recovering sulfur from smelting off-gases. Sulfur recovery may help offset costs associated with pollution controls to conform to emission standards.

Sulfates are not currently a significant commercial source of sulfur because of economic factors. Large inputs of energy are required to reduce sulfur from sulfates. Most of the chemical methods proposed involve reduction of a sulfate to a sulfide followed by acidulation of the sulfide to produce hydrogen sulfide, which is then processed to sulfur by the Claus process. Suitable reducing agents include coke, hydrogen, or reducing gases (hydrogen + carbon monoxide produced by partial combustion of a fuel).

World Production, Sulfur Reserves and Resources

Sulfur ore bodies that are worth exploiting on a large scale are restricted to a few regions in the world. However, there are many deposits of local importance. Significant sedimentary sulfur deposits are located in several regions. Deposits are found in the Gulf of Mexico Basin in Louisiana and Texas in the United States and also in Mexico. In the Mediterranean Basin, the main deposits are in Sicily, but there are other deposits on the Italian mainland and on the French and Spanish coasts of the Mediterranean. In the Eastern European Basin, sulfur deposits are found along the Volga River and the coast of the Caspian Sea along the Caucasus Mountains. North of the Carpathians in Poland, sulfur deposits are found in the Central European Basin. Sulfur deposits are located in Turkmenistan and Uzbekistan of the FSU and in Afghanistan.

Volcanic-related sulfur deposits are found in several areas of the world. In the East Pacific Basin, volcanic sulfur deposits extend along the Philippines, Japan, the Kuril Islands, and the Kamchatka Peninsula. In the West Pacific or Cordillera Basin, deposits extend along the western side of North and South America through Mexico, Peru, Bolivia, and Chile (Fischer, 1984).

Large deposits of pyrite are present in several areas of the world including India, Poland, Albania, China, and the FSU. However, the use of pyrites is not as technically or economically favorable as the use of other sources of sulfur. Pure pyrite contains about 53.5 wt % S, and high-grade ores may contain 46% sulfur. Freight charges for shipping pyrite are high compared to shipping pure sulfur. At approximately 35% S, pyrite combustion in pyrite-burning furnaces may not be self-sustaining, and auxiliary fuel sources may be required. Capital costs are higher for sulfuric acid plants using pyrites than for those plants using elemental sulfur, and operating costs are also higher. Pyrite-burning sulfuric acid plants have more pollution problems than do sulfur-burning plants due to materials-handling problems and particulate emissions. The disposal of the iron oxide sinter may also present problems in that pyrites may contain several potentially harmful heavy metals, which may be concentrated in the sinter.

It is difficult or impossible to make a significant estimate of the total world reserves of sulfur because of the wide variety of forms in which it occurs. Reserves from traditional sources may total 1.3×10^9 tons (U.S. Bureau of Mines, 1995). Total resources are much larger, of which more than 99% is present in coal, oil shales, and gypsum; these are materials that do not make a significant contribution to present world production. At the present time, the USGS does not attempt to make estimates of sulfur reserves (USGS, 2005).

Table III.21 shows the world production of sulfur from 2002 to 2004 as elemental sulfur and sulfur in all forms, including sulfur obtained from pyrites, non-ferrous metal ores, and crude oil and natural gas. World production of all forms of sulfur totaled about 64.9 million tons in 2002 compared to 69.7 million tons in 2004 (Kiho, 2005). World elemental sulfur production totaled about 42.9 million tons in 2002 compared with 46.4 million tons in 2004.

Sulfur consumption by region in 2002–04 is shown in Table III.22. Increasing demand for natural gas and the increased need for pollution control will lead to increasing production of recovered sulfur. Elemental sulfur from evaporites and volcanic rocks will be available for many years.

Table III.21. Production of Sulfur in All Forms and as Elemental Sulfur (2002–04)[a]

Region	2002		2003		2004	
	All Forms	Elemental	All Forms	Elemental	All Forms	Elemental
Canada	9,224	8,190	9,024	8,138	9,075	8,095
United States	10,491	8,481	10,869	8,920	11,235	9,258
North America	**19,715**	**16,671**	**19,892**	**17,058**	**20,310**	**17,353**
Brazil	390	108	409	117	439	122
Chile	1,265	25	1,470	25	1,516	35
New Mexico	1,360	887	1,475	1,032	1,650	1,135
Venezuela	500	500	550	550	845	845
Latin America	**3,993**	**1,769**	**4,418**	**1,989**	**5,000**	**2,428**
Belgium/Luxembourg	428	230	448	250	483	275
Finland	668	55	730	61	766	75
France	1,040	792	904	709	907	722
Germany	2,489	1,745	2,405	1,661	2,305	1,567
Italy	703	545	699	565	688	595
Netherlands	460	355	494	381	524	406
Norway	128	33	147	34	128	34
Spain	858	304	856	308	811	312
Sweden	251	46	272	60	278	60
United Kingdom	193	121	152	132	151	133
West Europe	**7,484**	**4,465**	**7,367**	**4,405**	**7,325**	**4,425**
Bulgaria	268	25	318	25	344	25
Czech Republic	44	44	45	45	45	45
Poland	1,221	940	1,263	966	1,269	975
Slovakia	61	61	60	60	60	60
Ex-Yugoslavia	52	7	43	7	40	10
Central Europe	**1,734**	**1,162**	**1,823**	**1,193**	**1,856**	**1,210**
Former U.S.S.R.	**9,224**	**7,670**	**9,453**	**7,913**	**9,918**	**8,355**
South Africa	553	245	557	255	559	265
Africa	**721**	**315**	**737**	**340**	**702**	**368**
Iran	990	990	1,464	1,464	1,481	1,465
Kuwait	634	634	714	714	682	682
Qatar	238	238	311	311	320	320
Saudi Arabia	2,364	2,364	2,179	2,179	2,450	2,450
United Arab Emirates	1,605	1,605	1,810	1,810	1,975	1,975
Middle East	**6,669**	**6,586**	**6,981**	**6,889**	**7,509**	**7,382**
China	6,609	335	6,412	420	8,557	655
India	963	465	1,024	515	1,141	565
Indonesia	358	102	370	106	367	111
Japan	3,478	1,865	3,503	1,951	3,466	1,895
Korea (South)	1,400	670	1,486	700	1,511	710
Philippines	192	45	208	45	213	50
Singapore	210	210	200	200	200	200
Taiwan	242	212	250	225	330	300
Asia	**14,366**	**4,180**	**15,258**	**4,446**	**16,177**	**4,776**
Oceania	**960**	**60**	**956**	**60**	**953**	**67**
World Total	**64,867**	**42,878**	**66,885**	**44,293**	**69,750**	**46,364**

a. Tons x 1,000.

Source: Kiho (2005).

Table III.22. Consumption of Sulfur in All Forms and as Elemental Sulfur (2002–04)[a]

Region	2002		2003		2004	
	All Forms	Elemental	All Forms	Elemental	All Forms	Elemental
North America	14,259	11,215	14,574	11,470	14,798	11,840
Latin America	5,419	3,195	5,494	3,065	6,092	3,520
West Europe	6,789	3,770	6,687	3,725	6,560	3,660
Central Europe	1,437	865	1,495	865	1,476	830
Former U.S.S.R.	5,014	3,460	5,050	3,510	5,088	3,525
Africa	6,745	6,339	7,127	6,730	7,389	7,055
Middle East	2,174	2,091	2,161	2,069	2,188	2,061
Asia	20,046	9,860	21,448	10,636	23,917	12,516
Oceania	1,830	930	1,806	910	1,836	950
World Total	**63,713**	**41,725**	**65,842**	**42,980**	**69,344**	**45,957**

a. Tons x 1,000.

Source: Kiho (2005).

CHAPTER IV.
ASSESSMENT OF FERTILIZER PROJECTS

Many developing countries are endowed with deposits of phosphate rock and other fertilizer raw materials. Often the existence of a material resource in a country raises expectations for the development of a viable fertilizer industry. However, many technical, economic, environmental, and other factors may affect the development of these resources and the development of fertilizer production units based on these resources and/or imported raw materials.

Sound investment decisions concerning the development of natural resources and/or associated downstream facilities require an appropriate level of analysis, which may range from cursory opportunity studies to very detailed feasibility studies. The feasibility of any project can be broadly considered in terms of technical feasibility and economic feasibility. Technical studies provide the basis for concurrent and subsequent economic evaluations. Both the technical and economic aspects of any project must be considered together in order to make sound decisions, whether they may be to discontinue activities or to invest in a venture that has the potential to be economically sustainable.

This chapter examines some of the technical and economic factors that determine the viability of exploiting raw material sources and developing fertilizer manufacturing facilities based on these resources. Discussion focuses primarily on phosphate resource development as an example. This chapter does not explore all the details of assessing agromineral deposits or hydrocarbon resources. In particular, the development of hydrocarbon resources is not detailed to any extent. Hydrocarbon exploration and oil and gas field development are very capital intensive and represent technologically specialized fields. Similarly, as indicated in the chapters concerning nitrogen fertilizers, nitrogen fertilizer plant design and development is a very specialized field serviced by a limited number of engineering firms on a worldwide basis.

The examples of phosphate resource development and general principles and methods of performing technoeconomic studies outlined in this chapter can be broadly applied to the development of other potential fertilizer material sources. Although it can be technically feasible to produce fertilizers from indigenous material sources, quite often economic studies indicate that development is not economically attractive. In other situations, development may seem to be economically attractive, but technical factors can eliminate projects from consideration.

This chapter attempts to provide a general overview of the methodologies used to perform technoeconomic studies. Various types of data and data analyses are required to make sound decisions on investments in resource development and fertilizer production units. Analysis of preexisting data is basic to any situation. Technical studies provide data for engineering decisions and design. Engineering design studies provide data for engineering cost estimates. Engineering cost estimates may be integrated into larger scale technoeconomic studies of overall project feasibility.

This chapter further attempts to note the complexities of this process, the interactions that may be involved, and some of the realities of performing preinvestment studies.

Determination of Technical Feasibility

Determination of technical feasibility is defined for the purpose of this document as the assessment of deposits of agrominerals and the processing characteristics of raw materials obtained from these deposits, and other sources, by conventional or nonconventional methods for eventual use as fertilizers. The determination of technical feasibility is one of the first stages in the evaluation of agromineral deposits, and a preliminary economic study may or may not be included. When the economic analysis or determination of the commercial viability of a situation is the main emphasis of study, technical studies become support or functional studies.

Technical studies must be instituted in several areas in the early stages of the evaluation of agromineral deposits. These studies can include geologic studies of phosphate rock or other agrominerals, assessment of quality and processing characteristics, and mining studies.

Geologic Studies

Phosphate rock and other agromineral deposits (sulfur, limestone, and potash) are usually discovered during the course of exploration for more valuable mineral deposits (gold and rare earths), oil exploration, or groundwater investigations. Phosphate rock is a relatively low-value bulk commodity. Potash is a relatively higher value product. At the present time, sulfur is a relatively low-value bulk commodity.

The discovery of an agromineral deposit does not imply that the agromineral exists in a form, quantity, or quality that is technically or economically feasible to exploit. By definition a deposit is "earth material of any type either consolidated or unconsolidated that has accumulated by some natural process or agent" (Bates and Jackson, 1980). For example, the average abundance of P_2O_5 in the earth's crust is 0.22 wt % (Carmichael, 1982); a concentration of 1.0 wt % P_2O_5 is certainly anomalous and may be called a phosphate deposit.

Geologic studies are initially performed to determine the geologic characteristics and extent of potential ore bodies. Geologic studies evolve over time, usually in an attempt to define the resources and reserves.

The use of the term "reserves" usually indicates that enough exploration or development work has been done to define the extent and grade of a deposit or portion of a deposit and to determine that the deposit could be mined and processed to recover a marketable product at the time of the study or under a specified technoeconomic scenario. The use of the term "ore" also indicates that a deposit can be mined and processed to produce a product that can be sold at a profit. Reliable estimates of the amount of a product potentially available from a deposit require extensive detailed information. The term "resources" usually implies that the deposit or a portion of the deposit cannot be economically exploited under current conditions or has not been sufficiently explored to place it in the reserve category.

If an anomalous agromineral concentration is discovered and initial results of geologic studies are encouraging, more funding may be allocated for developmental work. Usually the deposit is drilled to obtain geologic data and samples for test work. Drilling is an expensive undertaking requiring the mobilization of costly equipment and significant personnel. Quite often several drilling campaigns are needed to adequately define a deposit. Each drilling campaign may take place over a single season. In the interim between drilling campaigns, decisions must be made concerning further work, and funding must be secured.

Figure IV.1 indicates the progressive nature of the evaluation of a mineral deposit. During the initial stages of deposit development, the extent of the deposit is explored and the size of the resource is generally expanded. At some stage in the process, the limits of the potential ore body are found and infill drilling is continued to define the continuity of the deposit. Further drilling is used to definitively establish reserve estimates.

First evaluations of possible resources and reserves tend to overestimate the amount of potential ore that will eventually be recovered. In general, most geologists are not familiar with the complexities of mining and processing methods. During the first stages of evaluation, there are no data to evaluate potential mining methods and losses, limitations in mining, or losses during processing. As the evaluation of a deposit proceeds and as complementary technical studies are performed, estimates of the amounts of potential ore resources and reserves generally decrease (Figure IV.2). Quite often final reserve estimates, in terms of product, are less than 30% of initial resource estimates. If studies show that a product cannot be produced profitably from a deposit, technically speaking, there is no ore and there are no reserves.

Characterization and Processing Studies

At some point during the exploration of an agromineral deposit, samples are tested to make

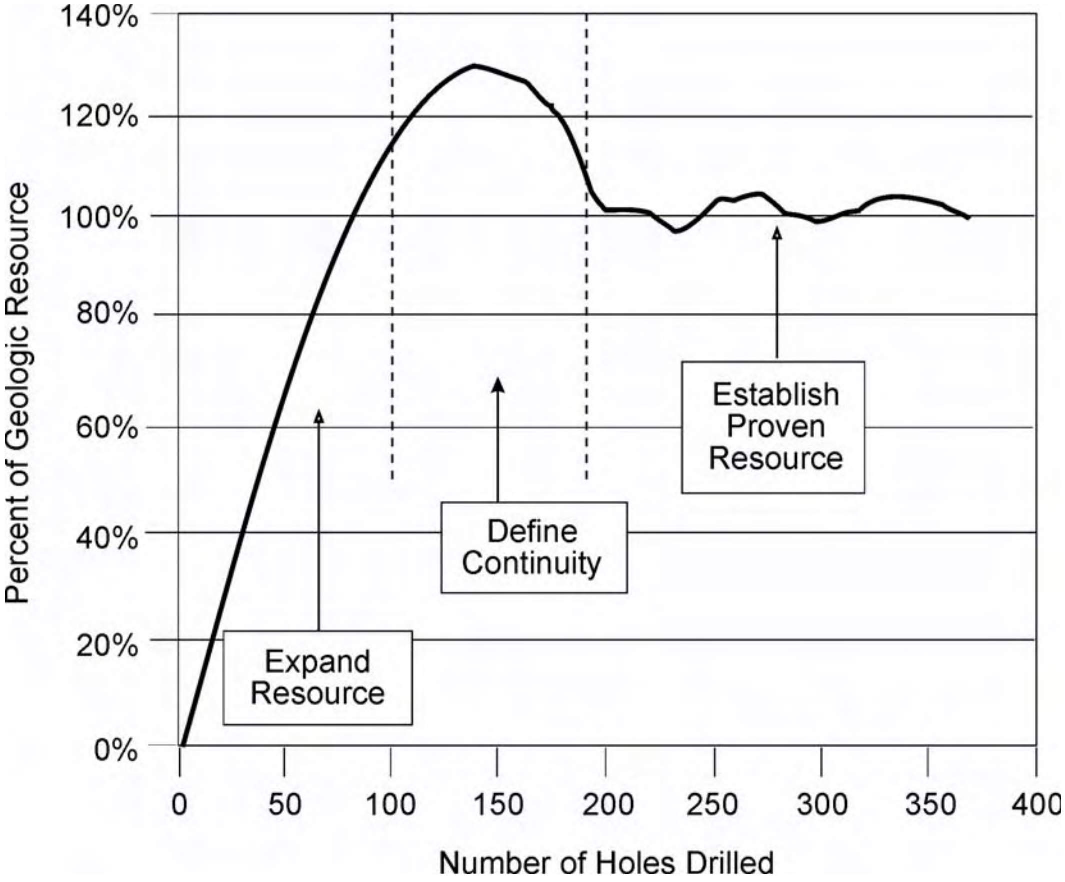
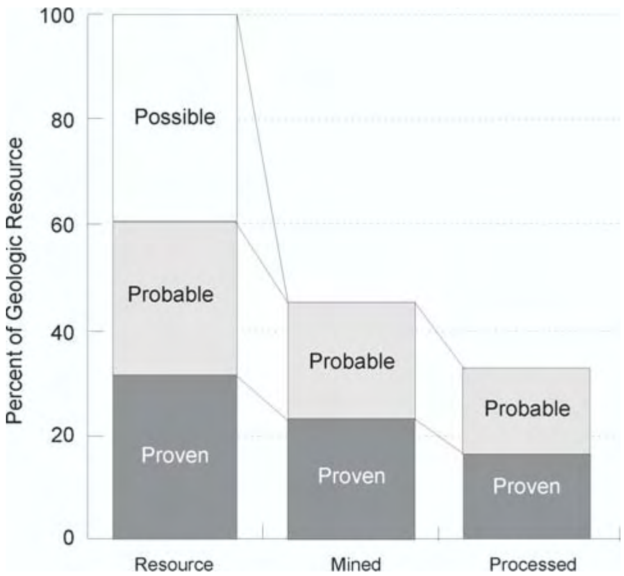


Figure IV.1. Stages of Resource Quantification During the Course of Exploratory Drilling

preliminary assessments of their potential value either as feedstocks for fertilizer manufacture or for use as a direct-application fertilizer. These tests may include (1) characterization of the potential ore or concentrates, (2) beneficiation tests, (3) fertilizer processing tests, and possibly (4) agronomic tests of products.

Ideally, when a potential ore sample is submitted for test work, it would be a single sample that is representative of potential production from a mine developed on the deposit throughout the life of the mine. This is rarely the case. If the deposit is incompletely explored and some parts of the potential ore body have not been sampled, the sample cannot truly be a representative sample. Phosphate rock and other agromineral deposits can be highly variable according to rock type, and secondary weathering processes can alter portions or zones of deposits. Quite often several ore types can be identified in a deposit. These ore types are often classified according to the predominant minerals or gangue minerals. Some common examples of names for potential phosphate ore types include (1) aluminophosphate ore, (2) siliceous ore, (3) dolomitic ore, and (4) ferruginous (high iron) ore. Different ore types generally require specific beneficiation treatments to produce usable products. Some potential ore types may not be suitable for eventual production of usable products.

Characterization studies of potential ore samples can provide valuable data that can be used to make a preliminary assessment of the potential value of a deposit and to guide further studies. Characterization studies can provide (1) an assessment of the composition of potential ore and gangue minerals, (2) estimates of the potential for beneficiation and possible beneficiation routes, and



Source: Noble, 1993.

Figure IV.2. Progression of Quantification of Geologic Resources to Reserves of Processed Product

(3) preliminary assessment of suitability of concentrates for various fertilizer production processes and/or applicability for direct application.

Characterization studies can provide guidance in exploration and resource assessment. Specific ore types in a deposit may be found to be unsuitable for further processing. Portions of deposits with unsuitable ore types may be eliminated from resource/reserve calculations.

The first step in performing an evaluation of a phosphate rock or other agromineral deposit is to search for literature concerning the deposit in question and previously performed technical analyses. The client submitting the sample is also asked to supply any information (unpublished reports, etc.) that is not openly available.

Critical examination of preexisting data can provide valuable insight into specific problems and answer many questions. What are the host rocks? What are the dominant potential ore minerals? What are the dominant gangue minerals? What type of geologic variability is found in the deposit, and could this affect mining and beneficiation? What types of studies have been done previously, and what were the results of such studies? These and innumerable other questions can be asked in specific situations. Perhaps one of the most valuable results of the critical examination of preexisting data is the determination of what additional data are needed.

The results of characterization studies may determine potential ore types or ore zones in a particular deposit that are not suitable for processing. A common mistake made in evaluating phosphate deposits is to evaluate the deposit solely on the basis of the P_2O_5 content of samples. All or a portion of the P_2O_5 may be present as nonapatitic phosphates. In many cases these minerals are detrimental to downstream processing.

Beneficiation of phosphate rock and potash ores is usually required to upgrade ores and remove undesirable impurities. In some cases, nonapatitic phosphate minerals and other gangue minerals such as iron oxides and silicates (clays, quartz, feldspars, etc.) may be removed from phosphate ores by simple size-classification methods such as water washing and screening, hydrocycloning, or dry screening methods. In other cases with phosphate rocks and potash ores, more complicated beneficiation techniques such as flotation must be employed. Magnetic separation might be employed to remove ferromagnetic minerals from phosphate rocks. The results of beneficiation studies provide the basic process design and configuration of equipment for processing plants, sizing of equipment, amounts and types of reagents needed for processing, and grade and quality of processed concentrates.

As previously mentioned, a common mistake made in evaluating phosphate deposits is evaluating the deposit based on the P_2O_5 content of samples. Even if all the P_2O_5 is contained within apatite, a portion of this apatite is lost during various stages of processing, depending on the type and degree of processing required. Mining, crushing, and/or grinding create fine phosphate particles, which usually have to be removed in subsequent processing stages. Even if crushing or grinding is not required, relatively simple processing steps such as washing and screening or hydrocyclone treatment to remove clays may remove a significant amount of naturally occurring fine phosphate particles. For instance, about 40% of the phosphate in Togo ores is lost in hydrocyclone treatment to remove clays. In Florida, ores are washed and screened at approximately 0.1 mm. The slimes resulting from this treatment are discarded and pumped to large storage areas. Quite often the P_2O_5 content of these slimes is as high as or higher than that of the untreated ore. Significant losses can also occur at other stages:

- During flotation.
- During the handling and movement of concentrates to storage facilities.
- During loading.

The grade of concentrates is almost invariably inversely proportional to the recovery of phosphate; that is, as the grade of product is increased, more phosphate is lost during processing. Commonly encountered total losses of phosphate during beneficiation may range from as little as 15%–20% to over 70% depending on the type of ore and processing configuration.

The most significant aspects of beneficiation test work are the determination of losses and recoveries by various processes, selection of a process, and eventually the determination of the ratio of concentration. The ratio of concentration is defined as the amount of ore processed, divided by the amount of concentrate recovered from the original ore sample. Table IV.1 shows the total material balance of the beneficiation of an African igneous phosphate ore. In this case, the ratio of concentration is about 6.6:1. This ratio determines the sizing of the beneficiation plant and the design of the mine feeding the beneficiation plant. For example, using a ratio of concentration of 6.6:1, a mine feeding a beneficiation plant that must produce 100,000 tons of concentrate per year must process 660,000 tons of ore per year.

It should be mentioned that the data produced by beneficiation studies are wholly dependent upon the samples used for the test work. These samples are usually generated by geologic studies. In the worst case, a single sample considered "representative" is submitted for analysis. However, deposits are very rarely homogeneous throughout any potential mining area and a single collected sample is usually not representative of a deposit. Better results are possible when the deposit has been extensively sampled and samples are compounded, perhaps according to ore types. One of the main objectives of developing a mining plan is to provide a constant

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Table IV.1. Total Material Balance for Beneficiation of an Igneous Phosphate Rock From Africa[a]

Product	Weight	Assay			Distribution		
		P_2O_5	CaO	Fe_2O_3	P_2O_5	CaO	Fe_2O_3
	(%)	(wt %)			(wt %)		
Primary slimes (–200 mesh)	37.52	5.7	2.0	22.3	23.25	8.48	51.92
Washed product[b] (+200 mesh)	62.48	11.3	13.0	12.4	76.75	91.55	48.08
Attrition scrubbed oversize (+16 mesh)	1.69	3.3	2.1	25.8	0.61	0.40	2.71
Attrition scrubbed[b] product (–16 +200 mesh)	51.78	12.7	15.2	9.4	71.53	88.43	30.23
Secondary slimes (–200 mesh)	9.01	4.6	4.0	27.0	4.51	4.05	15.11
Phosphate float[c]	15.21	38.8	47.5	1.5	64.15	81.18	1.42
Iron nonfloat	36.57	1.9	2.5	12.5	7.55	10.27	28.39
Run-of-Mine (ROM) rock	100.00	9.2	8.9	16.1	100.00	100.00	100.00

a. **Test Conditions**:

Conditioning: 2 min with 0.25 kg/ton caustic pearl starch (pH = 10.0).
2 min with 0.5 kg/ton collector mixture (oleic acid in kerosene at 1:1 by weight ratio)

Flotation: Phosphate flotation at pH = 9.5 until a demineralized froth (1–2 min).

b. Not added in total.

c. Contains 0.95% Al_2O_3 and 2.8% SiO_2.

feed, in terms of grade and impurities, to a beneficiation plant. The best studies are based on extensive beneficiation data detailing ore variations from across the deposit. When these data are available, mining plans and preprocessing schemes can be designed and cost of production can be estimated. At this stage it may also be necessary to reevaluate geologic studies and perhaps gather more data if needed.

Fertilizer processing studies are conducted in laboratory and bench-scale facilities and at several pilot plant sites. Processing studies can be conducted to study the production of various superphosphates, phosphoric acid, ammonium phosphates, nitrophosphates, and the bulk blending and granulation of various products. The objectives of processing studies are varied. Many studies are conducted to determine the suitability of specific phosphate rocks in standard processing schemes. Processing schemes may be modified to accommodate raw material characteristics or to produce special products. Novel processing schemes may also be developed.

Processing studies may be conducted in batch and continuous modes. Continuous studies provide much more data on operating conditions, operational difficulties, flow rates, recycle systems, and other factors to be considered in real-world operational situations.

Table IV.2 shows the partial results of IFDC laboratory-scale test work involving the production of SSP from an African igneous phosphate rock concentrate; an igneous phosphate rock from Araxa, Brazil, that is used commercially was tested in parallel in order to perform a comparative analysis. The samples used for testing were prepared from different ore types by various beneficiation methods. The results indicated that products produced from some of the African igneous concentrates had P_2O_5 availabilities similar to those of products produced from the Araxa rocks. In ROP-SSP production, a sulfuric acid acidulated SSP mass is confined in a den to allow chemical reactions to take place and allow the mass to solidify or "set" before it is disintegrated by a cutter and transported to a curing

Table IV.2. Partial Results of Laboratory Production of SSP From an African Igneous Rock Concentrate and Araxa Concentrates

Run No.	3	5	7	9	11	1
Rock source	Africa	Africa	Africa	Africa	Africa	Araxa
Sample No.	1	2	3	4	Composite	R230.84
Amount, g	200	200	200	200	200	200
Water						
Amount, g	50	50	50	50	50	50
Water/rock, wt ratio	0.25	0.25	0.25	0.25	0.25	0.25
Sulfuric acid						
Concentration, %	99.3	99.3	99.3	99.3	99.3	99.3
Amount, g	121.94	124	121.6	115.36	122.35	119.57
Acidulation ratio						
$(P_2O_5+SO_3)/CaO$, mole	1	1	1	1	1	1
H_2SO_4/P_2O_5, wt	1.50	1.53	1.54	1.49	1.57	1.60
Set time, s	>120	>120	>120	>120	>120	60
Temperature in den after						
5 min (°C)	92	91	92	88	87	84
10 min (°C)	93	91	91	87	87	81
20 min (°C)	94	92	91	85	86	81
30 min (°C)	96	93	91	84	86	83
40 min (°C)	99	92	92	83	85	83
50 min (°C)	102	95	92	81	84	83
60 min (°C)	106	96	91	80	83	81
Product quality from den	Not set	Not set	Not set	Not set	Not set	Set

(Continued)

Table IV.2. Partial Results of Laboratory Production of SSP From an African Igneous Rock Concentrate and Araxa Concentrates (Continued)

Run No.	3	5	7	9	11	1
Rock source	Africa	Africa	Africa	Africa	Africa	Araxa
Sample No.	1	2	3	4	Composite	R230.84
Analysis after 1 day, %						
Total P_2O_5	23.4	23.2	23.0	22.0	22.4	21.6
Water-soluble P_2O_5	17.8	17.3	16.7	16.0	15.0	16.2
Available P_2O_5	18.3	17.8	17.1	16.5	16.9	18.3
Free acid	7.3	8.6	9.6	8.0	8.7	5.5
AOAC H_2O	5.0	5.5	5.7	5.7	5.6	3.7
Water solubility, % of total P_2O_5	76.1	74.6	72.6	72.7	70.0	75.0
Availability, % of total P_2O_5	78.2	76.7	74.3	75.0	75.4	84.7
Analysis after 1 week, %						
Total P_2O_5	23.3	22.8	22.4	21.6	21.9	22.0
Water-soluble P_2O_5	18.4	17.9	16.6	14.4	14.5	16.4
Available P_2O_5	19.3	19.0	17.9	15.9	17.5	19.2
Free acid, % P_2O_5	5.3	6.4	6.5	7.3	6.6	3.9
AOAC H_2O	3.4	5.3	5.0	5.3	5.4	3.4
Water solubility, % of total P_2O_5	79.0	78.5	74.1	66.7	66.2	74.5
Availability, % of total P_2O_5	82.8	83.3	79.9	73.6	79.9	87.3

pile. Significantly, none of the African samples had solidified in the SSP denning process after 60 min. This factor affects the design and cost of a SSP plant built on feed from this rock, increasing the size of the denning section and length of time the acidulated rock must spend in the denning section of the plant.

Table IV.3 shows a summary of data produced by a study of phosphoric acid production from a Middle East phosphate rock; calcined North Carolina phosphate rock was run in parallel with the Middle East phosphate rock for comparative purposes. Phosphoric acid production tests provide a wealth of data for process design purposes. One of the most significant results of this test was the determination of the filtration rate and P_2O_5 recovery. The calcined Middle East rock tested had a very low Fe_2O_3 and Al_2O_3 content. This factor led to very low P_2O_5 recoveries during filtration (45.0% of the total P_2O_5) and a low filtration rate [1.9 tons P_2O_5 produced/(day)(m)^2] as shown in Table IV.3 (Test 2). When an aluminum source was added to the acidulation step (Test 3), P_2O_5 recovery increased to 96.8% and the filtration rate to 11.6 tons P_2O_5 produced/(day)(m)^2. Filtration rates for typical Florida dihydrate phosphoric acid plants are about 7–8 tons P_2O_5 produced/(day)(m)^2. Determination of the filtration rate and P_2O_5 recovery rate can be critical when evaluating the viability of specific phosphate rocks for phosphoric acid production and can have a significant impact on the design and size of the filtration section.

Test programs for a variety of fertilizer processes can be designed to gather critical data. The main purpose of many granulation studies is to determine whether a product with suitable physical and chemical characteristics can be produced from selected raw materials. One of the most significant pieces of data gained by such studies is the determination of the recycle ratio. The recycle ratio is defined as the circulating load divided by the amount of product drawn off the system. In many granulation processes, granules are built up through repetitive passes through the system. Some granules become oversize, are crushed, and are returned to the system as recycle with undersize granules. The recycle ratio varies according to the type of process employed and equipment configuration, the characteristics of individual raw materials, the mixture of raw materials, and/or chemical reactions taking place during the granulation process.

Table IV.3. Summary of Data for Operation of Bench Scale Phosphoric Acid Unit Using North Carolina Ground Calcined Rock (NCGC) and Middle East Phosphate Rock Concentrates (ME-1 and ME-2)

Phosphate rock	NCGC	ME-1	ME-2
Test number	1	2	3
Duration (h)	40	40	67
Retention time (h)	4	5	5
Actual Flow Rates, (g/h)			
Phosphate rock	371	312	302
Sulfuric acid (100% H_2SO_4)	316	279	274
Recycle acid (% P_2O_5)	1,067 (17.8)	1,050 (18.1)	1,030
Defoamer	0	0	0
Reactor slurry	1,513	1,401	1,470
Kaolin clay slurry (5% clay in water) (dry basis)	–	–	4.65
Actual Test Conditions			
Temperature, °C	74	74	75
Reactor slurry	63	65	66
Filter feed slurry	28.1–29.5	28.4–33.3	29.9–31.7
Solids in slurry, % range	28.8	30.4	30.5
% average	1.5–1.8	1.6–1.9	2.2–2.4
Free SO_4^{-2} in filter acid, % range	1.6	1.7	2.3
% average	27.6–28.1	27.7–28.0	28.0–28.9
P_2O_5 in filter acid, % range	27.8	27.9	28.5
% average	1.50	1.46	1.45
Slurry density, average, 10^3 kg/m^3	224	125	209
Filtration at ΔP = 56 cm Hg			
Number of washes	3	3	3
Cake drying time (s)	30	60	15
Filter cake thickness, average (mm)	73	78	67
Filtration rate [ton P_2O_5 produced/(day)(m)^2]	4.6	1.9	11.6
Results From Material Balance			
Dry filter cake production, kg/kg P_2O_5	5.2	4.6	4.8
Sulfuric acid consumption, kg 100%/kg P_2O_5	2.96	2.82	2.66
Defoamer consumption, kg 10% solution/kg P_2O_5	0	0	0
P_2O_5 reaction efficiency, %	99.3	93.25	99.1
P_2O_5 recovery, %	95.75	45.0	96.8
P_2O_5 washing losses, %	3.55	48.25	2.26
P_2O_5 coprecipitation losses, %	0.5	5.8	0.90

Determination of the recycle ratio is critical to plant design. If a granulation plant is built at a recycle ratio of 2.5:1 and the actual operational recycle ratio is found to be 5:1 after the fertilizer plant is built, production from the plant would be half of the design production rate. This factor would seriously affect the economics of any situation. Conversely, if a granulation plant is built on a recycle ratio of 5:1 and the ratio is actually found to be 2.5:1, production could be doubled. This situation would seem to be advantageous, and it may be; however, if no market exists for the product, the plant was built oversized and capital was not expended wisely.

Mining Studies

Mining studies are usually instituted after geologic studies have confirmed the extent of a deposit and test work has indicated that usable or salable products can be produced from a deposit. Mining studies are engineering endeavors and may be conducted at varying levels of effort and expense.

In the initial stages of mining studies, ground conditions and the known geometry of an ore body are examined and a simple technical assessment of the possibilities of mining is usually determined. A conceptual mining plan may be developed.

Phosphate rock mining may be very similar to coal mining. The largest phosphate and coal mines are open pits, and similar equipment is generally used. Similar methods and equipment are used in underground phosphate and coal mines. Mining companies or consultants with a broad range of mining experience can formulate effective mine plans for phosphate mining operations.

Because solid potash deposits are composed of water-soluble minerals, they are usually found at relatively great depths and are mined by various underground methods. Problems associated with potash deposits may include:

- The initial sinking of shaft through weak sedimentary strata with high hydrostatic pressure.
- Coping with plastic deformation of strata and weak roof rocks.
- Coping with potential flooding and water inflow and corrosion.
- Longevity of equipment.

If possible, given these considerations, companies or personnel experienced in potash mining should be engaged in feasibility studies and/or mine planning. Similarly, for both phosphate and potash mining, beneficiation is a specialized field. Specialists with experience should be engaged for the feasibility studies if possible.

It may become very apparent at an early stage in mining studies that more data are needed on the geometry, continuity, geologic variability, and processing characteristics of a potential ore body. More often than not, the results of geologic investigations simply do not provide enough data for mining studies. At this point geologic problems become mining engineering problems.

Substantial amounts of data in addition to the data produced by geologic studies are required for mining studies. For instance, what are the groundwater conditions? How much water may infiltrate into an open pit or underground mine? How much water may enter the mine from runoff? What pumping capacity will be needed if an open pit or underground mine is developed; how might this change as the mine is developed? What are the potential limits of ore grade? How variable is the ore across the deposit? How might ore variability affect providing a constant feed to the beneficiation plant? What are potential mining losses? What is the dilution factor? How might the geometry of the ore body affect mine design and the amount of potential ore that must be left in the ground for roof support (underground mines) or the amount of potential ore left in the ground below a level where a pit can be economically developed? These and many other questions can be asked in specific situations.

If the technical aspects of mining appear favorable, at some point the mining studies must provide production cost estimates. Substantial amounts of data are required for such estimations. For instance, the cutoff grade is the grade above which potential ore is economic to mine and process. Material below the cutoff grade is waste. If economic conditions change, material that was considered waste may be reclassified as ore. Conversely, a change in economic conditions may result in portions of ore body being reclassified as waste.

The break-even cutoff grade (BCOG) is needed to calculate ore reserves. The BCOG is the grade at which:

$$\frac{\text{Cost}_{\text{mine}} + \text{Cost}_{\text{process}} + \text{Cost}_{\text{G\&A}}}{\text{Recovery x (Price} \quad \text{Cost}_{\text{FSR}} \quad \text{Royalties)}} = 1$$

where:

Recovery = Process recovery.
Price = The sales price of product (including profit).
Cost_{FSR} = Cost of freight, sales, and refining.
Royalties = Royalties costs.
$\text{Cost}_{\text{process}}$ = The cost of processing.
$\text{Cost}_{\text{mine}}$ = The cost of mining ore and waste.
$\text{Cost}_{\text{G\&A}}$ = General and administrative costs.

Therefore, reserves of a mine can only be calculated after substantial amounts of data are developed and evaluated and after cost estimations are performed or certain values are fixed. The cost estimation techniques of mining studies are similar to the cost estimation and project evaluation techniques outlined in subsequent sections of this paper.

In summary, technical studies early in the evaluation of any project can eliminate the project from consideration or narrow the focus and provide direction for subsequent studies. A series of technical studies may be performed based on the results of the previous studies. At any point in this process it may be determined that the potential mining and processing of raw materials is not feasible or the original objectives upon which a study was based cannot be reached. At this point the objectives of a project can be redefined or the project can be shelved, eliminating the need for further studies and expenditure of time and funds.

Determination of Economic Feasibility

All studies that consider the potential economic feasibility or viability of a project can be broadly termed preinvestment studies. Several types of preinvestment studies can be performed. Opportunity studies are performed to identify investment opportunities or project ideas. Opportunity studies are usually rather broad in nature and rely on aggregate estimates rather than on detailed analyses.

When a project must be elaborated in more detail, prefeasibility and feasibility studies are performed. Such studies may also be termed technoeconomic studies. There is no set boundary between a prefeasibility study and a feasibility study. Table IV.4 is a typical table of contents for feasibility/prefeasibility studies. This table of contents is a modification of a proposed table of contents suggested by UNIDO (1986).

Prefeasibility studies are performed for several reasons: (1) to determine if an investment opportunity is so promising that an investment decision can be made on the basis of a prefeasibility study, (2) to determine if a potential project should be investigated by a more detailed feasibility study, and (3) to investigate any aspects of a project that are critical to its feasibility and recommend where functional or support studies are needed.

Detailed feasibility studies must provide a sound basis on which investment decisions can be made. Detailed feasibility studies should consider all technical, economic, environmental, and commercial factors in depth. The performance of a feasibility study is a systematic iterative process in which options are explored and facets of the project are optimized or reformulated. Ideally, such studies should be performed by a group of experts in respective fields.

Of primary importance to prefeasibility and feasibility studies is the determination of the present market and demand, as well as projections of the future market and demand. Without such analysis, mine and plant capacities and raw materials requirements must be arbitrarily fixed.

Sources and characteristics of raw materials must be evaluated. The potential costs of local and imported raw materials must be compared. A critical factor is the stability of any supply system. A fertilizer plant cannot operate without raw materials. Adequate buffer stocks of raw materials must be maintained; however, large stocks of raw materials in inventory may be an unnecessary expense. The availability of process and drinking water is often a primary constraint, particularly in semiarid or arid regions.

If a mine is developed as a source of raw materials, fertilizer plants are usually sited in a strategic location to save bulk shipping costs or to ensure that water is available. If a local mine is not the source of all raw materials, the location and site of the fertilizer plant must be carefully analyzed with respect to the transportation costs of obtaining raw materials and delivering finished products to market areas. The development of new transportation facilities or the utilization of preexisting facilities must be considered.

If the project is being developed in a remote area or where a considerable workforce must be assembled and maintained, infrastructure development must be planned. Workers must have housing and utilities, a viable transportation network (roads, perhaps public transport), and sources for goods and services. Health care for workers and their families is a primary concern, and the development of facilities for social interaction may be appropriate.

Table IV.4. Table of Contents for a Feasibility/Prefeasibility Study

Executive Summary Background and Justification General Economic Data Market and Demand for Specific Product Materials and Inputs Location and Site Project Engineering Plant Organization and Overhead Costs Manpower Implementation Schedule Financial Evaluation Commercial Profitability Conclusions
Background and Justification Project Background Project Sponsor, Promoter, and/or Initiator Project History Costs of Preparatory Studies and Related Investigations
General Economic Data General Characteristics Economic Characteristics Economic System Economic Policy Government Policies National Economic Justification
Market and Demand for Specific Product Demand and Market Study Sales Forecast and Marketing of Products and Byproducts Present Supply System Expected Local and Foreign Competition Production Programs Plant Capacity Cost of Marketing, Sales, and Distribution
Materials and Inputs Characteristics of Materials and Inputs Supply Programs Prices of Raw Materials, Local and Imported
Location and Site Location Site Transportation Costs Local Conditions

(Continued)

The environmental impact associated with any industrial project is an issue that is increasingly emphasized. It is highly advantageous to address any potential environmental issues as early as possible in any project in order to plan for mitigation of potential adverse effects and to analyze the cost of mitigation. Environmental assessments have grown to be more than just analyses of potential pollution and possible effects on local flora, fauna, and humans. Environmental assessments also include analyses of the potential archaeological, cultural, and social effects of development.

Project engineering, whether it be the development of a mine or a fertilizer plant or both, involves evaluation of the results of technical studies, selection of a process, development of a processing scheme, selection of equipment, and mine or plant design and construction. Project engineering also evaluates project organization, manpower, and

Table IV.4. Table of Contents for a Feasibility/Prefeasibility Study (Continued)

Project Engineering Project Layouts Scope of Project Technologies Pilot Plant Results Equipment Civil Engineering Works
Plant Organization and Overhead Costs Cost Centers Overhead Costs
Manpower Labor Staff Requirement for Expatriots Requirement for Training
Infrastructure Development Transportation Network Housing Utilities Commercial Development Health Care Social Development
Environmental Impact Potential Local and Regional Effects Archaeological Social and Cultural
Implementation Scheduling Data and Activities Project Implementation Program Selection and Time Schedule Cost Estimate of Project Implementation
Financial and Economic Evaluation Total Investment Costs Project Financing Total Production Costs Financial Evaluation Sensitivity Analyses
Commercial Profitability Rate of Return Repayment Period National Economic Benefits Sensitivity Analyses
Conclusions Summary of Financial and Commercial Aspects Recommendations Sequence of Next Steps to be Taken

implementation scheduling. As a part of project engineering, the capital costs and production costs are calculated and evaluated, usually under several scenarios.

In order to perform economic analyses, cost estimates of various facets of production must be prepared. Five levels of cost estimates are listed by the American Association of Cost Engineers: (1) order of magnitude estimates, (2) study estimates, (3) preliminary estimates, (4) definitive estimates, and (5) detailed estimates.

Order of magnitude estimates offer a relatively low level of accuracy—usually about ±40% of the true project cost. They are usually based on cost information derived from previous similar projects. One way in which order of magnitude estimates are performed is by applying simple ratio methods, an exponential method, and reliable factors.

Study estimates are considered to have an accuracy of ±25%. Study estimates are based on the knowledge of a flowsheet of a process and major equipment. This type of estimate is normally prepared by determining the approximate cost of major equipment, using data published in journals, and adding minor equipment costs and the costs of non-equipment items as percentages of the major equipment costs. Adjustments are made according to location.

A preliminary estimate is usually considered to have an accuracy of ±12% of actual project costs. This level of accuracy is usually considered adequate for budget authorization studies upon which a decision to implement a project may be made. Sufficient data must be acquired in order to prepare a budget. Preliminary design is required, and quotations should be obtained on major equipment. The design should include:

- General design basis.
- Process flow diagram and/or mining plans.
- Material and heat balances.
- Major process equipment sizes and descriptions.
- Process control diagram.
- Utility and fuel requirements.
- Motor listing.
- Equipment layout and elevations.
- Plot plans of processing facilities.

A definitive estimate is considered to have an accuracy of about ±6% of true cost. This type of estimate is used for project control and provides sufficiently accurate information for planning the appropriation of capital. A definitive estimate is based on detailed engineering specifications. Although fabrication drawings need not be complete, actual equipment prices are considered.

Detailed estimates are usually made by contractors as aids in tendering for projects, but only when absolutely necessary. Detailed estimates are considered to have an accuracy of about ±3%. Complete engineering specifications, fabrication drawings, and land surveys are required for detailed estimates. Detailed estimates are costly and time consuming. Actual equipment prices, labor availability and wage rates, subcontractors' estimates, and firm construction schedules should be considered in detailed estimates.

There are no set boundaries between the various levels of cost estimates. Entire projects may be subdivided into areas where experts in specific fields address specific components (mining plans, beneficiation plants, processing plants, distribution) of an overall project. The cost-estimating procedures of different experts may vary. Also, the amount of emphasis placed and level of effort and budget allotted to different aspects of a project may vary according to the objectives of key decisionmakers in the overall process.

The accuracy of cost estimating is much less when performing studies in developing countries, even for detailed estimates. In these cases an estimate based on scale-up factors from known costs provided by an engineering firm may be the most practical technique. Under these conditions an order of magnitude estimate may even be more accurate than a study estimate. When preparing cost estimates for developing country locations, a multiplier factor can be applied to the cost of a plant built at a well-known location (the U.S. Gulf Coast, for example). In particularly undeveloped areas, this factor can be as high as 2.0. In many locations, costs may be less than U.S. Gulf Coast costs and the factor may be less than 1.0. The best solution is probably to develop an appropriate location factor for each specific site.

Cost estimates are expensive and should only be performed to the degree of accuracy to which they are required. Figure IV.3 gives an indication of the costs of cost estimating as related to the cost of estimate as a percent of total project cost and the desired accuracy of an estimate.

The results of project engineering studies and cost estimations are intimately linked with financial and economic evaluations and the assessment of commercial profitability. At this point in a prefeasibility or feasibility study, it is advantageous to utilize financial and economic experts. The overall financial and economic evaluation considers all aspects of a project including total investment costs, project financing, total production costs, cash flow, marketing costs, and projected returns on investment. Basically, the potential amount of money generated

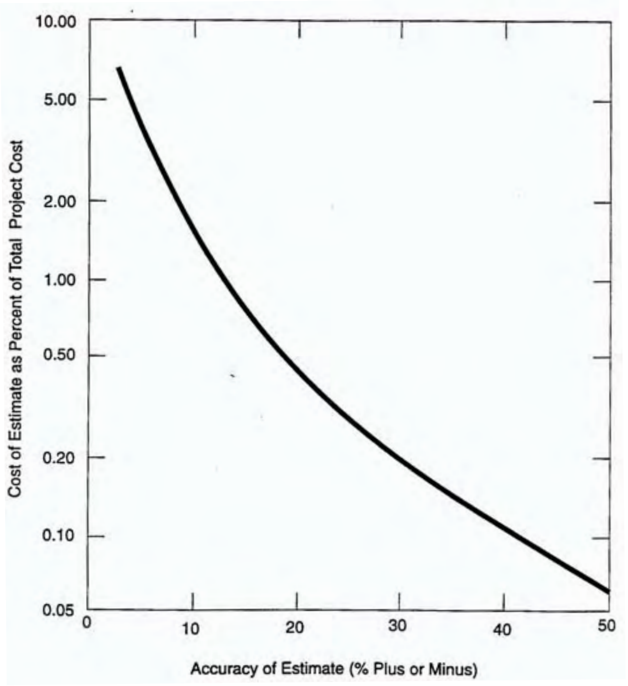

Figure IV.3. Estimating the Cost of Cost Estimating

over the life of a project must cover all costs associated with a project and provide a profit. The potential amount of profit generated generally must be at or above levels wherein investors could invest their money profitably at similar levels of risk.

In order to assess potential commercial viability, several points of reference are needed. One point of reference is the cost of raw materials available on the world market delivered to a production facility or distribution point within a country. The comparative cost of fertilizers may then be further analyzed by comparing the potential costs of materials delivered to main agricultural areas within a country.

Comparative raw material cost calculations are usually based on the amount of major element contents. Consideration may be given to characteristics of raw materials that may be detrimental to processing and thus may add costs or lower eventual product quality.

Fertilizers are compared on a nutrient cost basis. Usually the costs of DAP or TSP on the world market, plus shipping, handling, and insurance, are used. In comparing fertilizers, product quality and solubility in water are two other criteria that are used to compare products.

Another consideration is the cost of borrowing money. Low-cost loans with long repayment periods may be available from international lending institutions. When such loans are not available, shorter term loans at higher interest rates may be available from local institutions. Higher interest rates eventually translate to higher product costs.

When world market raw material or fertilizer prices are relatively high and interest rates are low, development of mining or production facilities is more favorable. When fertilizer prices are low and interest rates are high, the development of fertilizer raw material resources or manufacturing facilities becomes much more difficult.

Interest rates, exchange rates, costs of equipment and services, costs of raw materials, and prices of fertilizers change over time. Sometimes these changes can be quite unpredictable and dramatic. Cost estimates and the economic and financial evaluation portions of technoeconomic studies are performed at specific points in time; that is, costs, interest rates, exchange rates, and prices are fixed based on levels determined at the time of the study. Most technoeconomic studies include sensitivity analyses to evaluate potential changes in key cost components. Most technoeconomic studies also include evaluations of the utilization of production capacity and profitability.

Time Factors

The development of an in-country resource for eventual production of feedstocks and development of a fertilizer industry may consume substantial amounts of time. The length of time required to perform geologic studies is highly variable but can range from several years to tens of years depending on the level of interest and funding available.

Technical feasibility studies such as initial mining, beneficiation, and processing studies usually are implemented with relatively short timeframes (less than 1 year). More involved technoeconomic studies (prefeasibility studies) may require less than

1 year to 3 years depending on the level of effort required and budget available. Of course, these technoeconomic studies may indicate that more geologic and technical feasibility studies are needed. A detailed final feasibility study integrating all aspects of a project may require less than 1 year to several years.

Once a decision is made to develop a raw material resource and/or fertilizer manufacturing facility, all the components must be assembled and the physical works must be constructed. This is usually done through bidding processes. Detailed bid documents must be prepared, the bidders must have time to assemble their bids, and the bids must be evaluated. The process and the details of arranging financing may be very time consuming. The construction of a mine and processing facility and/or a fertilizer plant usually takes 2 years or more. The mine or other facilities must be commissioned, and it may take 1 to 2 years to reach design capacity. It is not inconceivable that the development of an indigenous resource from the discovery of a deposit to eventual production may take a minimum of 5–10 years and possibly much longer.

Conclusions

Significant amounts of time and money must be invested in gathering the data and performing the analyses that are necessary for making sound decisions on investments in developing in-country resources. The technical studies required include geologic studies, characterization-beneficiation-processing studies, and mining studies.

Geologic studies define ore bodies and provide preliminary estimates of potential ore resources and possible reserves. Initial geologic studies tend to overestimate potential ore reserves.

Characterization, beneficiation, and processing studies are performed to prove the technical feasibility of utilizing raw materials and their value as feedstocks. The results of technical studies can provide data to narrow the focus of subsequent studies or eliminate projects from consideration.

Mining studies are basically engineering studies. In the initial stages, mining studies may be largely conceptual. Mining studies evolve into mining cost estimation studies. Detailed mining studies require significant amounts of data. Quite often studies of a geologic nature and beneficiation studies must be reinstituted and/or expanded to provide data for detailed mining studies. Mining studies eventually become economic studies. Only through mining studies and cost estimations can the ore reserves of a deposit be determined.

Depending on the complexity of a situation, technical studies can become very involved. Technical studies are often best handled by specialists in particular fields. Technological problems unperceived by nonspecialists in the early stages of technoeconomic studies may have a profound influence on the results of subsequent studies.

Technical feasibility studies provide data upon which sound engineering decisions and designs must be based. Without technical studies many assumptions must be made in engineering studies. Technical studies can provide data that are critical to engineering decisions and design. Technical studies may also be implemented as support or functional studies in broader ranging prefeasibility or feasibility studies.

Engineering cost estimations of the development of mining and processing facilities are performed at varying levels of effort and cost and with varying levels of accuracy. Low levels of accuracy are associated with high levels of assumptions; higher levels of accuracy require increasing amounts of definitive engineering data and analysis.

Preinvestment studies are also performed at varying levels of effort and cost, and thus accuracy. The most basic preinvestment study is an opportunity study wherein investment opportunities are identified at a minimum of expense.

Preinvestment studies that examine all the technical, economic, and commercial aspects of a project are called prefeasibility or feasibility studies. The decision to call a preinvestment study a prefeasibility or a feasibility study is usually made very early in a project. When no previous prefeasibility study has been performed and the consultants are aware that significant, critical, technical or economic data may not be available for a study, a decision is usually made to call the study a prefeasibility study. Sometimes several studies of a prefeasibility nature may be performed in the course of a single project. Increasing amounts of data and data analyses are required to produce detailed feasibility studies upon which sound investment decisions can be based. The implementation of prefeasibility and feasibility studies is a systematic iterative process in which available data are evaluated, more data are obtained, and all the data are reevaluated.

The economic and financial analyses of a potential development project rely heavily on technical studies supporting project engineering decisions and engineering cost estimates. Location, transportation, and environmental factors are also significant when performing economic and financial analyses. Cost estimates and economic and financial analyses are performed at specific points in time. The costs of imported fertilizers, raw materials, construction costs, and equipment, as well as interest rates, exchange rates, and other costs are fixed at levels determined at the time of the study. The world market cost of fertilizers or raw materials can have a very serious impact on the results of any study, and the comparative delivered cost of fertilizers or raw materials is the primary criterion upon which the economics of a project must be judged. The amount of financing required to purchase equipment and the interest rates on loans can also have a serious impact on the economic viability of any project.

Many types of studies are needed to support decisions on investments in the development of in-country resources and fertilizer production units; collecting and analyzing the data required for these studies can be very costly and time consuming. The development of an agromineral deposit may take 5–10 years and sometimes much longer. The actual amount of work involved and expense associated with this work is usually not apparent to project originators. Compounding the time required for actual work on a project is the time required for decisionmaking processes. In this systematic iterative process, decisions must be made and further funding must be procured as it becomes apparent that further studies may be needed and/or as a project evolves. Many times in developing country situations, governmental agencies are involved and the decisionmaking process and procurement of funding may involve many other agencies and individuals. Each situation is different, but almost invariably this decisionmaking process may take more time than the actual performance of a study.

In the performance of preinvestment studies, eventually the consultants and clients may agree that enough data have been obtained and analyzed, and the study is then finalized. At this point an investment decision may be made. The investment decision may be to (1) discontinue all activities because the project is not technically or economically viable, (2) fund additional studies or consider other options, or (3) prepare an invitation to bid for actual development of a mine and/or construction of a fertilizer plant. All of these options are valid if the study was based on enough sound data and the data were interpreted and analyzed properly.

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COUNTRY DESCRIPTIONS

Country Descriptions

The country descriptions are presented in the following format. Each country is briefly described with respect to location, population, and other pertinent details, including transportation infrastructure. The general geology of each country is outlined because fertilizer raw material resources are directly related to the geology of each particular country.

Nitrogen Resources are described first, followed by Phosphate Resources, Potassium Resources, and finally Sulfur Resources. Although sulfur is not generally considered a primary nutrient, sulfuric acid is an essential component of many fertilizer processing schemes. Within each country description, the historical and current state of development of resources within the country is outlined. When available, chemical and other analyses of specific materials are given. In general the metric system is used throughout this document. In the country descriptions, resource/reserve estimates are presented in the units given in the original references. When both English and metric units were presented in a reference, both units are given. Because the computational methods or use of conversion factors within calculations to determine most of these figures are not known, no attempt was made to convert all the estimates to the metric system. At the end of each resource section, current and projected fertilizer production within each country is discussed. When available, costs of development or production are listed. No attempt was made to convert any costs to current U.S. dollars.

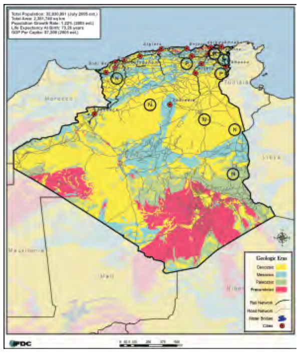
The first figure in each country report is based on a geologic map obtained from the Commission for the Geologic Map of the World (CGMW), Paris, France, utilizing their color scheme. For simplicity, only four geologic eras are delineated—from the oldest to the youngest: Precambrian, Paleozoic, Mesozoic, and Cenozoic. Within each country section, additional geological information is given where needed, particularly with respect to individual deposits.

The information in the country descriptions was obtained from traditional published literature, trade publications, unpublished technical reports, Internet sources, personal communications, and information in IFDC files. Quite often, nontraditional unpublished sources of information provide the best, and sometimes only, information on specific fertilizer raw material deposits.

Much of the information in the country descriptions was gathered in late 2005 to mid-2006. Quite often recognized information-gathering agencies do not release or print production or other data for 6 months to 1 year after the end of a calendar year. Sometimes this information is subject to revision for 2 years. In order to track ongoing projects, a reporter must practically be onsite or rely on press releases for information. The reader should be aware that, for the most current information on specific projects, the associated references, agencies, and organizations listed within this document should be consulted.

It should be noted that not every country within Africa is included in the country descriptions. Country descriptions are included for only those countries that have significant fertilizer raw material resources. Any omissions in this area are inadvertent; any discrepancies should be brought to the attention of IFDC and the author.

ALGERIA



The People's Democratic Republic of Algeria (Figure Algeria 1) is bordered to the east by Tunisia and Libya; to the south by Niger, Mali, and Mauritania; to the west by Morocco; and to the north by the Mediterranean Sea. Total area is 2,381,740 km^2. Approximately 3.2% of the land is arable. Algeria is the second largest country in Africa. The population was estimated in mid-2005 as 32.9 million inhabitants (World Factbook, 2006). Approximately 14% of the labor force is occupied by agriculture.

The transportation network consists of 71,656 km of paved roads, 32,344 km of unpaved roads, 2,888 km of 1.435-m-gauge railroad, and 1,085 km of 1.055-m-gauge railroad. There are 52 airports with paved runways and 85 airports with unpaved runways. Pipelines include 85,946 km for natural gas, 1,344 km for condensate, 2,213 km for liquid petroleum gas, and 6,496 km for oil. The main ports and terminals are Algiers, Annaba, Arzew, Bejaia, Djendjene, Jijel, Mostaganem, Oran, and Skikda.

The geology of Algeria is structurally complex because the country is located between several shield areas within Africa and the continents of Africa and Eurasia. The Reguibat Shield developed as a craton in the Eburnian Orogeny. The Hoggar Shield was deformed during the Panafrican Orogeny. The West African Craton and the Panafrican Mobile Belt collided along a feature known as the Tilemsi Suture. The Atlas Mountain Range of Morocco and Algeria is a result of Alpine deformation, which began in the late Eocene-Oligocene; the effects of this deformation are evident in both northern Africa and Europe.

Precambrian age rocks in Algeria are found in the Reguibat Shield near the Mauritanian border, in the Hoggar Shield in the extreme south of the country, and in the core of the Ougarta Mountains. The Reguibat Shield in Algeria consists of Birimian age rocks in two successions. The older succession consists of metasediments, lavas, and pyroclastics. The second succession consists of metasediments, lavas, and pyroclastics, which have been intruded by major granitic bodies. The Hoggar Shield has a central core area with gneisses and granites, and weakly to strongly metamorphosed metasediments and volcanics. The eastern Hoggar Shield consists of a sequence of shales and limestones followed by conglomerates, arkoses, graywackes, and siltstones. Volcanics are found in both of the sequences, and red beds top the entire sequence. On the east side of the Hoggar Shield, a variety of crystalline and metamorphic rocks are found in the Pharusian Belt. The Ougarta Mountains form a northwest-southeast trending extension from the Anti-Atlas in Morocco. Rhyolites form the base of the Precambrian sequence overlain by metasediments and volcanics.

Paleozoic rocks outcrop on the flanks and surround these Precambrian features. The occurrence of Cambrian age rocks is limited. A glaciation occurred at the end of the Ordovician in the southern Sahara, depositing a thick sequence of glacial sediments. Continental sediments were deposited during the Silurian. A major transgression occurred during the Devonian, depositing a shaly and sandy sequence with limestone lenses and reef structures. Limestones and dolomites were deposited in several areas during the Carboniferous. In the late Carboniferous in the Sahara Basin, shales and sands were

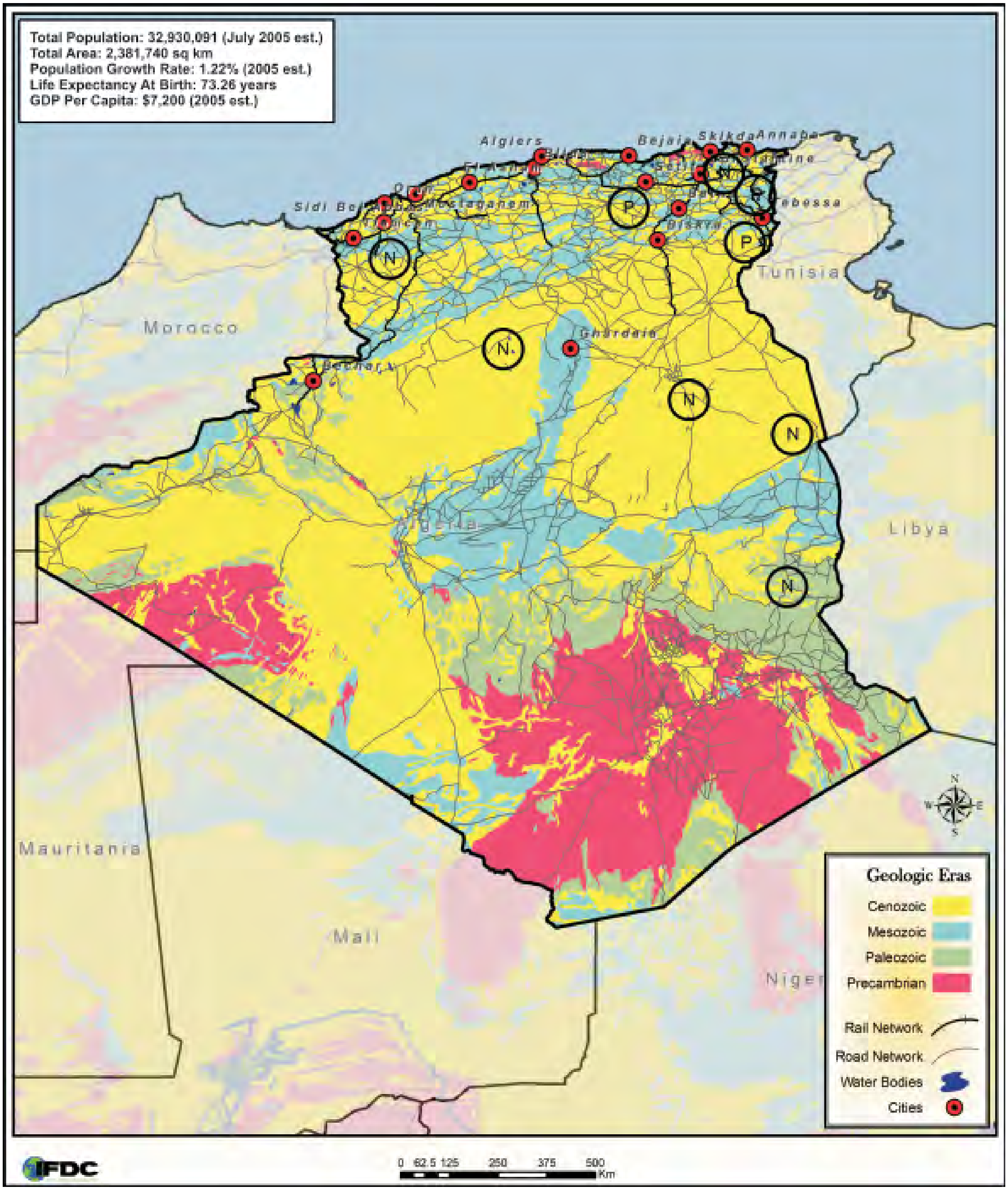


Figure Algeria 1. Geology, Major Cities, and Transportation Network deposited. Red beds of imprecise age were deposited over the Carboniferous age sediments. These red beds are overlain by volcanic rocks in areas.

In the Triassic, the area became emergent and a major delta system formed. Thick deposits of salt were laid down in northeast Algeria. Thin beds of limestones formed in the Upper Jurassic in several areas due to a marine transgression. Thick beds of clastic sediments were deposited in Algeria during the Lower Cretaceous. In the Upper Cretaceous to Eocene, two major marine transgressions occurred, and extensive deposits of limestones and marls were formed. After the post-Eocene regression, terrestrial conditions prevailed, leading to the deposition of coarse clastics and formation of dunes and desert pavements in the Sahara.

Nitrogen Resources

Algeria has produced oil since 1956. Sonatrach, owned by the Algerian government, domestically controls oil production, refining, and transportation. The Algerian government has, however, aggressively pursued foreign investment in the oil sector. In 2004 foreign companies were involved in 44% of Algerian crude oil production. However, all foreign operators must work in partnership with Sonatrach, and Sonatrach usually holds majority ownership in production-sharing agreements.

Crude oil production during 2005 was 1.373 million barrels per day (bpd) (World Factbook, 2006). This figure does not include 445,000 bpd of condensate and 250,000 bpd of natural gas plant liquids estimated by the Energy Information Administration (EIA) for 2004 (EIA, 2005). Production has been steadily increasing in the last several years. The Algerian production goal is 2.0 million bpd of crude oil by 2010 (EIA, 2005). Approximately 90% of Algerian crude oil exports go to Western Europe. The Algerian Sahara Blend Oil, 45º API with a very low sulfur content (0.05%), is among the highest quality crude oil in the world. European oil companies prize Algerian oil to make fuels that meet increasingly stringent European Union (EU) regulations on sulfur emissions from gasoline and diesel engines.

Sonatrach operates the Hassi Messaoud Field, the largest oil field in the center of the country, which produced about 350,000 bpd in 2004 (EIA, 2005). The largest foreign operator is Anadarko. Other foreign operators include BHP-Billiton, Amerada Hess, Burlington Resources, Talisman Energy, Agip, Arco (now owned by British Petroleum), Petrobas, China National Petroleum Company (CNPC), Cepsa, Total, Sinopac, Kuwait Foreign Petroeum Exploration Company, Petroceltic, Repsol-YPF (Spain), and Statoil (Norway). The seventh and eighth licensing rounds of foreign development of oil and gas reserves were held in 2005.

Commercial production of natural gas began in Algeria in 1961. Natural gas production was 82.4 billion m^3 in 2003 (World Factbook, 2006). Natural gas production exceeded oil production for the first time in 1997 (EIA, 2005). The Algerian government has encouraged the domestic use of natural gas, which represented over 63% of the total energy consumption of the country in 2002 (EIA, 2005). Use of natural gas accounted for 97% of the country's electric supply.

Natural gas is produced as associated gas and from nonassociated fields. The largest gas field in Algeria is the super-giant Hassi R'Mel, discovered in 1956. Reserves are about 2.4 trillion m^3. Hassi R'Mel accounts for about one-fourth of Algerian gas production. In 2003 about 11% of the associated gas in Algeria was flared (Mobbs, 2004). The Algerian government has banned the flaring of gas effective 2010. Numerous gas fields are currently under development.

In 2005 there were two natural gas pipelines to Europe. The 1,047-km-long Trans-Mediterranean pipeline runs from Hassi R'Mel via Tunisia and Sicily to mainland Italy. Capacity was doubled in 1994, and further increases in capacity are planned. The Maghreb-Europe gas line, completed in 1996, connects Hassi R'Mel with Cordoba, Spain via Morocco and then ties into the Spanish and Portuguese networks.

Several other pipelines are in the construction or planning stages. Medgaz, scheduled for completion in 2008, will link Beni Saf, Algeria to Almeria, Spain, with an eventual extension to France. Galsi, an Italian-German consortium, plans to put a pipeline to Italy onstream by 2008 (EIA, 2005).

Nigerian National Petroleum Corporation (NNPC), the Nigerian state oil company, wants to construct a 7,100-km-long natural gas pipeline from Nigeria through Niger to Algeria to link with existing pipelines and eventually transport Nigerian gas to European markets.

Algeria was the world's first producer of liquefied natural gas (LNG) when the Arzew GL42 plant became operational in 1964. In early 2004 a boiler exploded at the Skikda export terminal, destroying three of six LNG production trains and damaging the other three. Each LNG train has a capacity of 1 billion m^3 per year (Mobbs, 2004). Repairs were completed on three of the plants in late 2004. Three of the plants were to be replaced by one 4-billion m^3/year capacity LNG plant. Production should return to and exceed pre-2004 levels in 2008 (EIA, 2005).

Naftec, a subsidiary of Sonatrach, operates Algeria's four refineries. The combined capacity of the refineries is 450,000 bpd. Mobbs (2004) indicates that total production of all products was 139 million barrels in 2004. The Skikda refinery (300,000 bpd) provides the bulk of production, and the smaller Hassi Messaoud (30,000 bpd), Algiers (60,000 bpd), and Arzew (60,000 bpd) units mainly refine oil for domestic consumption.

Algerian crude oil proven reserves are considered to be 12.46 billion barrels (2005 estimate; World Factbook, 2006). The EIA (2005) indicated proven reserves were 11.8 billion barrels. These reserves are increasing as exploration is actively ongoing. Most analysts consider Algeria underexplored. As of 2005, Algeria had 4.53 trillion m^3 of proven natural gas reserves (EIA, 2005), the eighth largest natural gas reserves in the world.

Nitrogen Fertilizer Production—Ammonia is produced by EPE ASMIDAL at Annaba and Arzew (Table Algeria 1) (IFDC, 2006a). There are two trains at Arzew, and a third train is planned. At Annaba, EPE ASMIDAL also produces ammonium phosphates, nitric acid, and ammonium nitrate. At Arzew there is a 146,000-tpy urea plant and a 182,500-tpy ammonium nitrate plant (EIA, 2005). Total ammonia capacity in 2005/2006 was 990,000 tpy. Including the addition of a plant at Arzew and a plant by Fertalge Industries, ammonia capacity may be 2,684,000 tpy in the future.

Phosphate Resources

Algeria has a long history of phosphate production. Phosphates were discovered in Algeria at Djebel Kouif in 1873, and the Kouif Mine opened in 1894 (Savage, 1987).

The phosphates are best developed in Thanetian age sediments although some of the upper beds may be Ypresian in age. Localized occurrences of Maastrichtian and Danian age phosphates are known. The phosphate deposits can be grouped by the regions in which they occur—a northern region and two regions corresponding to similar phosphate occurrences across the Tunisian border.

Table Algeria 1. Algerian Ammonia Capacity

	Plant Status[a]	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	Indefinite
	(x 1,000 tons product)									
EPE ASMIDAL										
Annaba	OPR	330	330	330	330	330	330	330	330	330
Arzew 1	OPR	330	330	330	330	330	330	330	330	330
Arzew II	OPR	330	330	330	330	330	330	330	330	330
Arzew III	PLN	–	–	–	–	–	–	–	–	1,100
Company Total		990	990	990	990	990	990	990	990	2,090
Fertalge Industries										
Unknown	PLN	–	–	–	–	594	594	594	594	594
Algeria Total		990	990	990	990	1,584	1,584	1,584	1,584	2,684

a. OPR = operational; PLN = planned.

Northern Area—Phosphate beds of Eocene age outcrop south of Bou Saada in an area extending 75 km from east to west and 35 km from north to south. These occurrences have never been exploited (Savage, 1987).

Eocene outliers to the northeast extend in a belt from Sidi Bel Abbas to the northern coastline of Tunisia. Two mines were established on these deposits before 1900. The M'Zaita–Tocqueville and Bordj Redir Mines were located about 45-50 km southwest of Setif. The deposits were acquired by Compagnie Minière de M'Zaita in 1929 and worked by this company until 1958.

There are four phosphate beds in the area; three of the beds are 0.4- to 0.7-m thick, while the fourth bed, consisting of alternating beds of phosphate and limestone, is 2.5- to 3-m thick. All the beds were affected by severe faulting in the mining area. The phosphate content of the beds is indicated to be about 27% (Savage, 1987); however, this may have been selectively mined and processed product.

Usually only one of the middle beds was worked. Mining was by underground cut and fill methods. The ore was coarse crushed and hand sorted. It was railed to the port of Bejaia without further treatment. Proven reserves of 25 to 30 million tons at 23% to 28% P_2O_5 remain unmined in the area (Savage, 1987).

Deposits West and South of Tebessa—The phosphate deposits to the west and south of Tebessa are extensions of the deposits in Tunisia. The northern Djebel Kouif Deposit lies on the other side of the border from the Kalaa Khasba Deposit in Tunisia. It was formed on the north side of the Ile de Kasserine, a paleo-structural feature that existed during the Eocene. The Djebel Onk Deposit is similar in character to the deposits found near Gafsa, presumed to have formed in a littoral-lagoonal environment to the south of the Ile de Kasserine.

While the phosphate deposits of the Gafsa Basin are ascribed to the Thanetian (Late Paleocene) Metlaoui Formation in Tunisia (Savage, 1987), the stratigraphic column for the Algerian deposits has been refined on the basis of paleontological evidence. In Algeria the main phosphate beds occur in the Thanetian to Ypresian Chouabine Formation or Unit C, as described by Chabou-Mostefai and Flicoteaux (1989). Some phosphate is indicated to occur in the sediments at the base of the Metlaoui Formation, which is considered by these authors to be Ypresian (Early Eocene) in age.

The Djebel Kouif Deposit lies about 26 km northeast of Tebessa. The deposit was developed on a synclinal outlier called Kouif Sud in an area about 3.5 km by 1.5 km. Two other smaller perched synclines—El Bey and Kouif Nord—are located nearby. There are five phosphate beds in the area; three have been worked. The phosphate beds had a total thickness of 3.0 to 5.5 m.

The Kouif Mine opened in 1894. At one time, output was about 800,000 tpy (Savage, 1987). The mine was scheduled to close in 1963, but its replacement, Djebel Onk, was late in coming onstream. The mine was worked into the 1970s by robbing pillars and mining an extension of the beds to the south. Reserves were indicated in 1979 to be about 27 million tons.

The Djebel Onk Mine is located 100 km south of Tebessa and 20 km from the Tunisian border. The area is connected to Tebessa by road and railway. The main rail system connects Tebessa with the port of Annaba. An oil field 2 to 3 km from the site provides fuel for generating electricity and operating the calcination kiln. Water is piped in from an area to the southwest. At the Port of Annaba, there is a storage area and loading quay.

Originally founded as a private company, Société du Djebel Onk was controlled by the Algerian government through Société Nationale de la Recherche Minière (SONAREM). SONAREM was restructured in the early to mid-1980s, and the state iron and phosphate mining company, Enterprise Nationale de Fer et de Phosphate (Ferphos), was formed. The mine was intended to come onstream in 1963 to replace Djebel Kouif; however, operations did not start until 1966, and numerous technical difficulties delayed full production.

The phosphate beds occur in two asymmetrical anticlines—Djebel Onk and Djebel Djemi Djema. Gentle dips of less than 10º occur on the north limbs of the anticlines. Overburden is mainly in the form of sand, which may be from 0 to 100 m thick. The phosphate-bearing beds are in a compact unit from 30 to 35 m thick in an area of about 15 km^2. There are six individual phosphate beds (Beds A, B, D, E, F, and G) (Savage, 1987). An analysis of Djebel Onk ore is given in Table Algeria 2.

Mining began at Djemi Djema where the overburden to ore ratio was 1:1. The Djemi Djema area was worked out and the mine moved to Djebel Onk. Originally the maximum overburden to ore ratio was to be 4:1. However, the overburden encountered was thicker than expected in some areas, and additional earthmoving equipment was acquired.

After the overburden is stripped, the ore is blasted. Shovel excavators load the ore into large dump trucks for transport to the beneficiation plant. The original planned capacity of the mine was 3.5 million tpy of ore with increasing production to 6.0 million tpy as demand grew.

At the beneficiation plant, the ore is crushed in a gyratory crusher, hammer-milled, and screened. The material is then deslimed in vertical classifiers to remove clays and silica (Savage, 1987). The intermediate product is calcined at 850º to 900ºC, slaked, and washed to remove lime and magnesia. The concentrate is then dried in rotary kilns. The design capacity of the calcination unit was 900,000 tpy; however, practical experience refined the capacity to about 500,000 tpy. Chemical analyses of three products are given in Table Algeria 2.

Material is conveyed to a stockpile and hopper for feeding to railcars. A 1,500-ton train composed of 48-ton cars can be loaded in about 1 h. Production from Djebel Onk was 804,900 tons in 2004 (*Fertilizer International*, 2006). Production in 2002 was 741,300 tons.

IFDC studied 10 samples of Djebel Onk phosphate ore and concentrates. P_2O_5 contents ranged from 20.87% to 30.12% or about 60% to 83% francolite. The main impurity mineral was dolomite, ranging from about 2% to 26%. The quartz content ranged from about 1% to 5%. One sample contained about 2% calcite. Since all the samples contained carbonates, they had not been calcined.

Table Algeria 2. Chemical Analyses of Djebel Onk Ore and Concentrates

	Run–of–Mine Ore	Dust Free (63%–65% BPL[a])	Concentrate "Deslimed" (66%–68% BPL[a])	Calcined (75%–77% BPL[a])
	(%)			
P_2O_5	24.6	29.60	30.25	34.35
SO_3	3.0	2.40	3.40	2.01
CO_2	10.1	7.00	6.40	1.38
SiO_2	3.8	2.35	1.85	1.86
Fe_2O_3	0.6	0.42	0.38	0.37
Al_2O_3	0.8	0.44	0.44	0.46
CaO	46.1	46.39	50.47	54.69
MgO	2.7	1.35	0.71	1.08
K_2O	0.2	1.36	0.64	0.42
Na_2O	1.3	0.15	0.13	0.03
Cl	0.1	0.02	Trace	0.01
F	1.7	3.51	3.84	4.00
Organic content	1.3	NA[b]	NA	NA
Moisture	3.6	0.80	1.00	0.02–1.13

a. Bone phosphate of lime.
b. Not analyzed.

Unit cell a-values for the samples ranged from a = 9.325 to 9.328 ±0.002Å. The average unit cell a-value was 9.327. This corresponds to a francolite with a maximum P_2O_5 content of about 35 wt % and a CO_2 content of 5.7 wt %.

Extraction with common extraction media on seven samples containing greater than 28% P_2O_5 indicated the following solubilities:

	Average % P_2O_5
Neutral ammonium citrate (NAC), first extraction (AOAC Method)	5.3
NAC extraction on the same sample	5.8
2% citric acid	9.7
2% formic acid	17.8

Algeria phosphate rock is slightly less soluble in common extraction media than North Carolina or Tunisia phosphate rock. However, it is considered a relatively high-solubility phosphate rock suitable for direct application under appropriate cropping and agroclimatic conditions.

Resources of phosphate rock in Algeria were given by Savage (1987) as 1,000 million tons distributed between a number of sedimentary deposits. *Fertilizer International* (2006) indicates that Algeria's resources of phosphate rock have been estimated at 2 billion tons distributed among a number of sedimentary deposits in a westward extension of the Tunisian Basin. It is not known what criteria were used to develop these estimates.

Phosphate Fertilizer Production—EPE ASMIDAL SPA operates a phosphoric acid plant at Tebessa (Table Algeria 3). Capacity of the plant is 178,000 tpy of P_2O_5 (IFDC, 2006b). EPE ASMIDAL also operates an NPK plant at Annaba. Rated capacity is 550,000 tpy (IFDC, 2006c).

Ferphos had plans of opening two phosphoric acid plants at Djebel Onk in 2007/08. *Fertilizer International* (2006) reports Ferphos has plans to establish production at Wilaya, northeast Algeria. The complex would include three 1,000-tpd P_2O_5 phosphoric acid plants, three 3,200-tpd sulfuric acid plants, a 2,000-tpd ammonia plant, a 1,000-tpd complex fertilizer plant, and a 1,500-tpd diammonium phosphate (DAP) plant.

Sulfur Resources

Mobbs (2004) indicates 20,000 tons of sulfur as sulfuric acid was produced in 2004 in Algeria. In the same year, 300,000 tons of gypsum was produced. Lead and zinc metal are produced in Algeria (5,000, and 25,000 tons, respectively). Sulfuric acid could be produced from smelter offgases.

Table Algeria 3. Algeria Phosphoric Acid and NPK Capacity Listing by Plant

	Plant Status[a]	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	Indefinite
Annual Phosphoric Acid Capacity (x 1,000 tons P_2O_5)										
EPE ASMIDAL SPA										
Tebessa (2002)	OPR	178	178	178	178	178	178	178	178	178
Ferphos										
Djebel Onk I	PLN	–	–	–	–	–	178	178	178	178
Djebel Onk II	PLN	–	–	–	–	–	178	178	178	178
Company Total		0	0	0	0	0	356	356	356	356
Algeria Total		178	178	178	178	178	534	534	534	534
Annual NPK Plant Capacity (x 1,000 tons product)										
EPE ASMIDAL										
Annaba	OPR	550	550	550	550	550	550	550	550	550
Algeria Total		550	550	550	550	550	550	550	550	550

a. OPR = operating; PLN = planned.

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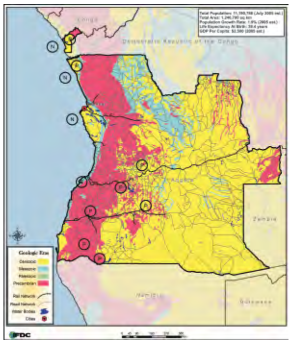
ANGOLA



The Republic of Angola (Figure Angola 1) is bordered to the north by the Democratic Republic of the Congo and the Republic of the Congo, to the east by Zambia, to the south by Namibia, and to the west by the Atlantic Ocean. The enclave of Cabinda is separated from the main body of Angola by the Democratic Republic of the Congo. The total area is 1,246,700 km^2 and approximately 2.4% of the land is arable. The population was estimated in mid-2005 as approximately 11.2 million inhabitants. Annual population growth was estimated at 1.9% (World Factbook, 2005). Agriculture occupies 85% of the labor force.

The transportation network comprises 5,349 km of paved roads, 46,080 km of unpaved roads, 2,638 km of 1.067-m-gauge railway, and 123 km of 0.600-m-gauge railway. There are 31 airports with paved runways and 212 airports with unpaved runways. Angola has 214 km of gas pipeline, 14 km of liquefied natural gas pipeline, 837 km of oil pipeline, and 56 km of refined products pipeline. It has 1,300 km of waterways. Luanda, Lobito, Soyo, and Cabinda City are the main ports.

The geology of the western half of Angola is dominated by Precambrian age rocks of mainly granitic or gneissic character. Mesozoic age sediments are found in the central basin to the north and near the border of the Democratic Republic of the Congo, and in a narrow band along the coast. These Mesozoic sediments extend offshore and thicken to the west, especially off the Congo River Delta and the associated basin north in Cabinda, and in the Kwanza Basin south and west of Luanda. Numerous carbonatite complexes penetrated the Precambrian basement during the Cretaceous age.

Cenozoic age sediments offlap the Mesozoic sediments in the coastal basins, and collectively the sequence may be over 5,000 m thick. Quaternary sands, clays, and laterites and Kalahari sands cover much of the western half of the country. In the northeast of the country this cover is incised by river valleys, and a complex sequence of Precambrian basement rocks is exposed.

Nitrogen Resources

In 1955 Petrofina, a Belgian company, first discovered oil onshore in the Kwanza Basin near Luanda. The Portuguese colonial authorities set up Fina Petroleos de Angola (Petrangol) with Petrofina and built an oil refinery on the outskirts of Luanda.

In 1966 substantial oil resources were discovered in the shallow waters off the coast of Cabinda. Production off Cabinda rapidly developed and continued uninterrupted through Angolan independence and civil war. The Energy Information Administration (EIA) notes that in 2004 Angola produced an average of 1.05 million barrels of oil per day (EIA, 2005). Angola is the fourth largest producer in Africa after Nigeria, Algeria, and Libya. Some sources indicate production may double by 2008-2010 (Coakley, 2003; *Afrolnews*, 2006).

Increased production will come from deeper water off the Cabinda coast north of the mouth of the Congo River and deep water off the coast of Angola south of the mouth of the Congo River. The deepwater discoveries were the result of highly successful exploration programs which began in the mid-1990s and continue to this day. Oil companies active in Angola include British Petroleum (BP), ChevronTexaco Corp., EniSpA, Exxon Mobil Corp., Norsk Hydro ASA, Royal Dutch/Shell Group, Statoil ASA, and Total ASA.

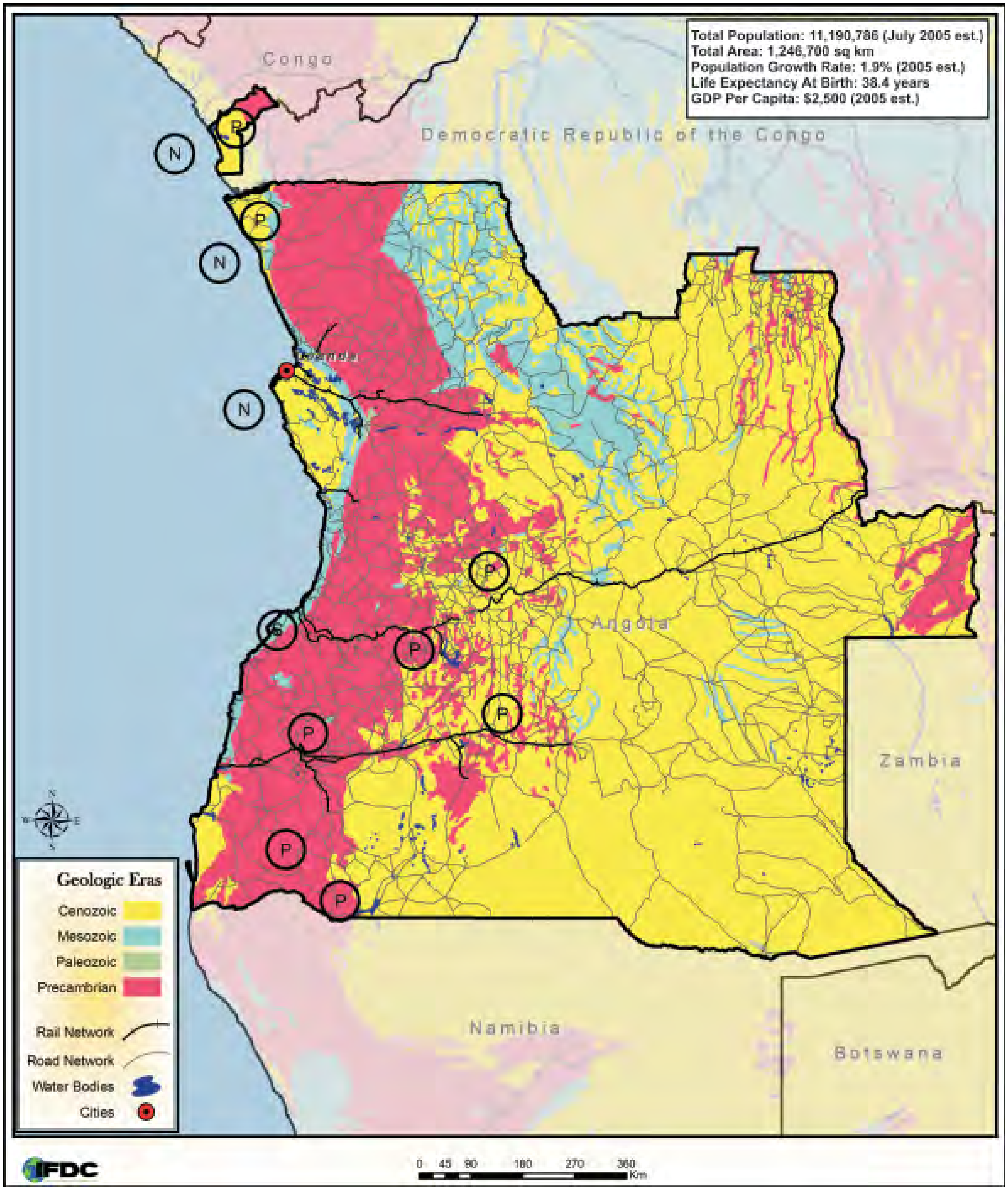


Figure Angola 1. Geology, Major Cities, and Transportation Network

Oil will be produced in water over 1,500 m deep. Development on the sea floor is handled by robots. Oil will be produced mainly through the use of floating production, storage, and offloading (FPSO) vessels. Several fields can be linked to one FPSO. The Angolan coast is a benign coast with low risk from major storm events. Production from the deep-water oil fields has already begun. Production from the Girassol Platform 200 km northwest of Luanda (Total, Exxon Mobil, BP, Statoil, Norsk Hydro, and Sonangol) increased to 250,000 barrels per day (bpd) in March 2006 (*Angola Press*, 2006).

Oil development is regulated by the state-owned Sociedad Nacional de Combustiveis de Angola (Sonangol), which was established in 1976. A hydrocarbon law passed in 1978 made Sonangol sole concessionaire for exploration and production. Associations with foreign companies have taken the form of joint ventures and production-sharing agreements.

Reserve estimates for Angola are under constant revision as discoveries are still being made. The EIA (2006) posted the following information on January 18, 2006:

Angola	Oil
	(billion barrels)
British Petroleum Statistical Review (year-end 2004)	8.801
Oil and Gas Journal (January 1, 2006)	5.412
World Oil (year-end 2004)	9.035

The Fina Petroleos de Angola refinery in Luanda had an original processing capacity of 39,000 bpd, and there were plans to increase the capacity to 60,000 bpd (African Energy, 2002). Plans were being developed for a 200,000-bpd refinery to be located at Lobito, south of Luanda. The products would be marketed regionally.

In 1999 Sonangol made the decision that the gas from new offshore development should not be flared and wasted. Approximately 80%-85% of the natural gas produced during the production of oil has been flared. Proven reserves are indicated as about 80 billion m^3 (World Factbook, 2006). Significant amounts of gas may be available from fields nearer to shore that contain natural gas only, without significant oil. Several such fields have been discovered but passed over by oil companies as there is no readily accessible market in Angola. In response to the new oil field development and to develop and utilize the associated gas, the Angola Liquefied Natural Gas (LNG) project was conceived.

At the present time, 15% to 20% of Angola's gas production is currently injected into fields to boost oil recovery, and a minor amount is used in the production of liquefied petroleum gas (LPG, a cooking fuel). The rest of the gas is flared.

Angola LNG is a joint project involving Sonangol (22.8%) and affiliates of ChevronTexaco (36.4%), Exxon Mobil (13.6%), Total (13.6%), and BP (13.6%). The Angola LNG project is considered to be of national importance and the cornerstone of the plans to exploit and develop the country's natural gas resources and reduce gas flaring. According to the lease agreements signed in the current wave of deep-water offshore development, the gas produced during the course of oil production is the property of Sonangol and the Government of Angola.

The gas would be collected from Blocks 0 and 14, north of the Congo River channel, by ChevronTexaco. Exxon Mobil would operate from Block 15 on the south side of the Congo Channel, and Total and BP would operate Blocks 17 and 18, respectively. Undersea pipelines would transport the gas to a site at the mouth of the Congo River near the town of Soyo.

The gas would be cleaned upon arrival at the complex. The gas is said to be a sweet gas; no significant amounts of sulfur would be recovered. Enough gas would be provided to supply an LNG plant capable of producing 5 million tons of product per year and an ammonia plant that would produce 1,800 tpd. There are also nonassociated gas fields in Blocks 1 and 2 that could be developed to supplement gas produced in association with oil.

The 100-acre site near Soyo where the LNG plant would be located would have 360,000 m^3 of LNG storage, LPG storage, and condensate storage. The loading jetty would be sized to accommodate 145,000-m^3 to 180,000-m^3 ships.

The LNG project has been active for several years. On March 10, 2005, Sonangol, ChevronTexaco, and their co-venturers, announced that agreements had been signed to establish principles for gas supply, corporate structure, and the legal and regulatory framework (Angola LNG, 2005). On April 21, 2005, Sonangol, ChevronTexaco, and their co-venturers in the LNG project announced the award of front-end engineering design (FEED) contracts for the 5 million-tpy onshore facility to be located near Soyo. The awards were made to Bechtel and a joint consortium of Kellogg Brown and Root Inc., JGC Corp., and Technip Corp.

The planned 15-month work program was to begin immediately. Following the completion of the FEED stage, it was expected that one of the two contractors would be selected to perform final engineering, procurement, construction, and commissioning activities. Estimated total cost of the project would be US $3 to $4 billion.

Ferrostahl, Germany, was engaged in talks with Sonangol concerning the proposed ammonia plant (IFDC, 2005). Apparently nothing had been signed, and no plans had been made concerning the site for the ammonia plant as of late 2004. The ammonia would apparently be for export because use of the ammonia to produce other fertilizers has not been mentioned.

IFDC (2005) made a preliminary estimate of the costs to develop a matched ammonia and urea plant. Table Angola 1 indicates preliminary investment costs for matched capacity ammonia and urea plants at a scale that is viable to compete under world market conditions. These were preliminary estimates, and a detailed study and a substantial amount of time would be required to develop firm figures. Typically, cost estimates for development at a remote greenfield site involve the use of a multiplier of 1.5, as well as other considerations, over the cost at an existing site in a developed country location (for example, the U.S. Gulf Coast). *Chemical Engineering* has listed a multiplier of 2.0 for southern Africa. The use of such a multiplier may be entirely appropriate for Angola at this time because essentially everything must be imported.

The cost of an ammonia/urea plant with a capacity of 2,500 tpd of urea at a developed site would be approximately US $409 million. The cost of a similar plant at a remote new site is estimated as US $674 million. The cost in Angola may be as much as US $900 million.

Table Angola 1. Preliminary Investment Cost, 825,000-tpy Ammonia/Urea Plant[a]

	Existing Site[b] (Developed)	New Site[c] (Remote)	Angola[d] (Remote)
Ammonia Plant (1,500 tpd)			
Battery limits	206	309	412
Infrastructure		60	82
Urea Plant[e] (2,500 tpd)			
Battery limits	203	305	406
Total Cost[f]	409	674	900

a. All costs adjusted to mid-2004 using *Chemical Engineering* Plant Cost Index.
b. Based on information in the UNIDO/IFDC *Fertilizer Manual*, 1998.
c. Assumes factor of 1.5 cost increase over existing developed site.
d. *Chemical Engineering* cost factor increase for central Africa is 2.0.
e. Includes cost of infrastructure.
f. Total cost does not include cost of land.

Based on a US $1/million Btu gas cost, the IFDC study concluded that Angolan ammonia production costs (without capital recovery) might be on the order of $68.50/ton. Due to a lack of critical information, the cost of producing urea was not estimated.

Phosphate Resources

Cabinda Phosphate Deposits—An IFDC geologist visited the Cabinda deposits in late 2004 (IFDC, 2005). Phosphates were discovered in Cabinda in 1947 by Geominas, the geologic survey department with the (then) Portuguese government. At some point in time the geologic survey became known as the Servicios de Geologia e Minas. Subsequent work in the 1950s and 1960s identified several deposits. In 1968 the Portuguese government granted an exploration concession for phosphate exploration to Companhia de Fosfatos de Angola (COFAN), which was owned by U.S. (Pickens Mather Co.), Portuguese, and other interests. COFAN studies were carried out in two main phases. COFAN closed operations in approximately 1973/74.

COFAN I included rotary drilling (201 boreholes, total length = 19,232 m), core drilling (29 boreholes, length = 626 m), and the sinking of nine shafts. COFAN II expanded the program to include data from 412 rotary boreholes and 40 cored boreholes. The first COFAN study included an economic analysis.

Hodge and Partners (1978) reevaluated the COFAN data, and indicated that resource estimates were too high. Chakravarty (1982) and Terraconsult AG (1983) also reviewed the COFAN data.

In conjunction with the Yugoslavian government, the deposit at Mondo Tando was further evaluated during 1982 and 1983 (Energoprojekt, 1983). Over 20 more boreholes were drilled to confirm and refine COFAN data. An economic evaluation was performed in conjunction with the study.

The COFAN report is summarized in Energoprojekt (1983) and Cunha Gouveia et al. (1993). The results of Hodge and Partners (1978) and Terraconsult AG (1983) are summarized in van Straaten (2002).

The coastal plains of Cabinda are blanketed with sediments that range in age from Cretaceous to Pleistocene (Figure Angola 2). Physiographically, the area is composed of rolling hills with perhaps 150-200 m of maximum relief crosscut by some river valleys. There are many marshy areas. The area is fairly structurally complex with numerous faults (Figure Angola 3) and broad anticlinal and synclinal features. One structural interpretation (originally part of a COFAN document) is given in Figure Angola 4.

The phosphate occurs in beds of two different ages. The upper phosphate sequence (termed “superior” in French and Portuguese documents) is approximately 2-12 m thick. The upper sequence is Eocene in age. There are beds of conglomerates, sandstones, and clays with intercalated calcareous lenses 20-100 m thick between the upper and lower (termed “inferior” in French and Portuguese documents) phosphate sequences.

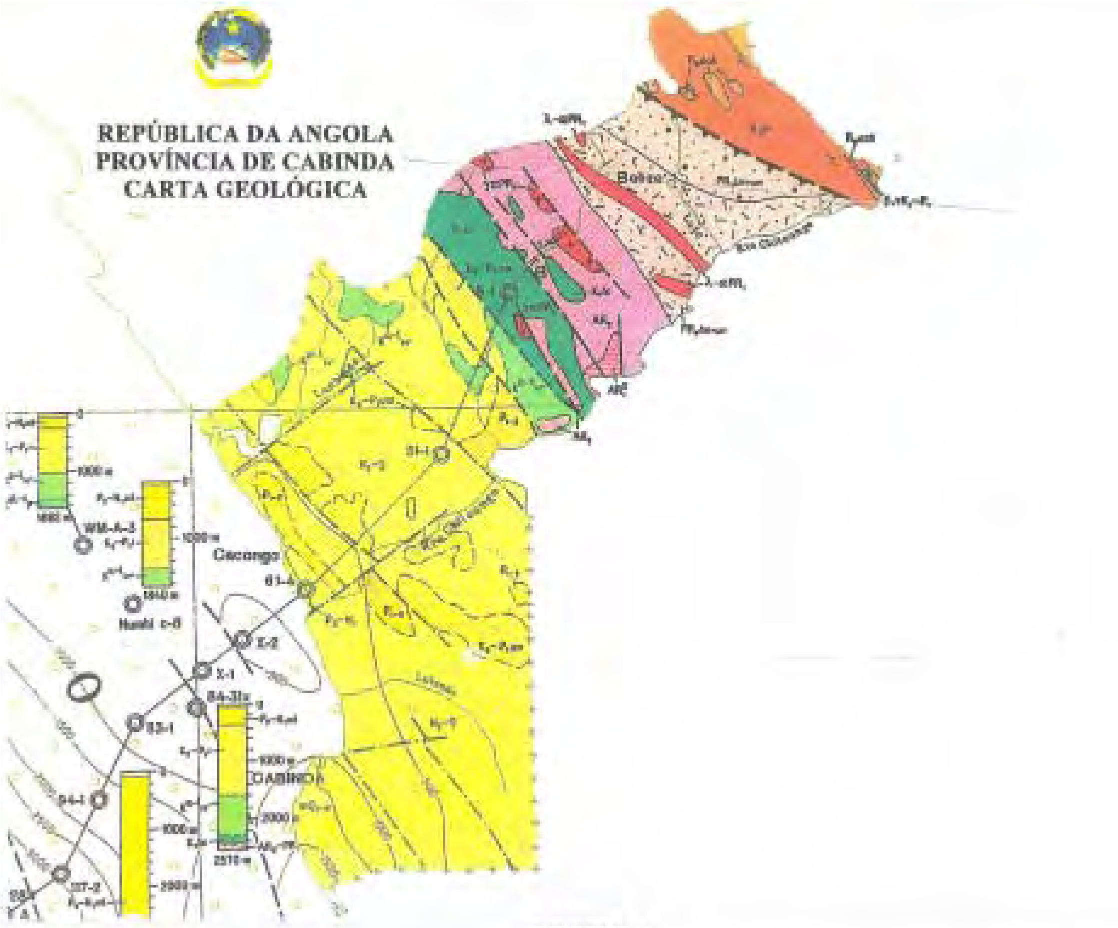
The lower phosphate sequence has been divided into three phosphate beds—A (7-8 m thick), B (10-15 m thick), and C (3-5 m thick). The beds may be separated by sandstone, clay, and dolomite beds from 2 m to 10 m thick. The phosphate sequences occur on the flanks of the broad-scale anticlinal-synclinal features (Figure Angola 5). There are numerous faults throughout the area mainly parallel to the main structure trends. The initial discoveries were made through surface surveys, which located outcrops mainly in river valleys. There is no mention of any radiometric surveys in any of the literature concerning the Cabinda deposits. One analysis of Cabinda phosphate rock performed at IFDC indicated 260 ppm uranium. This is very high considering the crustal abundance of uranium (2.7 ppm).

In some of the literature, the Cabinda ore is referred to as leached (lixiviados) or nonleached (não lixiviados) ores. When phosphate ores are surficially exposed, they often become enriched (other components are dissolved) and they may become white or off-white in color. They may also become highly indurated (hard with exposure). The nonleached ores are typically much lower in grade.

The Cácata Deposit is located in the valley of the Nhenha River near Cácata Village about 60 km east of Cabinda City. Only the upper phosphate sequence (Eocene) is exposed at Cácata. The deposit was originally drilled and pitted by the Servicios de Geologia e Minas. COFAN drilled an additional 30 holes in the area. The deposit is known to be about 400 m wide and 2.4 km long (apparently in the subsurface) and may extend to 3.5 km long. Detailed maps of this deposit were not examined.

COFAN indicated that 60.68 million tons of probable reserves of leached ore was available from beds with <20 m of overburden; the average thickness of the overburden is 28 m, and the average P_2O_5 content is 20.08%. Beneficiation tests indicated ore/concentrate ratios of 2.1:1 to 3.6:1. The amount of concentrate available, based on the probable ore reserves, was 23.55 million tons at 34% P_2O_5. Also listed are 6.65 million tons of probable reserves of concentrate from nonleached ore at 30% P_2O_5 in a southern block. No overburden thickness is listed. As indicated in a map produced by Energoprojekt (1983) (Figure Angola 6), this deposit has been insufficiently defined by drilling.

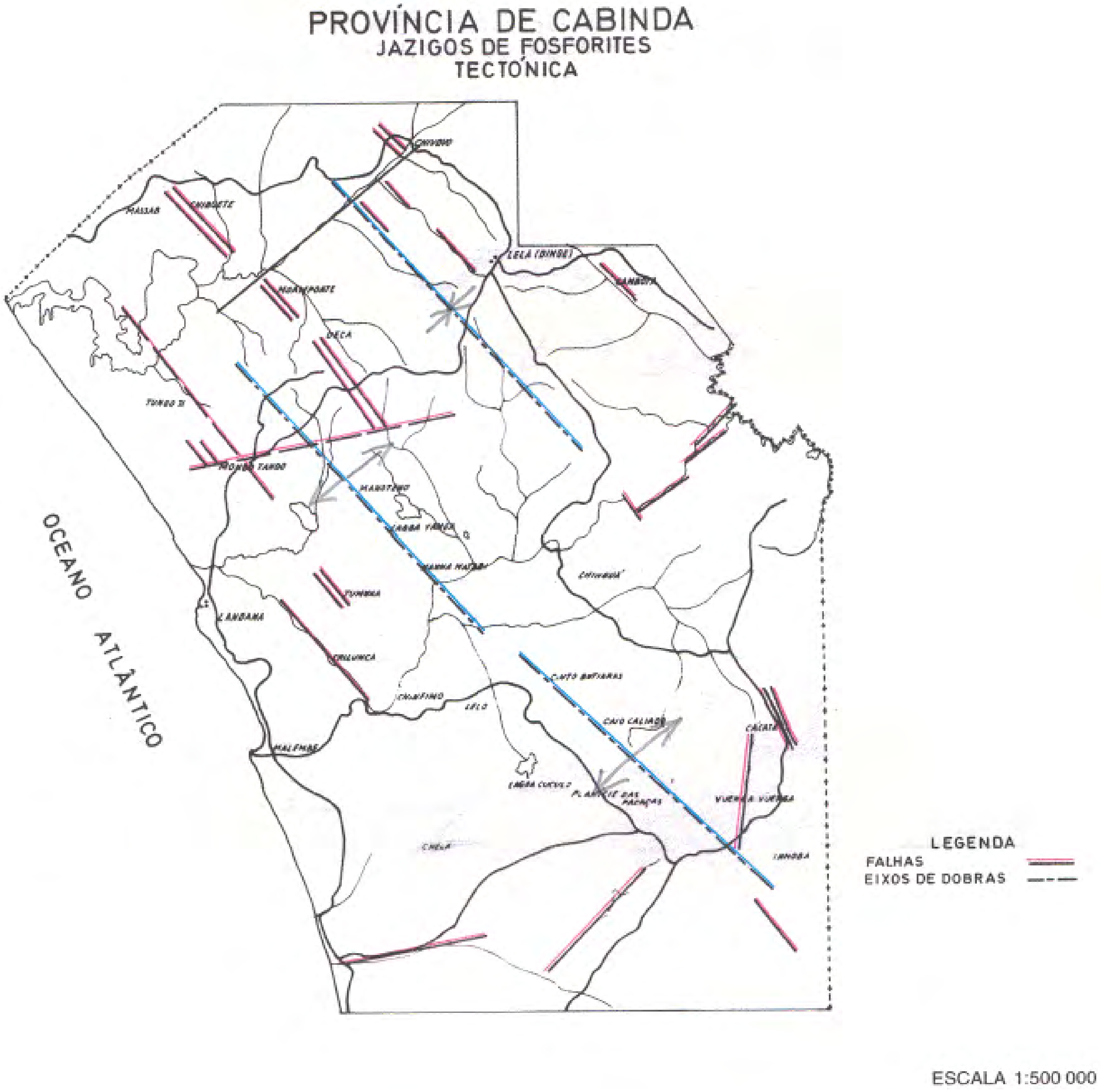
It should be noted that the beneficiation tests used by COFAN and Energoprojekt (1983) were



LEGENDA

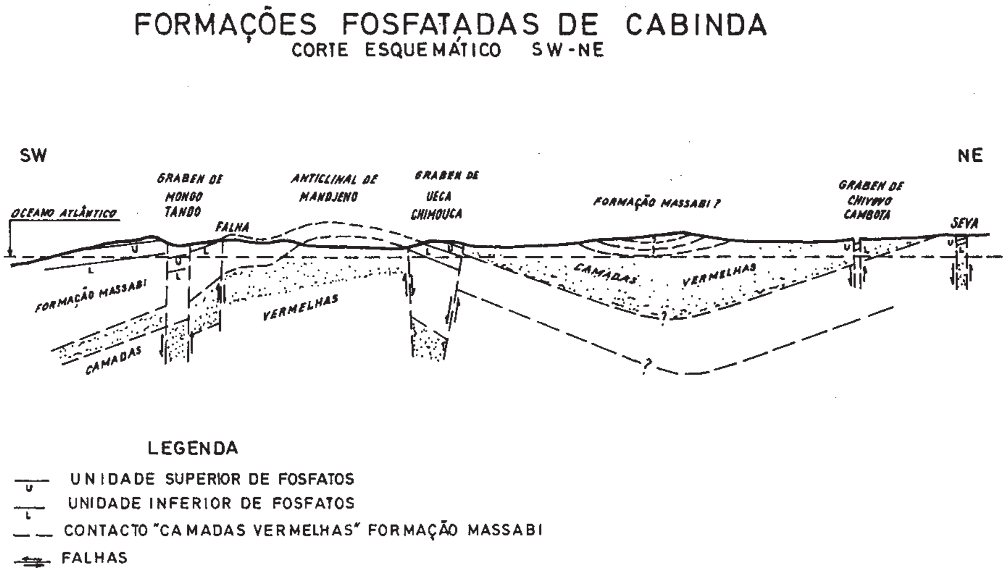
mQ I-m	Plistocénico – Depósitos de terraços marinhos, cascalhos, areias, argilas
N 2-Q	Pliogénico-Quaternário – Areias, grés, argilas, laterites, conglomerados.
P_3–N_1	Oligocénico-Miocénico – Argilas, calcários, margas, areias.
P 2-N 2	Eocénico-Pliocénico – Grés, margas, argilas, calcários, conglomerados.
P 2-N 1 ml	Formação Malembo – Argilas, siltes, grés.
P 1-2	Paleogénico-Eocénico – Margas, calcários, grés.
K_2-P_1^{am} K_2-P_1^{i}	Formação Ambrizete – (am) Grés, calcários organogénicos. Formação Iabe (I). Calcários, dolomites, grés, argilas.
K $_{al-t_{ve}}$	Formação Vermelha – Grés, calcários, argilas.
K^{al-t} P	Formação Pinda – Calcários, dolomites, calcários recifais, argilas.
K 1 lc	Formação Lucula – Conglomerados, grés, argilas.
AR 2	Arcaico Superior – Gneiss biomicáceos, plagiognaisses, xistos biomicáceos com granada e distena, às vezes carbonáceos; epidotitos, paranfibolitos, calcíferos e mármores, quartzitos.
AR_1^2	Arcaico Inferior- Grupo superior
PR_1^{lu+un}	Grupos Lulumba e Uonde – Tufos, arcose, metariolito-dacitos, conglomerados, xistos; cloritos-moscovítico-quartzosos, clorito-sericíticos, quartzo- sericíticos, moscovito-cloríticos com magnetite. Intercalações de metassiltitos, de xistos calcários e carbonáceos.
γπ PR 1	Pórfiros graníticos
λ - πPR 1	Riolitos, dacitos, andesitos, tufos
R_1^{tr}	Grupo Terreiro. Xistos argilosos calcários e argilosos com intercalações de quartzitos e siltitos, grés, grauvaques, calcários com chert.
R_2^{ach}	Grupo Alto-Chiloango. "Tiloides", calcários estromatolíticos, xistos argilosos, grauvaques,arcoses, grés, quartzitos
βvk 1-P 1	Basaltos, doleritos, espelitos, traqui-andesito-basaltos, latitos, traquitos, tefritos.

Figure Angola 2. Geologic Map of Cabinda



Source: Cunha Gouveia et al. (1993).

Figure Angola 3. Structural Map of the Cabinda Coastal Plain



Source: Cunha Gouveia et al. (1993).

Figure Angola 4. Structural Interpretation, Cabinda Coastal Plain

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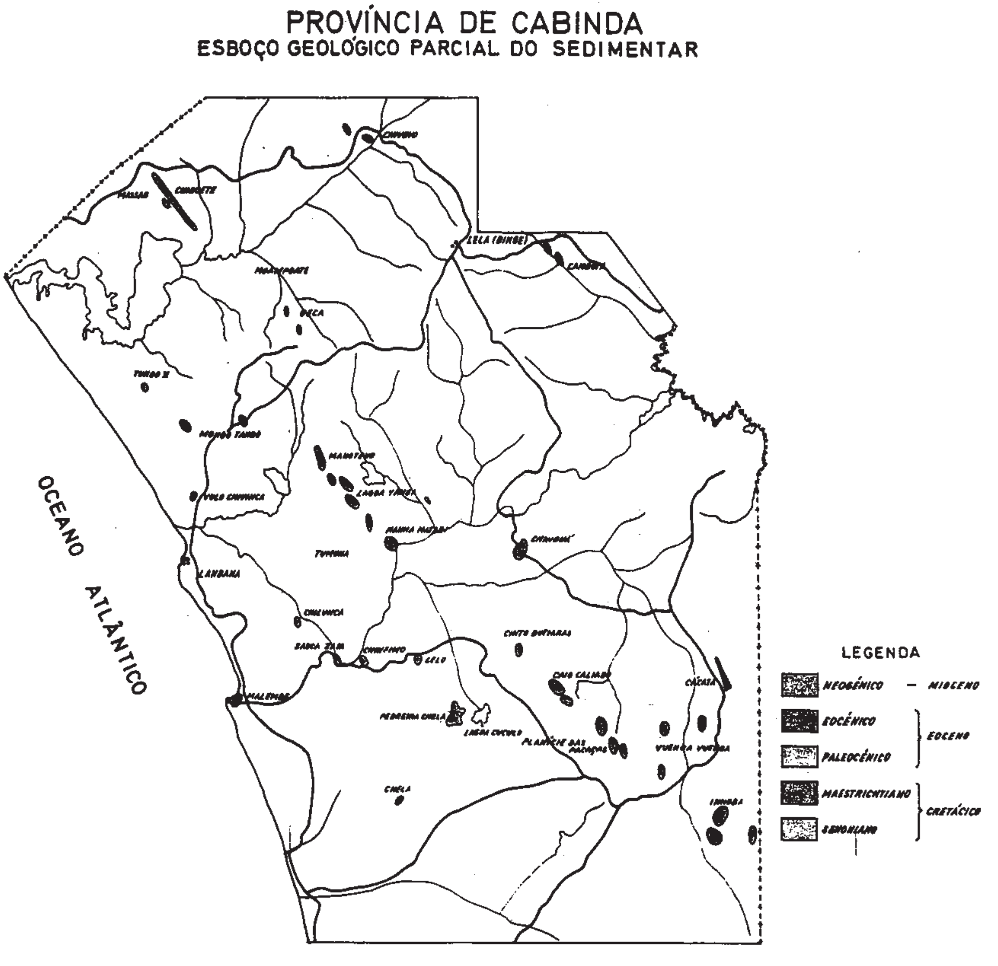
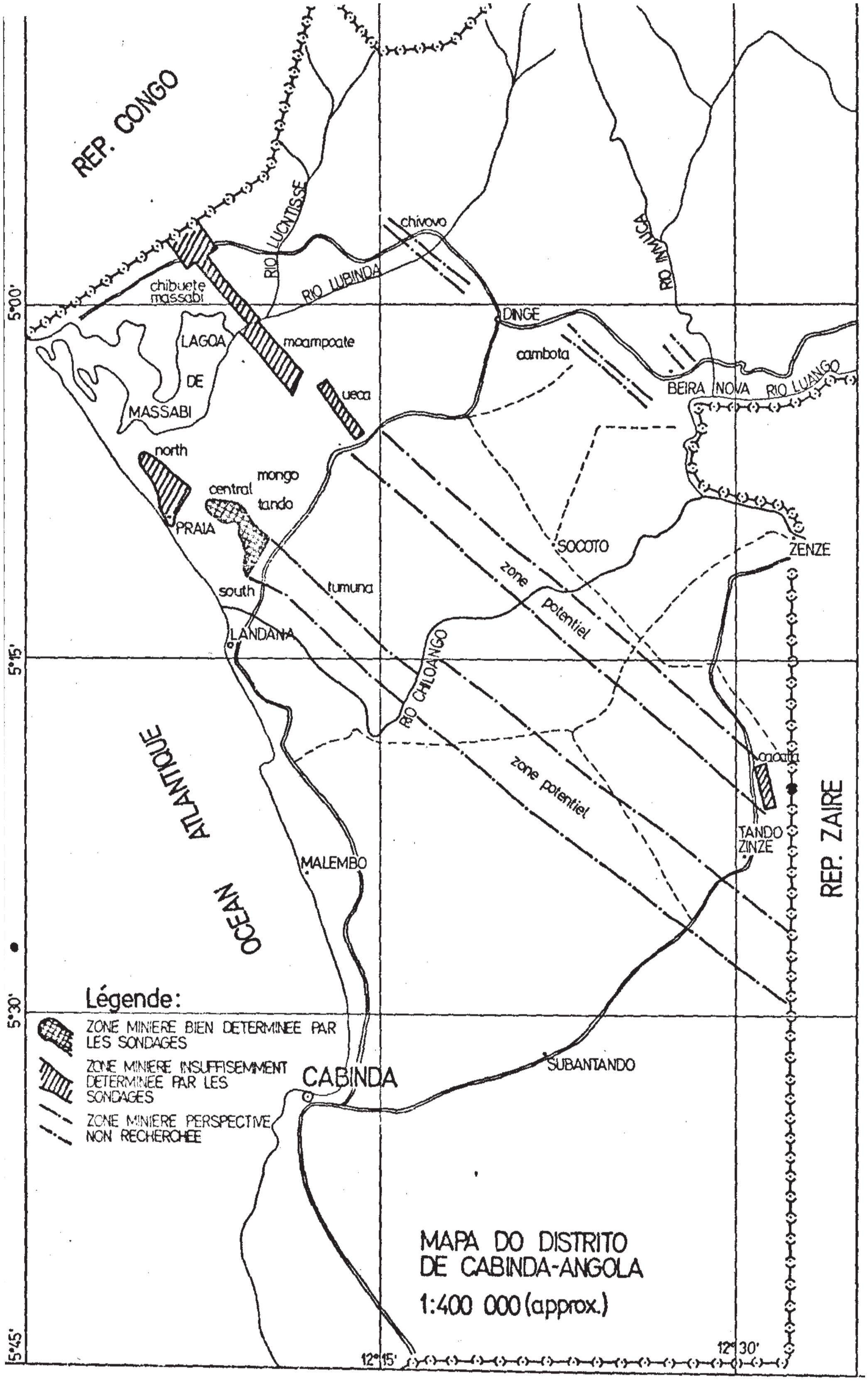


Source: Cunha Gouveia et al. (1993).

Figure Angola 5. Location of Cabinda Phosphate Deposits



Source: Cunha Gouveia et al. (1993).

Figure Angola 6. State of Phosphate Deposit Development, 1983

apparently quite extensive and intensive. Final flowsheets include washing, conditioning, and several stages of flotation. These flowsheets are similar to treatment sequences that are presently used in the world phosphate rock industry; probably only minor improvements could be made.

The Chibuete Deposit lies to the north-north-east of Lake Massabi in the north of the enclave near the Congo (Brazzaville) border. The Servicios de Geologia e Minas initially pitted and drilled the deposit. COFAN drilled more than 40 holes and dug 6 pits. Both the upper and lower beds occur in the area. Beds A, B, and C are present in the lower beds.

COFAN estimated 93.66 million tons of probable reserves at an average of 15.55% P_2O_5 with less than 30 m of overburden. At ore to concentrate ratios of 3.6:1 to 5:1, 22.28 million tons of concentrate at 36% P_2O_5 is considered probable.

COFAN also estimated additional indicated reserves at Chibuete at 20 m to 130 m of overburden as 211.9 million tons at an average of 11.7% P_2O_5. At an ore to concentrate ratio of 4.9:1, 44.69 million tons of concentrate at 32% P_2O_5 was considered indicated.

Figure Angola 6 indicates that the Chibuete area is insufficiently drilled. The COFAN listing of 44.69 million tons of indicated concentrate reserves at Chibuete is criticized in several later documents.

The Ueca Deposit is located about 25 km from Landana, and the course of Mucongola stream follows the deposit. The deposit was discovered in 1957 by the Servicios de Geologia e Minas. In the first phase of the COFAN study, 33 holes were drilled and 3 pits and trenches were dug; in the second phase, 136 more holes were drilled and 4 more pits were dug. The deposit is about 8.25 km long and 460-550 m wide. The A, B, and C beds of the lower phosphate sequence are present.

COFAN estimated probable leached ore reserves under an average of 9.8 m of overburden as 147.08 million tons at an average of 11.91% P_2O_5. The combined average thickness of the A, B, and C beds is 17.1 m with 9.4 m of interbeds between the A and B, and B and C beds. At raw ore to concentrate ratios of 4.8:1 to 6.3:1, 28.31 million tons of concentrate at 37.4% P_2O_5 would be available from the deposit. Figure Angola 6 indicates the area is insufficiently drilled. This is the deposit COFAN proposed to mine and on which the economic calculations were based.

The Moampoate Deposit occurs between the Chibuete and Ueca Deposits. Drawings by the COFAN group indicate beds A, B, and C of the lower phosphate sequence are present in the area. The area is very marshy. Half of the boreholes drilled for the COFAN study did not encounter phosphate rock. Tables in Cunha Gouveia et al. (1993) indicate calculated indicated reserves of leached ore concentrate as 13.19 million tons and 35% P_2O_5 in the North Block and calculated indicated reserves of nonleached ore concentrate as 14.44 million tons at 32% P_2O_5. Calculated indicated reserves of leached ore concentrate in the South Block are 7.02 million tons at 36% $P_2O_{5,}$ and calculated indicated reserves of nonleached ore are 3.18 million tons at 23% P_2O_5.

No overburden thicknesses are listed in available reserve descriptions, and the amount of detail suggests that the level of effort in the area was not as significant as in other areas. Figure Angola 6 does not acknowledge this deposit. It is in a “zone potential.”

The Chivovo Deposit was first discovered in 1956 by the Servicios de Geologia e Minas. It is located to the northeast of the Chibuete Deposit along the road from Dinge to Pointe Noire. COFAN executed seven boreholes in the area. The lower phosphate sequence was found, but beds A, B, and C were not differentiated. No reserves are listed for this deposit. Figure Angola 6 indicates this deposit as “zone potential.”

The Cambota Deposit was located in 1951 along the Sanvo River to the southeast of Dinge. COFAN drilled eight boreholes in the area. They found what was interpreted to be a thin bed of the lower sequence. No reserves are listed in the documents examined.

The Tumuna Deposit is apparently an extension of the Mondo Tando Deposit. COFAN drilled nine boreholes in the area. Both the upper and lower phosphate sequences are present. The phosphate values were much lower than at Mondo Tando. The average for the upper bed was 6.8% P_2O_5. The average for the lower beds was approximately 5% P_2O_5. There are no reserve estimates for this area.

The Mondo Tando Deposit (Figures Angola 7, 8, 9, and 10) is located about 60 km north of Cabinda City and 15-20 km north of Landana. The Mondo Tando Deposit is the deposit closest to the coast. During the first phase, COFAN executed 36 boreholes in the area. During the second phase, COFAN executed 104 boreholes and 9 pits. The area explored extensively was about 1.6 km long and 800 m wide. Several boreholes encountered a 2- to 3-m zone at the top of the upper phosphate sequence with phosphate values as high as 36% P_2O_5. Beds A, B, and C of the lower sequence can be found at Mondo Tando at depth. COFAN expended significant time and funding at Mondo Tando but only calculated the reserves of the upper sequence. At an overburden thickness of 38.3 m, and average 14-m bed thickness, 37.2 million tons of leached ore was estimated. No average ore grade is listed. From this ore, at an ore to concentrate ratio of 2.8:1, 13.19 million tons of concentrate at 36% P_2O_5 was estimated.

The Energoprojekt (1983) focused on Mondo Tando, probably because its location is the nearest to the coast and perhaps for security reasons. Existing

Figure Angola 7. Mondo Tando Deposit, Outcrop and Site of Quarrying Operation

Figure Angola 8. Mondo Tando Deposit, Collecting Phosphate Rock Samples From Outcrop

Figure Angola 9. Mondo Tando Deposit, Highly Weathered and Leached Phosphate Rock

Figure Angola 10. Mondo Tando Deposit, Weathered Surface of Outcropping Phosphate Rock Showing the Coarse Granular Texture of Many of the Beds of the Cabinda Deposits

COFAN data were used to design the project and in the calculation of reserves. According to Figure Angola 6, Mondo Tando was divided into north, south, and central areas. The north area is indicated as not sufficiently drilled in Figure Angola 6.

Mondo Tando south and central areas were infill drilled, and reserves were calculated according to a block method and according to categories based on depth of overburden and proximity to the "edges" of the deposit. The following table is found in the conclusions of the Energoprojekt document.

Reserve Category	Ore	
	Wet	Dry
	(tons)	
A	13,913,633	11,687,453
B_1	1,671,696	1,404,225
C_1	5,295,493	4,448,214
A+B+C	20,880,822	17,539,892
C_2	1,952,678	1,640,250
Total Geologic Reserves A+B+C+C_2	22,833,500	19,180,142

Based on the total geologic reserves and the yield based on beneficiation studies, the total amount of concentrate available would be 6,317,522 tons at 32.06% to 33.42% P_2O_5. It should be noted that a detailed mine plan would be needed to determine what portion of the geologic reserves are economically minable, and the amount available would probably be ultimately reduced. Basically, the more detailed analysis by the Energoprojekt cut the reserve estimates of COFAN in half.

The COFAN studies indicated the Cabinda deposits were located in graben structures and extensively bounded by faults (Figure Angola 4); however, this interpretation is probably too simplistic. Examination of detailed Energoprojekt geologic maps indicates the Mondo Tando Deposit is bounded by a fault on one side. The deposit appears to simply "pinch out" on the other three sides. There is another interpretation for the formation of the deposits: (1) the deposits were originally lens shaped, that is, they were formed or reworked as sediments into lens-shaped bodies generally elongated like sand bars, (2) the beds were exposed and truncated by erosion at some point in time, (3) the beds were eventually deformed and faulted. The coarse rounded nature of phosphate particles in many of the beds suggests the sediments were reworked and sorted. The fact that the deposits are significantly enriched in P_2O_5 content at the contacts with overlying beds indicates they were exposed at one point in time and non-phosphate components were leached from the beds. The interpreted geometry indicates thick portions of the deposits were truncated by erosion. In some cross sections, the deposits simply seem to pinch out on the periphery or break into interfingering beds with contemporaneously deposited sediments.

While there are portions of the beds near the top of the sequence that are "leached" and have very high P_2O_5 contents, the cross sections and maps indicate these portions of the deposits are only 2-3 m in thickness and are of limited extent. Basically, the deposits have average P_2O_5 contents in the range of 12% to 15% P_2O_5. Any project to utilize the deposits would have to rely on beneficiation to upgrade the ores.

During the course of the IFDC (2005) study, the IFDC geologist collected samples. Initially, all the samples were analyzed for the total P_2O_5 content and neutral ammonium citrate (NAC)-soluble P_2O_5. Composite samples from Mondo Tando (CABMTC) and Cácata Pit 2 (CABCP2) were submitted for more detailed analyses. All of the samples were submitted to X-ray diffraction (XRD) analysis to determine the mineralogical components. Samples CABMTC, CABUT, and CABCP2 were also submitted to XRD analysis to determine the theoretical apatite composition. The chemical and mineralogical compositions of Samples CABMTC and CABCP2 were equated through the use of a mineral chemical mass-balancing program. Chemical analyses of the samples are given in Table Angola 2. Mineralogical analyses of the samples are given in Table Angola 3.

The samples ranged from 20.5% to 35.4% in P_2O_5 content. The NAC solubility ranged from 3.39% to 6.38% P_2O_5. The 6.38% P_2O_5 solubility determination was replicated, is anomalous, and will be further discussed with respect to the XRD analyses later in this section. Depending on the classification system used, the Mondo Tando and Cácata samples would be ranked as medium reactive phosphate rocks. The main diluent in all the samples is SiO_2. The mineralogical analysis indicates the main phosphate mineral is carbonate-containing francolite.

Table Angola 2. Chemical Analyses, Cabinda Phosphate Deposits

Sample	CABMTC[a]	CABUT[b]	CABCPI[c]	CABCP2[d]	CABCWH[e]
Analyses	(wt %)				
P_2O_5	35.4	28.7		32.1	20.5
NAC P_2O_5[f]	4.02	6.38		4.09	3.39
CaO	48.0			47.7	
F	3.34			3.33	
Cl (ppm)	68			50	
SiO_2	3.36			4.38	
Al_2O_3	2.48			2.26	
Fe_2O_3	1.43			2.16	
Na_2O	0.23			0.49	
K_2O	0.10			0.14	
MgO	0.12			0.28	
SrO	0.06			0.06	
CO_2	2.04			2.65	
Organic C	0.18			0.39	
TS[g]	0.69			0.62	
Cd (ppm)	65.2[h]	48.0	10.9	13.4	8.2
AI[i]	3.54			4.65	
Free H_2O[j]	0.66			0.78	
LOI[k]	5.18			6.07	

a. CABMTC = Mondo Tando excavation composite.
b. CABUT = Ueca trench composite.
c. CABCP1 = Cácata Pit 1 composite.
d. CABCP2 = Cácata Pit 2 composite.
e. CABCWH = Cácata waterhole composite.
f. Neutral ammonium citrate-soluble P_2O_5, AOAC method.
g. TS = Total Sulfur.
h. Average of the analyses of two sample splits.
i. Acid-insoluble residue, perchloric acid digestion.
j. Free H_2O = weight loss, 105ºC, 1 h.
k. Loss on ignition = weight loss, 1000ºC, 1 h.

Wavellite, an aluminum-containing phosphate generally formed in weathering, is found in some of the samples.

Based on the apatite unit cell a-value, the NAC solubility of the samples should range from about 2.88% to 3.68% P_2O_5. The NAC contents of the samples are generally in this range although perhaps a little higher, with the exception of Sample CABUT. Sample CABUT has the highest unit cell a-value (9.355Å) and should have the lowest NAC value. The only possible explanation is that the trench from which the samples were collected ended at a tunnel inhabited by a colony of bats. There was a significant amount of bat guano on the floor of the tunnel. Trees were canopied over the tunnel entrance, and bats were observed flying the length of the trench upon leaving and entering the tunnel. The samples from the trench may have been contaminated with bat guano, which has a highly reactive P_2O_5 content.

Two samples from Cabinda were previously characterized at the Tennessee Valley Authority (TVA) Fundamental Research Branch, Division of Chemical Development, in Muscle Shoals, Alabama (U.S.A.), in 1971 (McClellan, 1971). The deposits from which the samples were taken were not identified. The samples were indicated to be untreated and were from the upper and lower zones. The grade of the lower zone sample was 37.0% P_2O_5 while the grade of the upper zone sample was 37.2%. The mineralogy, unit cell a-values of the apatite, and NAC solubilities of these samples are similar to the results obtained for the samples gathered for the IFDC study.

The chemical and mineralogical analysis of samples CABMTC and CABCP2, the TVA characterization studies, and data from COFAN and Energoprojekt documents indicate beneficiated concentrates of the material could probably be used in a wide variety of fertilizer processing applications. The impurity content is potentially problematic in that the combined Al_2O_3 and Fe_2O_3 contents of the CABMTC and CABCP2 samples and subsequent $Al_2O_3 + Fe_2O_3/P_2O_5$ ratios (R_2O_3 ratios) for the samples (CABMTC $R_2O_3/P_2O_5 = 0.11$, CABUT $R_2O_3/P_2O_5 = 0.14$) are at or above the limits of 0.11 where these impurities may be a problem in processing. However, these were surface-collected samples and have not been submitted to any washing process, which can lower the contents of these impurities. McClellan (1971) indicates lower combined $Fe_2O_3 + Al_2O_3$ (R_2O_3) values of 2.3% to 2.4% and R_2O_3/P_2O_5 ratios of about 0.6. Energoprojekt (1983) documents do not indicate any Al_2O_3 contents for beneficiated concentrates. Contents of Fe_2O_3 are about 1.5%.

Literature on the Cabinda deposits did not indicate any tests were performed assessing the suitability of concentrates for phosphoric acid or fertilizer production. Such tests would be required if a substantial investment were to be made in developing the deposit or for fertilizer facilities based on raw materials from the deposit.

Another significant finding of the IFDC (2005) study was the cadmium contents of samples CABMTC and CABUT, which were 65.2 and

Table Angola 3. Mineralogical Analyses, Cabinda Samples

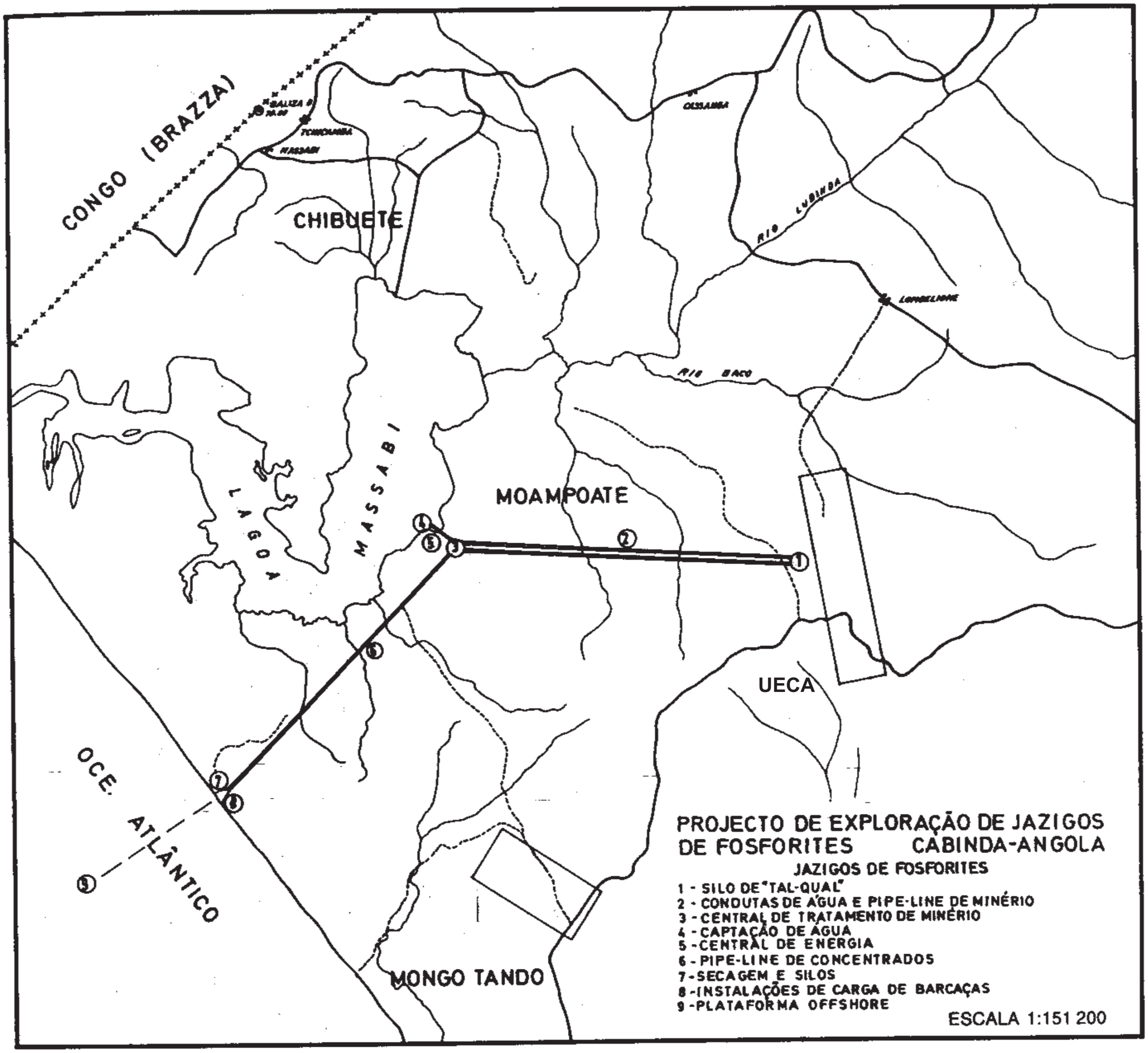
Sample	Mineralogical Composition[a]	Francolite Composition
CABMTC	Francolite (87.1)[b] Wavellite (3.4)[c] Quartz (6.8)[d] Unidentified (2.7)	Unit cell a-value francolite = 9.351Å $Ca_{9.80}Na_{0.15}Mg_{0.06}(PO_4)_{5.47}(CO_3)_{0.53}F_{2.1}$ Theoretical composition (wt %); CaO = 55.47, Na_2O = 0.47, MgO = 0.22, P_2O_5 = 39.18, CO_2 = 2.36, F = 3.96
CABUT	Francolite Wavellite Quartz	Unit cell a-value francolite = 9.355Å, $Ca_{9.84}$, $N_{0.12}$, $Mg_{0.04}$, $PO4_{5.59}$, $CO3_{0.41}$, $F_{2.08}$ Theoretical composition (wt %) = CaO = 55.5, Na_2O = 0.36, MgO= 0.17, P_2O_5 = 39.87, F = 3.91
CABCP1	Francolite Quartz Microcline[e]	ND[f]
CABCP2	Francolite (82.2) Quartz (4.4) Wavellite (6.2) Unidentified (7.2)	Unit cell a-value francolite = 9.348Å, $Ca_{9.76}$, $N_{0.17}$, $Mg_{0.06}$, $(PO_4)_{5.38}$, $(CO_3)_{0.62}$, $F_{2.12}$ Theoretical composition (wt %); CaO = 55.44, Na_2O = O.55, P_2O_5 = 38.66, CO_2 = 2.77, F = 4.01
CABCWH	Francolite Quartz	ND[f]

a. Composition normalized to total of analyzed components.
b. See text for composition.
c. Wavellite formula = $Al_3 (PO_4)_2 (OH_3)_3 \bullet 5H_2O$.
d. Quartz formula = SiO_2.
e. Microcline formula = $KAlSi_3O_8$.
f. ND = not determined.

48.0 ppm, respectively. The Mondo Tando sample is from the upper phosphate sequence, which is Eocene in age. The Ueca sample was from the lower (Cretaceous) phosphate sequence. It is not known how extensive this high cadmium content might be in the deposits. However, it would be practically impossible to sell this rock with such cadmium contents to any company making fertilizer where legislation with low cadmium limits is pending. Shipment to Europe of rock and/or fertilizer products made from phosphate rock with similar cadmium contents ceased several years ago. Legislation in Europe is still pending, but products with high cadmium contents will either not be tolerated or will be labeled accordingly at specified cadmium levels.

In 1971 COFAN performed a preliminary economic analysis based on a production rate of 3 million tons of concentrate per year from the Ueca area (Figure Angola 11). This was the amount of concentrate production considered necessary for the project to be economically viable. The following capital costs were indicated in U.S. dollars:

Mine equipment	US $9,066,200
Transport to the beneficiation plant	1,430,000
Beneficiation plant	2,695,000
Transport to coast	1,379,000
Dryer after beneficiation	2,249,500
Dock	5,560,000
Electrical plant	7,408,500
Communications system	100,000
General offices	287,870
Housing	3,800,000
Laboratory	290,400
Other offices	203,500
Vehicles	330,000
Overhead expenses	1,740,000
	US $36,539,970



Source: Cunha Gouveia et al. (1993).

Figure Angola 11. COFAN Exploitation Plan

Mining equipment included two draglines, bulldozers, tractors, and trucks. The ore would be transported by pipeline to the beneficiation plant. The platform offshore would only be sited for water deep enough to bring in barges holding 5,000 tons. No detail was available on this study, but it was stated that a loading facility for oceangoing vessels off Landana would have to extend 6 km offshore due to very shallow water off the Cabindan coast. The central electrical generating facility would provide 50,000 KVA (Kilovolt-Ampere).

Multiplying the cost of US $36,539,970 by a correction factor between 1971 and mid-2004 costs (*Chemical Engineering* Plant Cost Index, ~3.33) indicates the 2004 plant cost would be approximately US $110,835,147. It is not known if any location multipliers were used in this cost estimate. However, the cost of mining equipment, even for 1971, appeared very low. Two draglines for mining 3 million tpy of phosphate rock in 2004 costs would be on the order of US $25 million each. Using *Chemical Engineering* Plant Cost Index figures for equipment indicates a cost for a dragline at over US $7.0 million/unit in 1971. It would certainly appear that no location multiplier factors were used. It would also appear that the COFAN estimates were very optimistic. The following table from IFDC (2005) illustrates a more probable scenario:

Mine	3.0 million tons concentrate
COFAN estimate (1971)	$ 36,539,900
COFAN (adjusted to mid-2004 dollars)	110,835,147
COFAN (adjusted to mid-2004 w/1.5 multiplier, developing country, undeveloped site)	166,252,720
COFAN (adjusted to mid-2004 w/2.0 Angolan multiplier)	$221,670,294

Note: The 2.0 Angolan multiplier is based on *Chemical Engineering* multiplier for central Africa of 2.0 and the fact that all equipment and materials would have to be imported.

No attempt was made to correct any of the specific costs at the time of the IFDC study.

Phosphate mines are planned to have a working life of at least 20 years, and most major phosphate mine equipment can last on the order of 30 years, or longer, with suitable maintenance and care. In order to provide 3 million tons of concentrate per year for 20-30 years, COFAN would have had to define 60-90 million tons of producible concentrate in deposits in proximity to each other. COFAN did locate this amount of material. However, only the portions of the deposit with relatively low overburden to ore ratios would be economically producible, and there was not enough information available to evaluate these potential costs. COFAN did not find enough material in close proximity. It should be noted that there apparently was not a more refined capital cost estimate at the end of COFAN II. It should also be noted that the more refined study at Mondo Tando by the Energoprojekt cut COFAN reserve estimates in half.

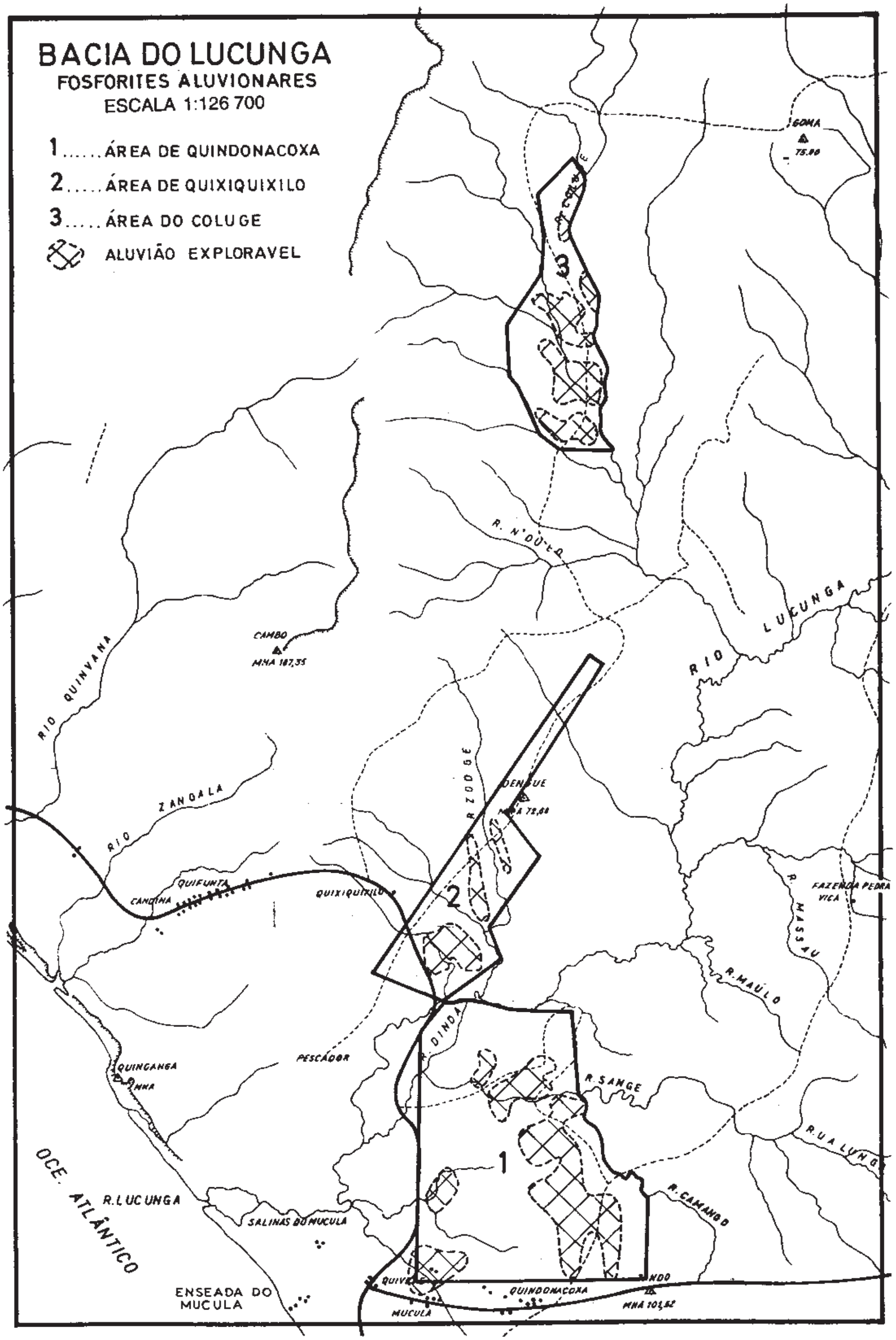
The Energoprojekt economic study was rather detailed. The beneficiation plant would produce 400,000 tons of concentrate per year for 14 years. The total cost to establish the facility would be US $48,405,419 (1982). Adjusting to 2004 dollars (simply using the *Chemical Engineering* Plant Cost Index) indicates a cost of US $65,404,359 in mid-2004 dollars.

The Energoprojekt document indicates that the price of the phosphate concentrate would be between US $37.33 and US $39.00 per ton depending on several factors including the production rate. An alternative plan was considered wherein 640,000 tpy would be produced and the deposit would be mined out in 9 years. Although the document concluded that production was economically feasible, the project was never implemented.

Zaire Province Deposits—Phosphate deposits in Zaire province were discovered in the 1950s by the Servicios de Geologia e Minas. The Quindonacaxa (Quindonacoxa, Quindonacaxe) Deposit was studied in detail in the early 1960s (Martins, 1963). A Bulgarian team (Bulgargeomine) and Geomina studied the deposit in 1979. The deposits were outlined by an airborne geophysics radiometric survey. The Quindonacaxa Deposit was sufficiently drilled to formulate a mine plan. The deposit was mined and a pilot plant was operated between 1981 and 1984 by the state-owned company Fosfatos de Angola (FOSFANG) under a joint venture with Bulgaria (Premoli, 1994). Apparently the phosphate was used for direct application.

The Zaire Province deposits are located about 30 km from N'Zeto (Figure Angola 12). The radiometric survey in 1960 further defined three areas of interest: Quixiquixilo, Rio Coluge, and Quindonacaxa. The Rio Coluge and Quixiquixilo Deposits are Eocene in age while the Quindonacaxa Deposit is the result of reworking of preexisting phosphate beds during the Pleistocene. The phosphate beds may be up to 2 m in thickness. However, the beds average less than 1 m thick.

Total resources of the three deposits were estimated at 28 million tons at 18% to 26% P_2O_5. The phosphate particles have been described as coprolitic and containing other organic phosphate



Source: Cunha Gouveia et al. (1993).

Figure Angola 12. Zaire Deposit Locations

debris. These particles are generally fairly large and can often be separated by simple screening. Following are some data from screening tests of samples of the Quixiquixilo Deposit:

Size Fraction	Sample	P_2O_5	CaO	R_2O_3	SiO_2
	(% of total)	(wt %)			
+9 mesh	50.8	32.3	48.3	3.4	5.7
-4+9 mesh	8.2	21.7	33.3	4.5	31.4
-40 mesh	41.0	4.2	–	–	–

Note: The R_2O_3/P_2O_5 ratio of the +9 mesh fraction is near the limit where chemical processing becomes problematic (0.11).

Based on screening tests the following reserves are estimated:

Area	+9 Mesh	+40 Mesh
	(million tons)	
Quixiquixilo	0.76	0.88
Quindonacaxa	5.52	6.34
Rio Coluge	2.33	2.82
Total	8.61	10.04

Note: Screen sizes in the above tables are expressed as U.S. standard mesh.

Other Sedimentary Deposits—McClellan and Notholt (1986) indicate that a phosphatic limestone bed (5% P_2O_5) outcrops along the Koroka River at Subida, 10 km south of Mocamedes. Calcareous phosphates are reported to occur near Sassalemba, 40 km northeast of Luanda and at Lunga Riamica, 15 km south of Dondo (Terraconsult AG, 1983).

Igneous Deposits—Apatite-bearing carbonatite deposits are known to occur in central and southern Angola (Figure Angola 1). The apatite-bearing Canaba Carbonatite Deposit occurs about 10 km southwest of Andulo. The Bailundo Carbonatite Deposit contains phoscorite (apatite-forsterite-magnetite) with apatite contents reaching up to 39% P_2O_5 (Alberti et al., 1999). The Longonjo Carbonatite Deposit, southwest of Longonjo, contains apatite, barite, and magnetite (Premoli, 1994). It has been reported that grab samples of niobium ore from the Bonga Carbonatite Deposit contained up to 10% P_2O_5 (Terraconsult AG, 1983). Additional carbonatites with reported phosphate occurrences include the Virulundo, Supongola, and Capuda Complexes (Terraconsult AG, 1983; Alberti et al., 1999). All of these carbonatites lie within areas severely affected by the Angolan civil war. Very little work has been done in these areas in the last 30 years.

Sulfur Resources

Gypsum is reported from Cabo Ledo, 80 km north of Luanda and Dombe Grande, 50 km south of Benguila (van Straaten, 2002). The Dombe Grande Gypsum Deposit is of Cretaceous age and may be up to 50 m thick (Duarte Morais and Sgrosso, 2000). Angola produced approximately 20,000 tons of gypsum per year in the 1980s (van Straaten, 2002).

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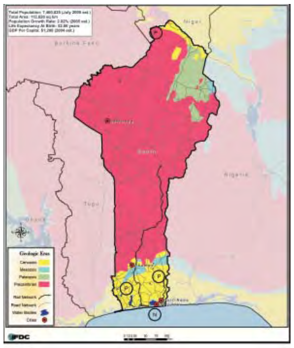
BENIN



The People's Republic of Benin (Figure Benin 1) is bordered by the Gulf of Guinea on the south, Burkina Faso and Niger on the north, Nigeria on the east, and Togo on the west. Total area of the country is 112,620 km^2. Approximately 18.1% of the land is arable cropland. The population was estimated in mid-2005 as 7.5 million inhabitants (World Factbook, 2006). Annual population growth was estimated at 2.8%. The economy is dependent on subsistence agriculture, cotton production, and regional trade. The transportation network (Figure Benin 1) consists of 3,500 km of main roads, 7,700 km of secondary roads, and 579 km of railroads (Cotonou to Parakou). Cotonou is the main port.

Geologically, the People's Republic of Benin is almost entirely represented by the Precambrian age Panafrican Chain of the Dahomeyids. Two major geologic subdivisions can be distinguished within the Dahomeyids Chain:

1. The Dahomeyan Basement (Benin Plain Complex) of Precambrian age, which is composed of metamorphic rocks intruded by granites, gabbro, and microgabbro dikes. There are also some metavolcanic facies within the basement complex.
2. The external units of the Dahomeyids, which include the Atakora and Buem Units of Upper Proterozoic age.

West of the Buem Units in Northwestern Benin, the Volta Basin formations are represented by a narrow band through Niger, Burkina Faso, and Togo and become well developed in the main undisturbed central part of the basin in Ghana. Paleozoic sedimentary formations are located in the northeastern corner of the country in the Kandi Basin (Alidou, 1987). The Kandi Basin is the southwestern extension of the Iullemenden Basin of Niger and the Sokoto Basin of Nigeria. In south Benin, sedimentary formations of Cretaceous to Recent ages overlie the Benin Plain Complex in the coastal basin.

Nitrogen Resources

Oil was discovered in 1968 by the Union Oil Company in the Seme area 15 km offshore at a depth of 1,900 m in 24-54 m of water. During the 1980s, petroleum production was about 8,000 barrels of oil per day. The oil field was shut down in 1995. In 2003 Kerr-McGee, in partnership with Malaysia's Petroliam Nasional Berhad (PETRONAS), were exploring and drilling wells on Block 4, offshore. Kerr-McGee does not list any activity in the area at the present time on its website. PETRONAS lists its association with Kerr-McGee in Benin as "Status: Exploration" on its website. Total reserves of oil have been estimated to be 5,500 million barrels (Crankshaw, 2004). This estimate does not appear to be realistic. Proven natural gas reserves are estimated at 608.8 million m^3 (World Factbook, 2006).

Phosphate Resources

The phosphate deposits of the People's Republic of Benin can be placed in two categories. Upper Proterozoic phosphate rock is found in the Volta Basin in the Mekrou area of north Benin. Paleocene to Eocene phosphates occur in the formations of the coastal basin in south Benin.

Mekrou Zone Phosphates—Discovered by Kusnir in 1973 within the Benin portion of the Parc "W" (Kusnir, 1973; Kusnir and Cardoso da Fonseca, 1973), the Mekrou zone phosphates have been studied in detail in the south Marikire area located between the Mekrou and Marikire Rivers. The phosphate-bearing formation is a monoclinal

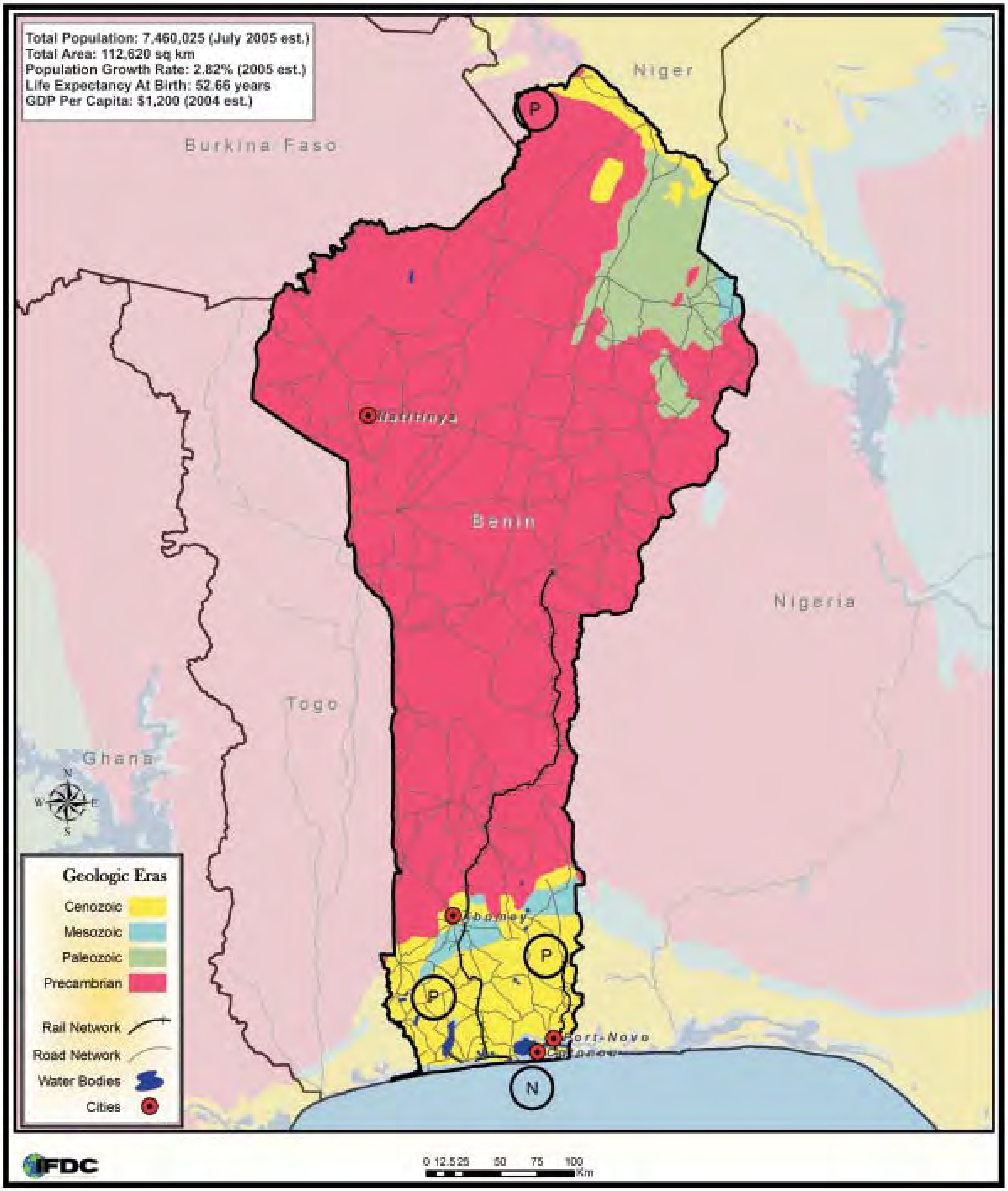


Figure Benin 1. Geology, Major Cities, and Transportation Network structure and is slightly folded. The phosphate beds can be horizontal, but most of the beds dip from 3° to 5° to the south-southeast.

The regional geological framework in which the Mekrou Deposit is found is similar to that of the Kodjari Phosphate Deposit in Burkina Faso and the Tapoa Deposit in Niger. Phosphate beds in the region occur within both the Dapaong (Dapaon)-Bombouaka and Pendjari-Oti Super Groups (Figure Benin 2). The phosphate beds of the Mekrou Series are found in the Pendjari Group of Middle Voltaian age within the upper Pendjari Formation. The Kodjari Deposit, which also occurs in the Pendjari Group, is located within the Lower Kodjari Formation. The Mekrou zone phosphates directly overlie the quartzites of the Dapaong-Bombouaka Super Group.

There are two main facies in the deposit, sandstones and clays, which form lenticular undulating horizons. Evidence from boreholes indicates there are three main phosphate beds that are more or less continuous across the area (Kirov et al., 1980). The thickness of the entire phosphatic formation varies between 0.50 and 25 m. Samples from the coarse-grained phosphate sandstone facies can assay near 30% P_2O_5, with a cumulative thickness from 0.50 m to more than 10 m for one to six phosphatic beds. The clayey facies can assay up to 15% P_2O_5 with cumulative thickness from 1 to 10 m for one to three phosphatic levels.

Chemical analyses of some Mekrou phosphate rock samples are shown in Table Benin 1. In some of the phosphatic sandstone samples, the apatite phase is about 65% of the total rock. The exogangue is composed of detrital quartz, iron oxides, and recrystallized silica.

One sample of Mekrou phosphate rock containing 29.3 wt % P_2O_5 from the South Marikire Deposit

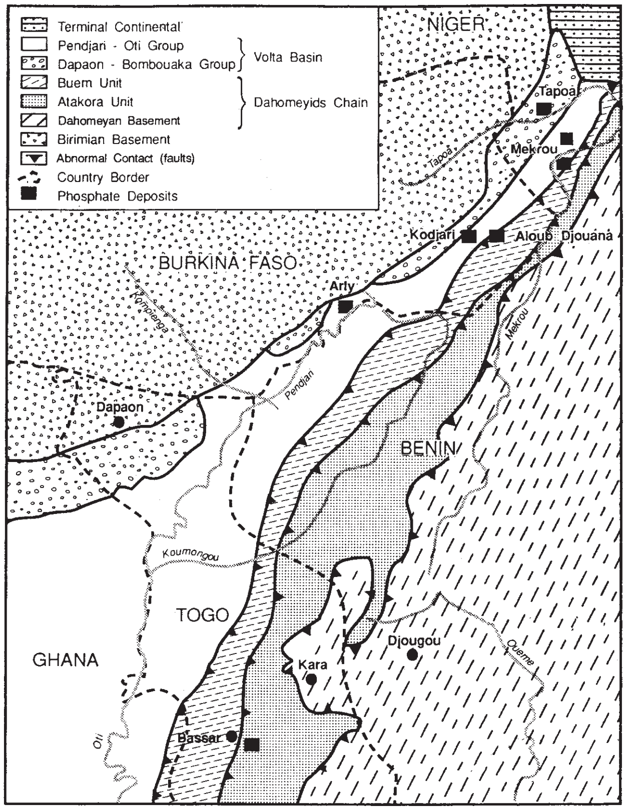


Figure Benin 2. General Geologic Map of a Portion of the Volta Basin Showing the Location of Known Phosphate Deposits

Table Benin 1. Chemical Composition of Some South Marikire Area Phosphate Samples

Chemical Analyses	Sample Number Outcrop	Borehole SA-1	EEM	Outcrop 5N/10W
	(wt %)			
P_2O_5	29.93	23.40	31.10	22.45
CaO	40.52	32.06	43.00	39.12
MgO	0.07	–	0.05	0.01
Al_2O_3	0.75	4.91	0.68	1.26
Fe_2O_3	3.20	3.13	1.52	3.35
TiO_2	–	–	0.04	–
SiO_2	21.40	32.02	19.70	21.00
SO_3	0.28	–	1.00	0.43
F	2.85	–	2.92	2.13
CO_2	1.63	–	1.06	7.94
Na_2O	0.16	–	0.14	0.21
K_2O	0.02	–	0.06	0.22
Cl^-	0.03	–	0.03	0.03
Organic C	–	–	0.09	–
H_2O	–	–	0.08	–
H_2O^+	–	–	0.80	–
LOI at 1000°	–	–	1.65	–
CaO/P_2O_5	1.35	1.37	1.38	1.76
P_2O_5/F	10.50	–	10.65	10.54

Source: Kirov et al. (1980).

was characterized at IFDC (1985) (Table Benin 2). The rock is approximately 71% carbonate fluorapatite (francolite) with 23% quartz, 2% aluminophosphates, and 1% limonite. The unit cell a-value of the francolite was determined to be 9.357 ±0.001 Å. The amount of carbonate substitution in the francolite would be about 1.6 wt % (100% francolite basis). The neutral ammonium citrate (NAC) solubility of the rock at 1.9% P_2O_5 is low. Particle-size measurements indicated effective liberation would be achieved at about 90 µm. The low Fe_2O_3+Al_2O_3+MgO/P_2O_5 ratio of the Mekrou rock and low chlorine levels (51 ppm) indicated that the rock or a concentrate has good potential for use in a number of fertilizer processes.

The Bureau de Recherches Géologiques et Minières (BRGM) studied the beneficiation of a Mekrou phosphate rock sample from the South Marikire Deposit (Durand, 1979). The head sample contained 31.1 wt % P_2O_5 (Table Benin 3), and the main impurity was silica (19.7 wt %). A heavy-liquid separation of a ground plus 80- minus 100-µm fraction sample produced a 37.6 wt % P_2O_5 concentrate with a 5.85 wt % SiO_2 (Table Benin 4). Several flotation options were studied. A concentrate was produced with over 34% P_2O_5 (Table Benin 5) and about 60% overall P_2O_5 recovery.

Table Benin 2. Chemical Analyses and Approximate Modal Analyses of Mekrou Phosphate Ore

Chemical Analyses		Approximate Modal Analyses						
Constituents	Wt %	Francolite[a]	Quartz (SiO_2)	Goethite $FeO(OH)\cdot nH_2O$	Variscite $Al(PO_4)\cdot 2H_2O$	Goyazite $SrAl_3(PO_4)_2\cdot H_2O$	Gorceixite $BaAl_3(PO_4)_2\cdot H_2O$	Unassigned Components
		(wt %)						
P_2O_5	29.30	28.32		0	0.68	0.27	0.03	
CaO	41.50	39.25						2.25
F^{1-}	2.80	2.80						
SiO_2	22.6		22.6					
Al_2O_3	0.81				0.48	0.30	0.03	
Fe_2O_3	1.00			1.00				
MgO	0.01	0.01						
MnO	0.02							0.02
Na_2O	0.09							
K_2O	0.03							0.03
TiO_2	0.01							0.01
SrO	0.20					0.20		
BaO	0.03						0.03	
CO_2	1.3	1.14						0.16
SO_4^{2-}	<0.1							<0.01
S	<0.1							<0.01
Cl^{1-} (ppm)	51							51
Organic C	0.1							0.1
Free H_2O [b,c]	0.54							
LOI [b,d]	2.5							
NAC P_2O_5 [b,e]	1.9							
	100.00	71.60						
$-O^{2-} \equiv F^{1-}$ [f]	–1.18	1.18						
	98.83	70.42	22.6	1.00	1.16	0.77	0.09	2.79

a. See text for theoretical composition.
b. Not included in totals.
c. Free H_2O determined by heating 1 h at 105ºC.
d. Loss on ignition (LOI) determined by heating 1 h at 1000ºC.
e. Neutral ammonium citrate-soluble P_2O_5.
f. Fluorine correction: two F^{1-} substitute for one O^{2-}, molecular weight of one O^{2-} divided by molecular weight of two F^{1-} multiplied by the measured F^{1-} concentration.

Table Benin 3. Chemical Analysis of Mekrou Phosphate Used by the BRGM for Beneficiation Tests

Chemical Analysis	Wt %
P_2O_5	31.1
CaO	43.0
F	2.92
SiO_2	19.7
Al_2O_3	0.68
Fe_2O_3	1.52
MgO	0.05
TiO_2	0.04
Na_2O	0.14
K_2O	0.06
CO_2	1.06
SO_3	1.0
Cl^-	0.03
Organic C	0.09
Free H_2O	0.08
LOI[a]	1.65

a. 1000ºC.

Source: Durand (1979).

Table Benin 4. Chemical Analysis of a Mekrou Concentrate Prepared From the Size Fraction Plus 80 Minus 100 µm and Separated by Heavy Liquids (d>3.00)

Chemical Analysis	Wt %
P_2O_5	37.6
CaO	50.6
F	3.48
SiO_2	5.85
Al_2O_3	0.26
Fe_2O_3	1.12
MgO	0.05
TiO_2	0.045
Na_2O	0.16
K_2O	0.05
CO_2	0.96
SO_3	0.13
Cl^-	0.54
Organic C	0.05
Free H_2O	0.2
LOI[a]	2.05

a. 1000ºC.

Source: Durand (1979).

Table Benin 5. Chemical Analysis of a Concentrate Produced From the Mekrou Phosphate Rock by Cationic Flotation

Chemical Analysis	Wt %
P_2O_5	34.6
CaO	46.7
F	2.83
SiO_2	13.4
Al_2O_3	0.28
Fe_2O_3	1.13
MgO	0.05
TiO_2	0.035
Na_2O	0.12
K_2O	0.03
CO_2	1.0
SO_3	0.11
Cl^-	0.24
Organic C	0.01
Free H_2O	0.10
LOI[a]	1.6

a. 1000ºC.

Source: Durand (1979).

BRGM measurements of the unit cell a-value of the apatite (9.359Å) indicated a low-carbonate-substituted francolite. The NAC solubility of the Mekrou sample was determined to be 2.0% P_2O_5. The BRGM report concluded that the reactivity of Mekrou rock was probably insufficient for direct application.

The United Nations Development Programme (UNDP) (Kirov et al., 1980) investigated the resources of the south Marikire area. Fourteen pits, two trenches, and forty-eight boreholes were put down in the deposit, and over 2,000 samples were analyzed for P_2O_5.

For the reserve-resource estimation, the deposit was divided into 31 blocks; only phosphate beds at a depth of less than 35 m were considered. The minimum P_2O_5 considered was 19.00 wt %, and the minimum phosphate bed thickness considered exploitable was 0.4 m. Total proven reserves are estimated at 3,265,500 tons assaying 25.10 wt % P_2O_5 using a waste/ore ratio of 2.6. Phosphate beds at the surface represent 842,000 tons of proven reserves assaying 25.73% P_2O_5. Probable reserves are estimated to be 2,204,900 tons assaying 25.77% P_2O_5 with a waste/ore ratio of 6.5. Additional possible reserves are estimated at 2,053,500 tons assaying 25.10% P_2O_5. Resources of the South Marikire Zone are summarized in Table Benin 6.

Coastal Basin Phosphates—Discovered in 1956 by the Bureau Minier de la France d'Outre-Mer (BUMIFOM, 1958), the phosphatic beds of the coastal basin of Benin have never been considered economically exploitable. These Paleocene age and Eocene age phosphate beds are limited to the north by a topographic depression called the Lama Depression, which is oriented west-southwest/east-northeast from the west of Allada to north of Pobé. The Lama Depression continues into Togo and borders the Togo phosphate deposit. The general stratigraphy of the coastal basin is as follows:

- Maastrichtian—Sediments that are essentially sandy and clayey-sandy.
- Paleocene—Sands, limestones, clays, Togocyamus limestone, marls, and glauconitic beds.
- Lower Eocene—Fissile-laminated clays with attapulgite, limestones, marls, phosphatic limestones, and glauconitic beds.
- Middle Eocene—Marly phospharenites, clays, and marls with phosphate nodules.
- Mio-Pliocene—Clays, marls, and sands.
- Terminal Continental—Detrital continental sediments that dip from 1° to 2° southeast.

Table Benin 6. Phosphate Resources of the South Marikire Zone Area, Benin

Category	Geologic Reserves	P_2O_5 Content	Total Cumulative Thickness of Phosphate Beds	Waste/ Ore Ratio
	(tons)	(wt %)	(m)	
Proven	3,265,500	25.10	5.18	2.6
Surface (included in proven)	842,000	25.73	2.22	0
Probable	2,204,900	25.77	3.87	6.5
Possible	2,053,500	25.10	1.93	?

Source: Kirov et al. (1980).

Between 1950 and 1957, BUMIFOM drilled 58 wells within the coastal basin in Togo and Benin to explore for phosphate and to investigate water resources (Slansky, 1962). Hundreds of exploration pits were dug in the most promising areas for phosphate in Benin and Togo. Exploration in Benin was concentrated in the areas of Pobé, Séhoué, Bopa-Toffo, Lobogo, and Lokossa-Kpénou-Sè. These areas can be divided into three sectors. The Lokossa-Bopa sector lies between the Mono and Couffo Rivers, the Ouagbo-Toffo sector lies between the Couffo and Oueme Rivers, and the Pobé sector is east of the Oueme River.

The most interesting phosphate occurrences were found in the Lokossa area. A complete section similar to the Togo occurrence was discovered, but the upper phosphate beds were much lower in grade and thinner (3-5 m) than in Togo and contained interbeds of clays and carbonates. Chemical analyses of a relatively high-grade sample and a washed sample of phosphate from the Lokossa area are given in Table Benin 7.

Slansky (1962) came to the conclusion that the conditions for phosphatic sedimentation were less and less favorable eastward from Togo. To the east in Benin, the entire phosphate-bearing formation increased in thickness with the development of a gypsum-bearing clay facies. The phosphate beds are diluted by these clay beds and carbonates.

Table Benin 7. Chemical Analyses of Phosphate Samples From the Lokossa Area

Chemical Analysis	Raw Phosphate	Washed to Remove Clays
	(wt %)	
P_2O_5	28.8	34.4
CaO	42.2	47.6
SiO_2	11.4	2.6
Al_2O_3	6.8	6.7
Fe_2O_3	1.4	1.4
Free H_2O	3.0	1.9
LOI	5.4	4.3

Source: Slansky (1962).

The Shell Oil Company conducted an assessment of potential phosphate resources in Benin during 1965-67 (Atger et al., 1977). The Lokossa-Bopa, Ouagbo-Toffo, and Pobé areas were studied using an irregular network of pits and boreholes without encouraging results.

UNDP conducted a survey for phosphate resources in Benin during 1974-76. A geochemical soil survey was conducted, and over 6,500 samples from the Ouagbo-Toffo and Pobé areas were analyzed. Seven boreholes were drilled, 40 pits were dug near Ouagbo-Toffo, and four pits were dug near Pobé. The most interesting phosphate beds were found near Ouagbo-Toffo. Near Ouagbo, three phosphatic horizons were reported (Atger et al., 1977). The first horizon, or phosphatic set, occurs within clays. Some beds are over 3 m thick with 13% P_2O_5. Thin beds (less than a meter) with 20% P_2O_5 are present.

The second horizon varies in thickness from 0.10 to 0.65 m and is composed of phosphatic limestones assaying 0.92% to 9.66% P_2O_5. The thickness of the third horizon varies from 0.15 to 0.50 m and assays 3.07% to 14.72% P_2O_5. This horizon disappears to the east. In the Pobé area the phosphate beds are thin and sporadic. The maximum P_2O_5 content found in the Pobé area was 9.52%. Atger et al. (1977) reached the same conclusions as Slansky (1962), indicating that conditions for phosphate sedimentation were less favorable east of the deposit in Togo.

Further studies of the area south of Kpénou near Sè and Gbédji were conducted by the Office Beninois des Mines during 1983/84. Over 130 auger holes and pits were completed on a 200-m grid. Clayey levels in about 35 of the pits had P_2O_5 contents ranging from 0.8 to 28 wt % P_2O_5.

Instituto Ricerche Breda (1987) conducted exploration for phosphate in Benin during 1985/86. In the second phase of the study, 809 m of boreholes and 1,713 m of auger holes were drilled. Several boreholes were drilled south of the limit of the BUMIFOM exploration south of Kpénou. Phosphate beds approximately 1 m thick with nearly 20% P_2O_5 were discovered. In several auger holes in the Pobé area, many thin (~1 m) phosphate beds were found with up to 4% P_2O_5. Most of the holes augered in the Pobé area did not encounter beds with >1.0% P_2O_5.

In the third phase of the Instituto Ricerche Breda project, 1,800 m of boreholes and 1,174 m of auger holes were drilled and about 50 m of pits was dug. Several more boreholes were drilled south of Kpénou-Sè, and more auger holes were drilled near Pobé. In the Toffo area, thin phosphate beds (~1 m) were found with up to 20% P_2O_5. Instituto Ricerche Breda concluded that the entire coastal basin in Benin had been explored for phosphate by this study and previous surveys.

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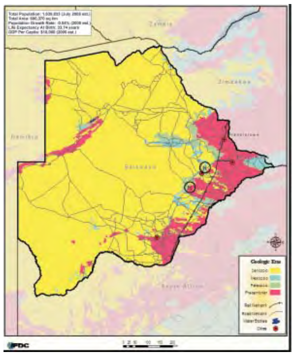
BOTSWANA



The Republic of Botswana (Figure Botswana 1) is bordered on the north by Namibia, Zambia, and Zimbabwe; to the south by South Africa; and to the west by Namibia. Botswana is a totally landlocked country. Total area is 600,370 km^2 and arable land is only 0.65%. The population was estimated in mid-2005 as 1.6 million inhabitants (World Factbook, 2006).

The transportation network consists of 8,867 km of paved roadways, 25,233 km of unpaved roadways, and 888 km of 1.067-m-gauge railway. There are 10 airports with paved runways and 75 airports with unpaved runways.

Geologically, Botswana can be divided into four broad time-based units:

1. Early Precambrian—Includes the metamorphic rocks of the Kaapvaal and Zimbabwe Cratons and the Limpopo Mobile Belt.
2. Late Precambrian—Metamorphic rocks of the Damara Belt.
3. Intrusives—Granitic rocks of the Zimbabwe Craton, Limpopo Mobile Belt, Gaborone Granite Complex, Mabalapye granite, syenites, gabbros, pyroxenites, diorites, and kimberlites. These intrusives range from Early Precambrian to Cretaceous.
4. Precambrian and younger sedimentary and volcanic rocks—Lobatse Volcanic Group, Transvaal, Waterberg and Karroo (Karoo) Supergroups, and the Kalahari Group.

Exposures of most of the Early Precambrian, intrusive rocks, and Paleozoic and Mesozoic sedimentary rocks occur in the eastern part of the country. Rocks of the Damara Belt are found in the west and extreme northwest. Vast areas of the country are covered by the Kalahari sands.

Nitrogen Resources

Coal—The Morupule Coalfield is located west of Palaye on the main Palaye-Serowe (or Serwe) road. The deposit contains four seams. The lowest (No. 1) has an average thickness of 8.5 m and averages 80 m below the surface (Morupule Colliery Ltd., 2004). The Morupule Colliery was established in 1973 to supply power to the copper-mining industry and for general power generation.

Coal reserves of the Morupule Coalfield are indicated as 5 billion tons by Morupule Colliery Ltd. (2004) and Coakley (2003). Another source indicates reserves of 2.9 x 10^9 tons (World Energy Council, 2001). Coal production in 2003 was 822,780 tons (Coakley, 2003).

The Mmamabula Coalfield is indicated to contain proven resources of 4.3 x 10^9 tons of coal (maximum depth of 200-250 m, minimum seam thickness of 0.25 m) (World Energy Council, 2001). In addition to the Morupule and Mmamabula coalfields, an additional in-situ amount of 205 x 10^9 tons, comprising 29 x 10^9 tons of indicated resources and 176 x 10^9 tons of inferred resources, exists in coalfields that have been explored in Botswana.

Kumba Resources, majority owned by Anglo American, was to institute a prefeasibility study of mining the Mmamabula Central Coal Resource (*Business Report*, 2006). Preliminary analysis indicated the production rate might be on the order of 2 to 2.5 million tpy for thermal (power station) coal and 0.5 million tons of coking coal.

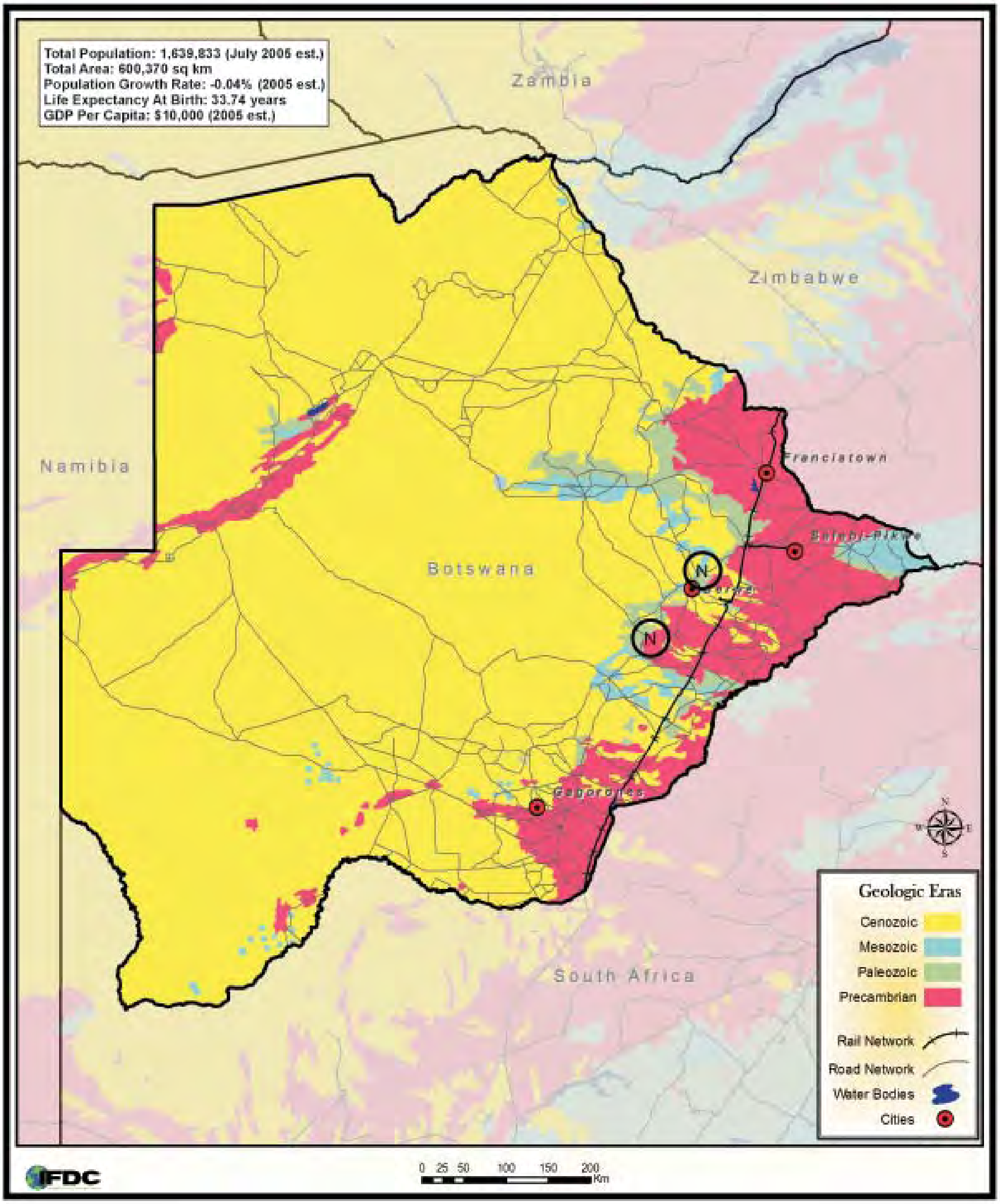


Figure Botswana 1. Geology, Major Cities, and Transportation Network

A study by Fichani and Labys (2003) indicated Botswana coal could be competitive in Asia and Western Europe markets using a global steam coal trade model. The results indicate costs are most sensitive to capital costs for mine development.

Coalbed Methane—Between 2001 and 2003, the Botswana Department of Geological Survey (2003) undertook and completed a preliminary exploration of resources of coalbed methane. The main objective of the study was to assess the availability and potential for development of natural gas resources associated with the coal-bearing sequences of the Kalahari Karroo Basin. The study indicated there were 60 trillion ft^3 of gas-in-place in coalbeds in the study area. Associated carbonaceous shales were estimated to contain an additional 136 trillion ft^3 for a combined total of 196 trillion ft^3. The highest potential for development was along the eastern margin of the basin where the sequence can be up to 80 m thick and contain up to 30% coal (by volume). Reservoir modeling indicated that 15% to 20% of the coalbed methane could be potentially developed at a gas price of US $2.00/thousand ft^3 at the wellhead.

Sulfur Resources

Gypsum resources located west of Foley and near Bojanamane (southwest of Serule) were reported by van Straaten (2002). No other information is available on these deposits.

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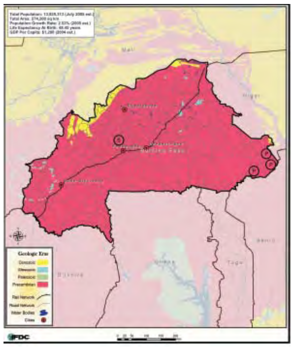
BURKINA FASO



Burkina Faso, a landlocked country, is bordered by Mali on the north and west; Côte d'Ivoire, Ghana, and Togo on the south; and Benin and Niger on the east. The total area is 274,200 km^2; 14.4% of the land is arable cropland. The population was estimated in mid-2005 at 13.9 million inhabitants (World Factbook, 2006) who are mostly engaged in the agricultural sector. Annual population growth was estimated as 2.53%.

The transportation network (Figure Burkina Faso 1) consists of 4,600 km of main roads, 4,100 km of secondary roads, and 520 km of railways. The shortest route from the capital, Ouagadougou, to the sea is via Ghana to Tema port (845 km). However, rail connections to the sea are through Côte d'Ivoire.

The topography of Burkina Faso is an expression of the geologic framework. Almost all of the country is underlain by a crystalline basement of Archean and Lower Proterozoic ages and volcano-sedimentary sequences. The basement is overlain at the northern and northwestern borders of the country by the Upper Proterozoic sediments of the Taoudeni Basin. At the southeastern border, the basement is overlain by the northern extension of the Upper Proterozoic to Infracambrian sediments of the Volta Basin (Figures Burkina Faso 1 and Burkina Faso 2). On this basement, which covers more than 80% of the country, a peneplain developed that averages 250-300 m in altitude. Lateritic crusts cover residual plateaus, hills, and inselbergs. The altitude of these secondary features on the peneplain can reach 500 m.

Phosphate Resources

Three Upper Proterozoic phosphatic deposits have been reported in the sedimentary formations of southeast Burkina Faso in the northeastern extension of the Volta Basin. The Arly Deposit and a prospect at Kaabougou (northeast of Kodjari) were discovered in 1970 (Pascal, 1972). The Kodjari Deposit was discovered in 1973 (Pourtal, 1973) during an investigation of the Kaabougou prospect, and the Aloub-Djouana Deposit was discovered in 1975 (Barthelet, 1975). Since 1980 several additional studies have been carried out on the deposits by Direction de la Géologie et des Mines (DGM)—known today as Bureau des Mines et de la Géologie du Burkina Faso (BUMIGEB)—by the Bureau de Recherches Géologiques et Minières (BRGM), and by CdF Ingénierie (originally named Etudes Techniques et Réalisations, Charbonnages de France). The emphasis of the studies was the Kodjari and Aloub-Djouana Deposits. The deposits are found in the same geologic sequence within the Precambrian sedimentary cover of the Man Shield and the external units of the Dahomeyids Chain.

The stratigraphy of the Volta Basin is divided into three groups. The Dapaong-Bombouaka Group, which is 450-1,100 m thick and lies on a regional unconformity with the Birimian crystalline basement, is formed of coarse quartzites, conglomerates, siltstones, argillites, and cherts. The phosphate-bearing Pendjari Group (200-400 m thick), unconformably overlies the Dapaong-Bombouaka Group and is divided into the Pendjari and Kodjari Formations. At the base of the Kodjari Formation is a tillite, and above the tillite is a succession of carbonate, siliceous, and phosphatic facies. This is the "triad sequence" (tillite, carbonates, chert) reported throughout the West Africa pericratonic area. The Obosum Group (400-500 m thick) overlies the Pendjari Group and is composed of argillites and red sandstones and is often conglomeratic.

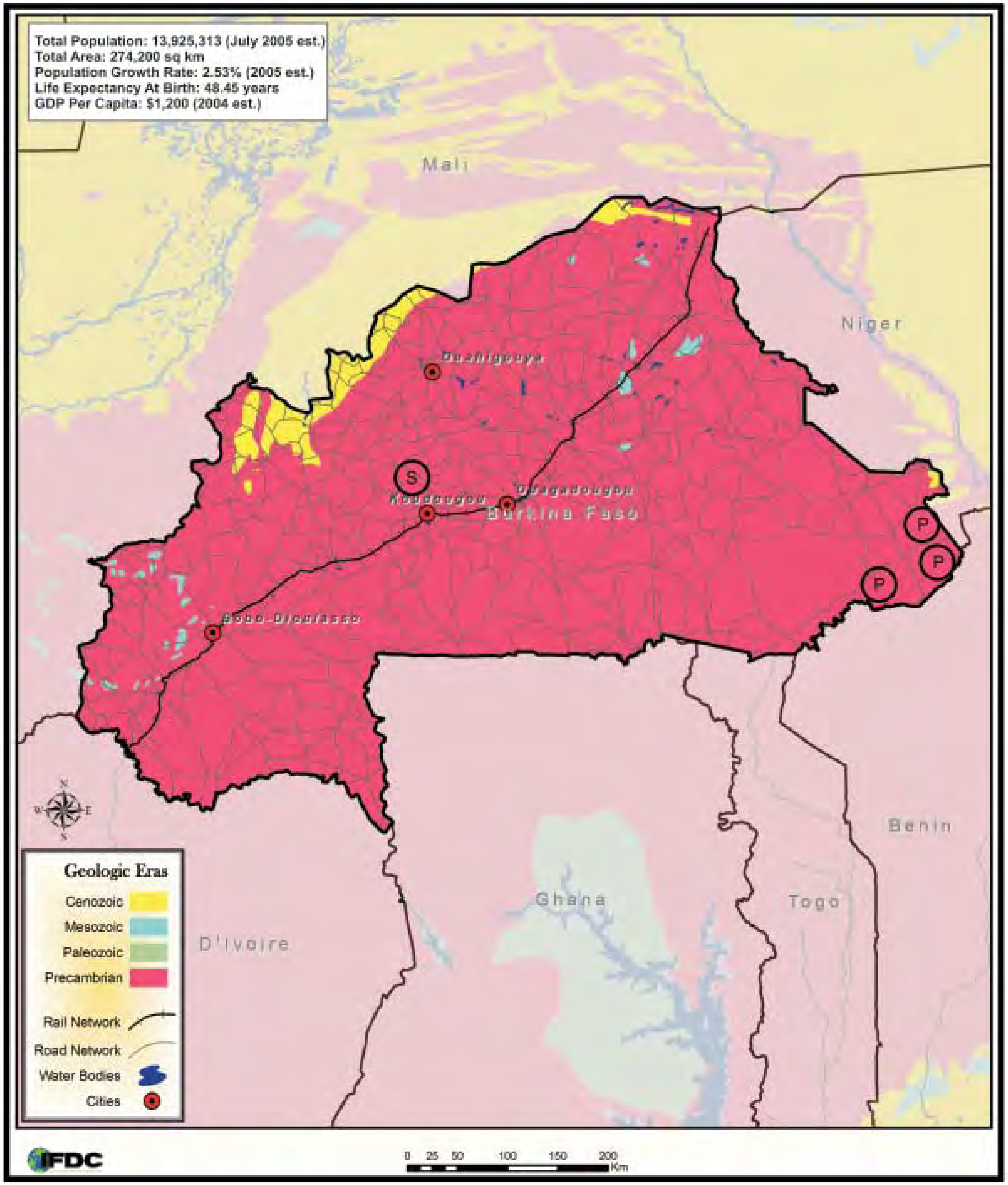


Figure Burkina Faso 1. Geology, Major Cities, and Transportation Network

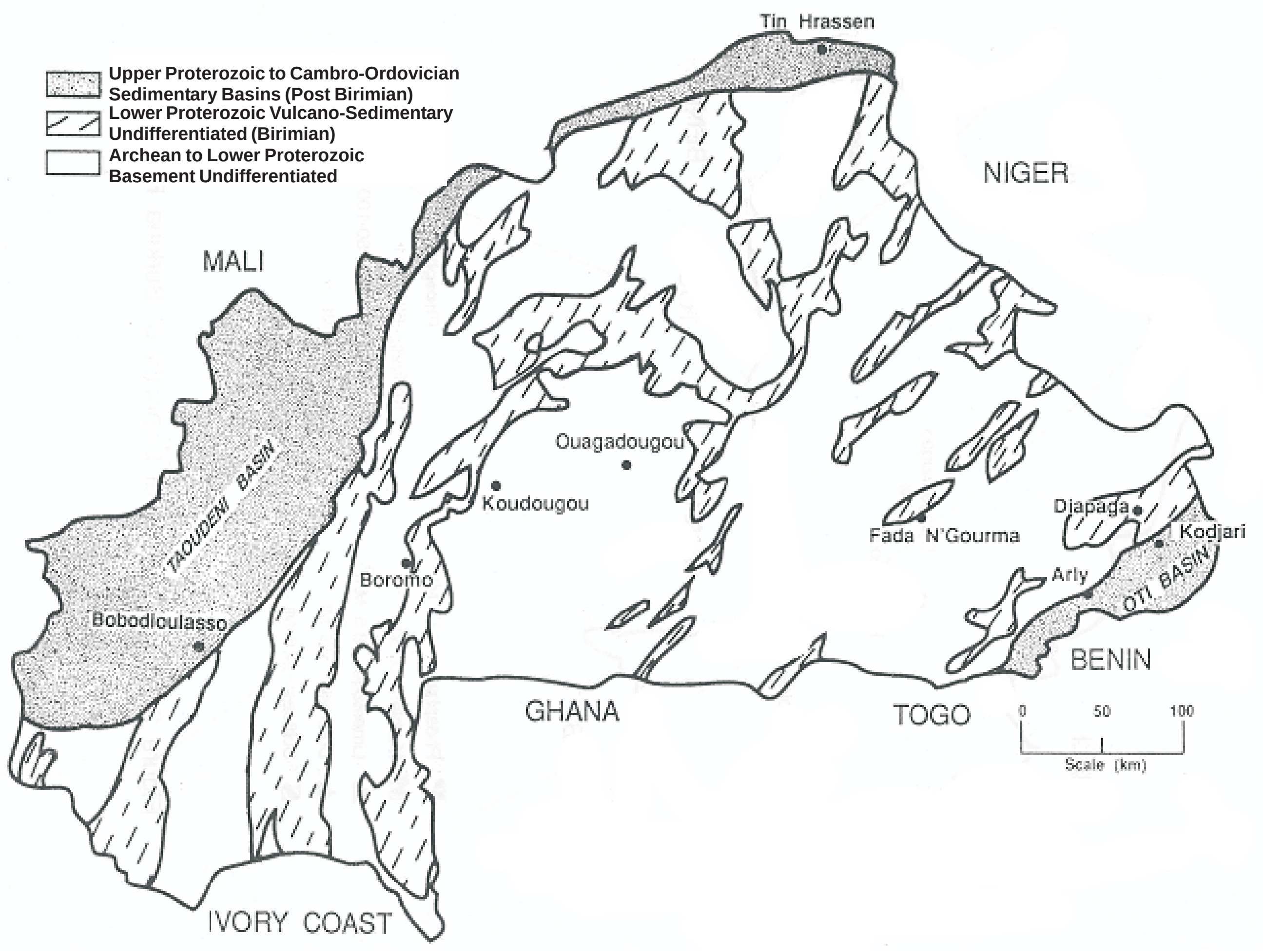


Figure Burkina Faso 2. Geologic Map of the Major Structural Units of Burkina Faso

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The Volta Basin formations of Burkina Faso and Niger are bordered on the east by folded and slightly to moderately metamorphosed formations (rejuvenated by the Panafrican orogenesis) that belong to the Dahomeyids Chain. Three structural units are distinguished in the Dahomeyids—the Buem Unit, the Atakora Unit, and the Benin or Dahomeyan Peneplain (Affaton, 1975; Affaton et al., 1980); these units are located from west to east.

The Buem Unit is composed of shales, feldspathic siltstones, quartzites, sandstones, and cherts. It shares many common characteristics with the Kodjari Formation. Volcano-sedimentary breccias, basalts, dolerites, and serpentinites also are associated with the Buem Unit.

The Volta Basin constitutes a transition zone between the West African Craton and the Panafrican Chain of the Dahomeyids with its allochthonous external units, the Buem and Atakora Units. The Buem Unit overthrusts the Pendjari Formation, and it in turn is overthrust by the Atakora Unit. The Buem Unit has been interpreted to be the tectonic equivalent of the Pendjari Group.

Kodjari Deposit—The Kodjari Deposit is located about 70 km northeast of Arly and 40 km south of Diapaga. The deposit is formed by three hills. The beds of Hills A and B (Figure Burkina Faso 3) are tabular with a 5°-10° dip to the southeast and have been traced by boreholes under the plain to the

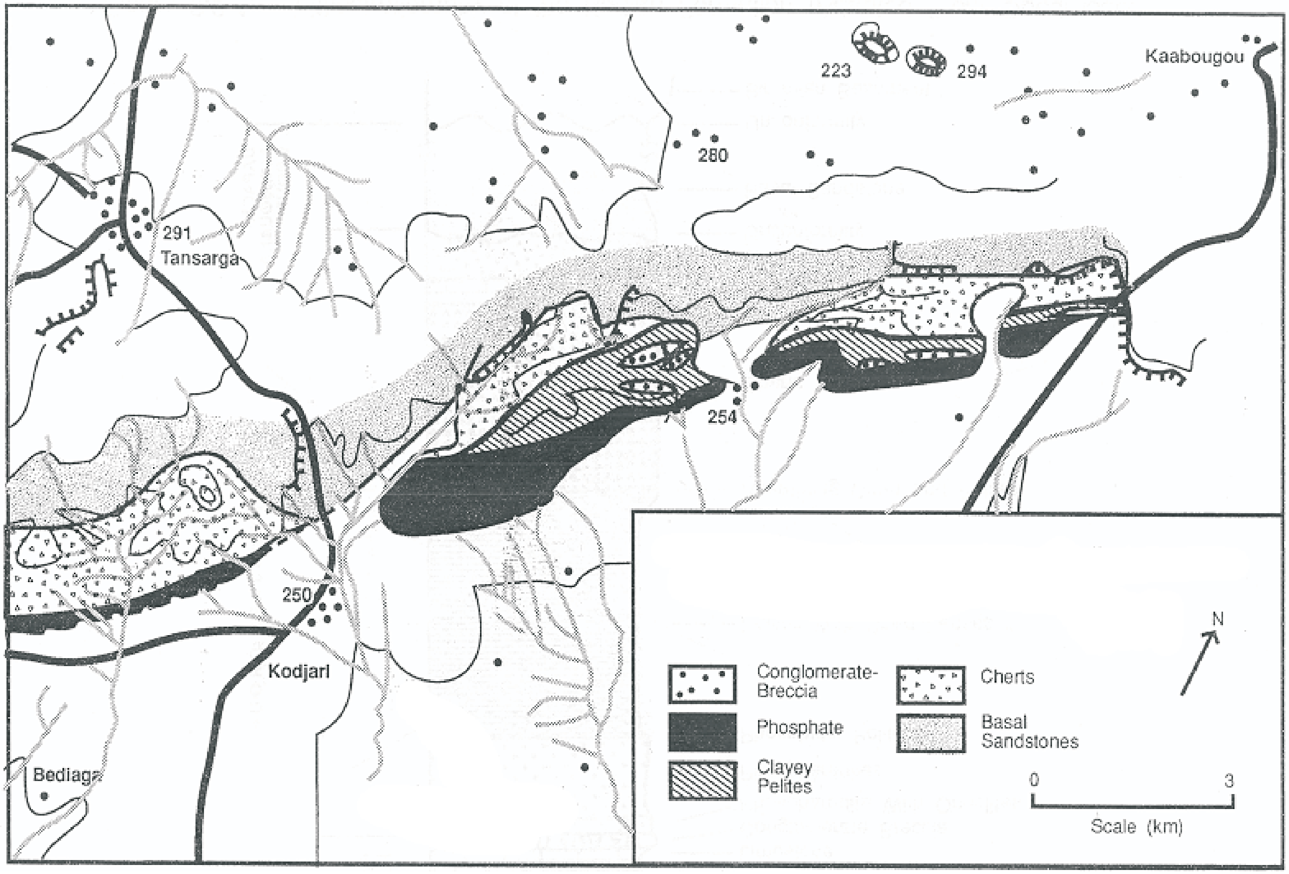

Figure Burkina Faso 3. Outcrops of the Kodjari Deposit (From Ouédraogo, 1982)

southwest. The phosphate formation outcrops in the hills for a distance of about 15 km.

At Kodjari, three main facies can be distinguished in the phosphate formation. Phosphatic laminates are located at the base of the formation. Fine phosphate grains occur in lenses or as laminae in clay beds. The thickness of this facies varies between 10 and 50 m. Phospharenites occur in the middle of the formation and are cemented by calcite or chalcedony. The phospharenites appear to have formed from reworking the laminates. The thickness of the phospharenites varies from 4 to 16 m. Phosphatic sandstones constitute the upper facies of the phosphate formation and represent the ultimate stage of reworking with the addition of detrital quartz grains.

The phospharenites form a continuous unit in the area and display zonations that are the result of weathering (oxidation and decarbonation) up to 12 m deep. Only the phospharenitic facies constitutes the ore zone in the area.

The phosphate grains of the Kodjari Deposit are subspherical (or ellipsoidal), structureless, and composed mainly of iron-stained cryptocrystalline carbonate-flourapatite (francolite). Phosphate grain size varies between 35 and 300 µm with an average of about 80 µm. Quartz is the major gangue mineral. Illite, chlorite, and kaolinite constitute the clay fraction. Pyrite and iron oxides are also present.

Sixty-six drill holes, nine pits, and six trenches have been put down in the Kodjari Deposit. The reserves of the deposit were calculated using data from 38 of the boreholes (CdF Ingénierie, 1980). Reserves were calculated according to three cutoff grades (18%, 23%, and 28% P_2O_5). Most of the reserves are located at Hill A at or near the surface; at 18% P_2O_5 cutoff grade there is 44 million tons that averages 26.1% P_2O_5. Most of the reserves of Hill B are at depths of up to 20 m; at 18% cutoff grade there is 19 million tons that averages 26.8% P_2O_5. The total resources of the deposit to a depth of 20 m and at 18% cutoff grade is 63 million tons at an average grade of 26.3% P_2O_5.

The average P_2O_5 content and other chemical characteristics of the Kodjari Deposit vary according to the cutoff grade chosen. At 18% P_2O_5 cutoff grade, 238 samples averaged 25.98 wt % P_2O_5. The CaO/P_2O_5 ratio of these samples is 1.50 and the Fe_2O_3 content averages 5.77 wt %. At 23% P_2O_5 cutoff grade, 178 samples averaged 27.71 wt % P_2O_5. The CaO/P_2O_5 ratio of these samples is 1.45 and the Fe_2O_3 content averages 5.47 wt %. At 28% P_2O_5 cutoff grade, 77 samples averaged 30.36 wt % P_2O_5. The CaO/P_2O_5 ratio of these samples is 1.38 and the Fe_2O_3 content averages 4.79 wt %.

The ore reserve estimates do not indicate that the ore has been divided into these distinct groups (Table Burkina Faso 1). Based on a statistical analysis of chemical properties of samples from across the entire deposit, Kodjari ore was divided into three ore types (A, B, and C) for beneficiation tests (CdF Ingénierie, 1980). Samples were composited and chemically analyzed for major elements (Table Burkina Faso 2).

Ore Type A is from the near-surface weathering zone. A low CaO/P_2O_5 ratio (1.25) indicates the presence of nonapatitic phosphates. Type A ore has comparatively higher Fe_2O_3 (2.86 wt %) and Al_2O_3 (5.33 wt %) contents than are found in ore Types B and C.

Type B ore represents a transition to Type C ore. The CaO/P_2O_5 ratio of l.37 is higher than that for Type A ore. This CaO/P_2O_5 ratio indicates a general lack of nonapatitic phosphates or carbonates in the sample. Type B ore is characterized by siliceous gangue (25.2 wt % SiO_2). Petrographic studies indicated a well-developed secondary porosity that can be attributed to the leaching of carbonates. Type B ore is higher in Fe_2O_3 (2.0 wt %) content than Type C ore (l.6 wt %).

Ore Type C appears to be the phosphate rock within the deposit that has been least affected by the present surficial weathering episode. Type C ore has a mixed siliceous and carbonate exogangue. The only carbonate detected was calcite ($CaCO_3$), although the presence of dolomite [$Ca,Mg(CO_3)_2$] is suspected due to the MgO content (0.88 wt %). Due to the presence of carbonates, the CaO/P_2O_5 ratio (1.59) is much higher than for the other ore types. The Fe_2O_3 (1.56 wt %) and Al_2O_3 (3.33 wt %) contents of ore Type C are lower than are found in the other ore types.

Ore Type C is the most prevalent ore type in the deposit. At 18%, 23%, and 28% P_2O_5 cutoff grades, Type C ore constitutes 82%, 79%, and 69%, respectively, of the total ore of the deposit. The decrease in Type C ore percentages with increasing grade is presumably due to secondary enrichment by leaching of carbonates. Decreasing CaO/P_2O_5 ratios with increasing cutoff grade can also be attributed to the leaching of carbonates and increasing percentages of Types A and B ores. Because Type C ore is the most abundant ore type in the deposit, beneficiation tests concentrated on Type C ore.

Petrographic studies indicated Type A ore was liberated at 50-100 μm. Type B ore was liberated at

Table Burkina Faso 1. Distribution of Ore Types in the Kodjari Deposit

Cutoff Grade (% P_2O_5)	Ore Type A (CaO/P_2O_5 <1.33)	Ore Type B (1.33<CaO/P_2O_5 <1.36)	Ore Type C (CaO/P_2O_5 >1.36)
	(% of total ore at cutoff grade)		
18	10	8	82
23	12	9	79
28	15	16	69

Source: CdF Ingénierie (1980).

Table Burkina Faso 2. Chemical Analysis of Bulk Samples of Kodjari Phosphate Rock Used for Metallurgical Testing

Major Elements	Sample		
	A	B	C
	(wt %)		
P_2O_5	29.30	25.40	26.20
CaO	36.75	34.72	41.70
MgO	0.23	0.59	0.88
Al_2O_3	5.33	4.86	3.33
Fe_2O_3	2.86	2.00	1.56
TiO_2	0.14	0.14	0.90
SiO_2	17.60	25.20	16.45
SO_3	0.10	0.07	0.09
F	2.55	2.10	2.35
CO_2	1.32	1.54	5.47
Na_2O	0.22	0.18	0.18
K_2O	0.39	0.75	0.50
Cl^-	0.05	0.04	0.04
C organic	0.08	0.09	0.13
S sulfide	ND[a]	ND	ND
H_2O^-	0.73	0.64	0.28
H_2O^+	3.48	2.70	1.73
Ignition loss 1,000°C	4.80	3.70	6.80
–O for F	1.07	0.88	0.99
–O for Cl	0.01	O.01	0.01
Total	100.05	100.13	99.98
CaO/P_2O_5	1.254	1.367	1.592
Feral (Fe_2O_3 + Al_2O_3)	8.19	6.86	4.89
F/P_2O_5	0.087	0.083	0.090
$Feral/P_2O_5$	0.280	0.270	0.187

a. Not detected.

Source: CdF Ingénierie (1980).

35-50 µm, and Type C ore was liberated at 50-60 µm.

Grinding studies of Type C ore further indicated effective liberation was achieved at 50-80 µm. Careful grinding was required to avoid the generation of excessive slimes. High-intensity magnetic separation on the minus 400- plus 40-µm fraction produced only minor decreases in the Fe_2O_3 and Al_2O_3 contents (~10%). Flocculation and agglomeration studies performed on slime fractions of Type C ore resulted in 1%-2% increases in P_2O_5 grades.

Four flotation processes were analyzed in the beneficiation of Type C ore, including direct anionic, reverse anionic, reverse cationic, and flotation with a phosphoric acid ester (HOE F 1415). The best results were obtained using the phosphoric acid ester. A concentrate was produced that analyzed 32.41 wt % P_2O_5 at 35.96% total P_2O_5 recovery. The flotation process was not considered optimized.

Beneficiation tests of ore Types A and B were limited to grinding and magnetic separation. Preconcentrates of Types A and B ores were produced at 31.7 and 28.2 wt % P_2O_5 and 60% and 50% P_2O_5 recovery, respectively.

The CdF Ingénierie report (1980) concluded it was possible to produce concentrates, under optimal conditions, at 31 to 33 wt % P_2O_5 with better than 50% P_2O_5 recovery. A conceptual beneficiation scheme included a primary crushing and grinding circuit; a secondary grinding circuit with an optional wet, high-intensity magnetic separator; a primary and secondary flotation treatment; and finally a second wet, high-intensity magnetic separator to remove unwanted Fe_2O_3 from the concentrate. The treatment of slimes by flocculation or flotation was also envisioned.

In 1989 a fact-finding mission was conducted by IFDC and Bundesanstalt für Geowissenschaften und Rohstoffe (BGR); three samples of Kodjari phosphate rock were collected and chemically analyzed (Table Burkina Faso 3). Four samples of Kodjari rock had been previously analyzed at IFDC (Table Burkina Faso 4).

The 1989 samples were collected in a progression from the surface (up dip) and back into the working face of the mine. Sample WABFK1 was collected from the surface. Sample WABFK2 was collected from about 1 m below the surface. Both of these samples were a yellowish-brown color. Sample WABFA1 (a distinct dark-gray color) was collected from near the base of the working face.

The P_2O_5 contents of these three samples are similar (28.2-29.3 wt %). A progressive decrease in the Fe_2O_3 and Al_2O_3 contents occurs from the weathered surface rock to the less weathered samples. The combined Fe_2O_3+Al_2O_3 (R_2O_3) content of the surface sample (WABFK1) is 11.3 wt %

Table Burkina Faso 3. Chemical Analyses of Kodjari Phosphate Rock[a]

	WABFK1 (Weathered at Surface)	WABFK2 (~1 m Below Surface)	WABFA1 (~3 m Below Surface
	(wt %)		
P_2O_5	28.3	29.3	28.2
CaO	35.2	40.9	39.5
F	2.5	2.9	2.7
SiO_2	18.4	18.4	24.1
Fe_2O_3	5.2	2.6	1.5
Al_2O_3	6.1	2.9	1.9
K_2O	0.5	0.3	0.2
Na_2O	0.2	0.1	0.1
MgO	0.2	0.3	0.3
$C1^-$ (ppm)	40	60	80
S	<0.2	<0.1	<0.1
CO_2	1.0	1.4	1.3
Free H_2O[b]	3.3	1.7	0.7
LOI[c]	8.0	3.9	3.2
NAC P_2O_5[d]	2.6	2.4	2.0

a. Collected during the joint IFDC-BGR fact-finding mission, 1989.

b. Free H_2O = weight loss, 105°C.

c. Loss on ignition, 1000ºC.

d. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).

Table Burkina Faso 4. Chemical Analyses of Kodjari Samples Analyzed at IFDC

	R230.33	R230.53	R230.76	R231.14
	(wt %)			
P_2O_5	24.3	25.4	31.0	25.3
CaO	32.9	34.5	42.9	33.5
F	2.6	2.54	2.9	3.1
SiO_2	25.7	26.24	20.5	25.7
Al_2O_3	4.0	3.08	2.0	4.0
Fe_2O_3	2.8	3.42	1.5	3.1
Na_2O	0.11	0.11	0.16	0.09
MgO	0.46	0.27	0.33	0.29
K_2O	0.48	O.23	0.21	0.43
S	0.03	0.04	0.02	0.03
CO_2	1.1	1.0	1.4	1.3
Free H_2O[a]	0.77	–	0.49	0.79
LOI[b]	4.1	–	3.3	4.5
NAC P_2O_5[c]	2.0	2.3	2.7	1.9

a. Free H_2O = weight loss, 105°C.

b. Loss on ignition, 1000ºC.

c. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).

(Table Burkina Faso 3). At 1 m below the surface (Sample WABFK2), the R_2O_3 content is 5.5 wt %. At 3 m below the surface (Sample WABFA1), the R_2O_3 content is 3.4 wt %. X-ray diffraction (XRD) analysis indicated crandallite [$CaAl_3(PO_4)_2(OH)_5 \cdot H_2O$] was present in Samples WABFK1 and WABFK2.

The CaO/P_2O_5 ratios of the rock collected in 1989 and samples previously analyzed at IFDC (Table Burkina Faso 5) indicate Sample WABFK1 is Type A ore; the rest of the samples are Type B ore. Type C ore, with a carbonate component and the most prevalent ore in the deposit, has not been analyzed at IFDC.

Measurements of unit-cell a-values of Kodjari apatite range from 9.351Å to 9.361Å (±0.001Å) (Table Burkina Faso 5) and indicate the apatite is a low-carbonate-substituted francolite. The composition of the francolite, based on previously established statistical models and an average a-value of 9.357Å would be:

$$Ca_{9.88}Na_{0.09}Mg_{0.03}(CO_3)_{5.63}(PO_4)_{0.37}F_{2.17}$$

The maximum amount of P_2O_5 in a 100% francolite concentrate is predicted to be about 4 wt % and the CO_2 content would be about 1.6 wt %. The CaO/P_2O_5 ratio of the francolite is predicted to be l.38.

The predicted neutral ammonium citrate (NAC) solubilities (Table Burkina Faso 5) (2.2%-3.3% P_2O_5) are similar to the measured solubilities (l.9%-2.7% P_2O_5). These NAC solubilities are typical of highly weathered, metamorphosed, or ancient phosphorites. Phosphate rocks with such low NAC P_2O_5 solubilities are not typically recommended for direct application.

Ores from Kodjari and Aloub-Djouana, calcined ores from Kodjari, and a flotation concentrate of Type C ore from Kodjari were tested for dissolution properties in sulfuric and nitric acids (CdF Ingénierie, 1980). Filter- and merchant-grade phosphoric acids were produced by the dihydrate process from the Type C ore concentrate. Chemical analyses of the acids (Table Burkina Faso 6) indicate very high impurity contents. These impurities may cause problems in fertilizer products, including sticky products and reversion to water- and citrate-insoluble compounds.

Table Burkina Faso 5. Chemical and Crystallographic Analyses of Kodjari and Arly Phosphate Rocks

Deposit	Sample No.	Total P_2O_5	Total R_2O_3[a]	Apatite CaO/P_2O_5	Measured CaO/P_2O_5	Unit-Cell A	Unit-Cell C	Predicted NAC P_2O_5	Measured NAC P_2O_5
		(wt %)				(±0.001Å)		(%)	
Kodjari	WABFK1	28.3	11.3	NA[b]	1.24	NA	NA	NA	2.6
	WABFK2	29.3	5.5	1.38	1.39	9.357	6.890	2.7	2.4
	WABFK3	28.2	3.4	1.38	1.40	9.358	6.891	2.6	2.0
	R230.33	24.3	6.8	1.37	1.35	9.359	6.894	2.5	2.7
	R230.53	25.4	6.5	1.36	1.36	9.361	6.893	2.2	2.3
	R230.76	31.0	3.5	1.42	1.38	9.351	6.886	3.3	2.7
	R231.14	25.3	7.1	1.40	1.32	9.355	6.889	2.9	1.9
Arly	WABFA 1	30.8	1.9	1.39	1.37	9.356	6.888	2.8	2.6

a. $Fe_2O_3 + Al_2O_3$.
b. Not analyzed.

Table Burkina Faso 6. Chemical Analyses of a Flotation Concentrate Produced From Kodjari Composite C Ore Sample and Resulting Phosphoric Acids

	Flotation Concentrate	Filter-Grade Acid	Merchant-Grade Acid (Decanted)
	(wt %)		
P_2O_5	28.9	29.7	54.5
CaO	42.2	–	0
SiO_2	–	1.34	0.20
Fe_2O_3	1.30	1.09	0.55
Al_2O_3	2.15	2.13	2.40
F	–	2.67	1.30
SO_3	–	1.90	2.70

Source: CdF Ingénierie (1980).

Studies of the Kodjari Phosphate Deposit have always been based on use in agriculture within Burkina Faso. Production of phosphate rock in Burkina Faso was the responsibility of the Projet Phosphate. This project resulted from a bilateral economic and technical cooperation agreement (signed in 1973) between the Burkina Faso government and the Federal Republic of Germany. The project started in 1978 and involved the procurement and placement of equipment for mining, extracting, and grinding l,800-2,000 tons of phosphate rock per year; bagging equipment; storage facilities; and vehicles for the distribution of the product (Figures Burkina Faso 4, 5, 6, 7, and 8). The German government also assisted in the promotion of the product through field trials and advertising. The rock mined at Kodjari was transported to Diapaga for grinding and bagging. The product was stored at Diapaga, Ouagadougou, and Bobo Dioulasso. The final product, in 50-kg bags, is called Burkinaphosphate. From 1978 to 1985, 5,462 tons of Burkinaphosphate was produced. Of this production, 4,599 tons was sold to farmers, agricultural centers, and various organizations within Burkina Faso.

Several studies have been performed to investigate the agronomic effectiveness of Kodjari rock for direct application and the suitability of Kodjari rock for fertilizer products. IFDC produced partially acidulated products at various acidulation rates, which gave better agronomic results when compared with ground rock. In one experiment using sorghum on an Affisol in Burkina Faso, Kodjari partially acidulated phosphate rock (PAPR) at 50% acidulation (PAPR 50) was 109% as effective as single superphosphate (SSP) (IFDC, 1985). Finely ground Kodjari rock (no acidulation) was 62% as effective as SSP.

In a residual study on maize at Saria during 1985, Kodjari PAPR 50 was 92% as effective as triple superphosphate (TSP) and increased yields over absolute control by 62% (IFDC, 1986). In a

Figure Burkina Faso 4. Working Face of the Kodjari Mine

Figure Burkina Faso 5. Block of Kodjari Ore

Figure Burkina Faso 6. Loading a Truck at the Kodjari Mine

Figure Burkina Faso 7. Unloading a Truck at the Grinding Mill at Diapaga

Figure Burkina Faso 8. Grinding Mill at Diapaga

1985 trial at Faroko-ba, maize was used as a test crop. Faroko-ba is in the Sudanian savanna region of West Africa, and the zone is marginal for maize production. The results of the Faroko-ba trials indicated that Kodjari phosphate rock, Kodjari PAPR 25, and Kodjari PAPR 50 increased yields only 24% over control, and they averaged an agronomic effectiveness rating of 84% when compared with SSP.

Reversion of water- and citrate-soluble compounds to insoluble compounds in Kodjari PAPR has been documented (Hammond et al., 1989) and may lower its agronomic efficiency. The effect also has been documented using Tahoua (Niger) and Tilemsi Valley (Mali) rock, and has been attributed to the high Fe_2O_3 and Al_2O_3 content of the phosphate rocks.

An IFDC feasibility study (1984) investigated three schemes for fertilizer production in Burkina Faso. Under Scheme A, bulk-blended NPK compound fertilizers would be produced using imported materials. PAPR would be produced under Scheme B using Kodjari rock. Two types of PAPR products were considered, namely, granular PAPR (Scheme B_1) and semigranular or run-of-pile (ROP)-PAPR (Scheme B_2). Both PAPR and bulk-blend plants are included in Scheme C. Demand projections were based on figures supplied by the Government of Burkina Faso. The fixed and working capital investments (in 1984 U.S. dollars) were based on conceptual plant designs for each of the manufacturing schemes. Ex-plant product prices were based in part on imported product and raw material cost estimates. The economic internal rate of return (IRR) for Scheme A was about 13%. The IRRs for Scheme B are negative, and for Scheme C the IRR was less than 1%. The IFDC study concluded that only Scheme A provided a basis for a potentially viable project in Burkina Faso.

ATFER (1986) studied various scenarios for the production of compound fertilizers in Burkina Faso. For a plant producing 42,188 tons of product using partially acidulated Kodjari rock as a phosphate source, the IRRs ranged from negative to 4.l% (without taxes) using different financing alternatives.

The Autorité de Développement Intégré de la Région du Liptako Gourma (ALG) investigated the possibility of producing a compound fertilizer from Kodjari rock using organic materials and a nitrogen gas process (ALG, 1987, 1988). The product would assay 3.7-13.4-0 based on total P_2O_5 and 3.7-10.l-0 based on available P_2O_5. Plant capacity would be 29,790 tons of product per year. The initial fixed investment was 2,379,200,000 CFA (or ~US $8 million at 300 CFA = US $l). Based on available P_2O_5 in the product, the IRR for the project was calculated at 2.1% with taxes and 15.7% without taxes. The IRR calculated on total P_2O_5 was 26.8% without taxes. Including the costs of distribution and marketing, the IRR (without taxes) was calculated as 11.7% on the basis of available P_2O_5 and 23.2% on the basis of total P_2O_5.

In 1995, IFDC performed an economic/ financial analysis of the Kodjari Mine (IFDC, 1995). Two scenarios were considered in the evaluation. In the first scenario, the existing equipment—much of which had been in service approximately 18 years—was rebuilt or replaced as needed; the mine and grinding mill were worked a maximum of 6 months, 22 days/month, for two shifts (16 h/day). Six months is the approximate duration of the dry season in Burkina Faso; wet rock cannot be effectively milled. The two-shift format had been used in the past and is acceptable to workers and residents in the village of Diapaga. Under these conditions, the potential production capacity was approximately 3,600 tpy. The second scenario involved increasing production to 10,000 tpy in a 6-month season (22 days/month, two shifts). This scenario involved the procurement and installation of a grinding mill with increased capacity (5 tph), procurement of additional equipment, and replacement of existing equipment.

Under each scenario, additional warehouse space was provided for storage. The production season slightly overlaps with the onset of the planting season in Burkina Faso. In the evaluation, warehouse space was provided to store 4 months of the 6 months of production.

Using the techniques, data, and assumptions of this study, rebuilding the existing operation at the 3,600-tpy capacity resulted in production of a lower cost product. Under both scenarios, variable costs per ton were the same at US $37.12 because the costs for both scenarios were based on the same actual production data.

With the exception of interest on loans, fixed costs per ton for the 10,000-tpy scenario were lower than for the 3,600-tpy scenario. Basically, the high capital costs associated with purchasing and installing a new grinding mill, purchasing additional equipment, and paying off the loans negate and exceed any savings in fixed costs per ton at the higher production rate.

Arly Deposit—The Arly Deposit is located about 70 km south of Diapaga within the Arly Wildlife Reserve. Stratigraphically, the Arly Deposit is similar to the Kodjari Deposit. The thickness of the formation varies between 0 and 15 m. The Arly Deposit has been interpreted to have formed by reworking in an agitated environment. The phosphate grain size (100-l,000 mm) is much larger than at Kodjari.

One sample of Arly phosphate rock was collected from the outcrop by IFDC in 1989 and chemically analyzed (Table Burkina Faso 7). The grade of this sample was 30.8 wt % P_2O_5 and the main impurity was quartz (SiO_2 = 20.9 wt %). The combined Fe_2O_3 and Al_2O_3 contents are less than 2.0 wt %. The only phosphate detected by XRD was apatite. The measured unit-cell a-value (9.356 Å ± 0.001) (Table Burkina Faso 5) indicates the apatite is a low-carbonate-substituted francolite. Based on established statistical models, the composition of the francolite is predicted to be:

$$Ca_{9.83}Na_{0.12}Mg_{0.05}(PO_4)_{5.50}(CO_3)_{0.50}F_{2.20}$$

The maximum P_2O_5 content of a 100% francolite concentrate would be about 40 wt %, and the carbonate substitution would be about 1.7 wt %. The predicted CaO/P_2O_5 ratio (1.39) for the francolite compares favorably with the ratio (1.37) of

Table Burkina Faso 7. Chemical Analyses of Arly Phosphate Rock[a]

	Wt %
P_2O_5	30.8
CaO	42.1
F	3.0
SiO_2	20.9
Fe_2O_3	1.3
Al_2O_3	0.6
K_2O	0.1
Na_2O	0.2
MgO	0.2
Cl^-	60 ppm
S	<0.1
CO_2	1.3
Free H_2O[b]	3.8
LOI[c]	7.0
NAC P_2O_5[d]	2.6

a. Collected during the joint IFDC-BGR fact-finding mission, 1989.
b. Free H_2O = weight loss, 105°C.
c. LOI = loss on ignition, 1000°C.
d. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).

the rock analysis. The measured and predicted NAC solubilities (2.6% and 2.8% P_2O_5, respectively) are similar to those for the Kodjari phosphate rocks.

Twenty-three pits were dug in the Arly Deposit on 200-m centers. Nine trenches were also excavated. There is about 610,000 m^2 of outcrop area. Resources are estimated to be 3-4 million tons. Work was discontinued on the Arly Deposit because of the discovery of the Kodjari deposits to the north.

Aloub-Djouana Deposit—The Aloub-Djouana Deposit is located 22 km southeast of Kaabougou and about 50 km east of Kodjari within the boundaries of the Parc W Reserve. The deposit is formed by a group of small hills of which Hills Al, B7, and C9 are the most important. While the Kodjari and Arly Deposits are found in the relatively undisturbed Precambrian sediments of the Volta Basin, Aloub-Djouana is located at the eastern tectonic margin of the basin in the Buem Unit of the Dahomeyids Chain. At Aloub-Djouana the phosphate beds typically dip about 45° to the southeast, and the dips may approach 90°.

Due to the structural complexity of the area and limited geologic work (five drill holes and seven trenches), no clear stratigraphic sequence can be established at Aloub-Djouana. The alternating phosphatic sandstones and argillites at Aloub-Djouana may be the equivalent of the upper beds of the Kodjari Formation.

Three bulk samples of Aloub-Djouana rock were taken for metallurgical testing (CdF Ingénierie, 1980). The samples are lower in P_2O_5 grade (19.6-24.2 wt %) than the Kodjari samples taken for testing (25.4-29.3 wt % P_2O_5). Similar to Kodjari, the main impurity is silica. The SiO_2 contents are much higher (28.8-34.9 wt %) than in the Kodjari (16.45-25.20 wt %); the Al_2O_3 contents (5.8-7.3 wt %) of Aloub-Djouana rock are also higher than those of the Kodjari (3.33-5.33 wt %).

Testing of Aloub-Djouana rock was limited to grinding tests and magnetic separation (CdF Ingénierie, 1980). Concentrates near 29 wt % P_2O_5 were produced from Sample E with a Fe_2O_3 content of 0.90 wt % and 2.53% Al_2O_3 at 88% P_2O_5 recovery during magnetic separation. The CdF Ingénierie (1980) study suggested that the paramagnetic fraction (calcium aluminum phosphates) could be heat treated similarly to the calcium aluminum phosphate products produced in Senegal (Phos-Pal).

The CdF Ingénierie study stated that, compared with Kodjari, Aloub-Djouana does not constitute a deposit. Based on the limited geological work at Aloub-Djouana, resources of phosphate rock in the area may be 100 million tons (Hottin et al., 1975).

Sulfur Resources

The Perkoa region belongs to the geologic province called the Birimian Band of Borromo in Burkina Faso. Volcano-sedimentary formations that have been affected by several tectonic events are found within this province. The Perkoa Zinc (Zn) Deposit displays many of the characteristics of massive sulfides associated with volcanism within Precambrian shield areas around the world.

The Perkoa Deposit was discovered in 1982 by a BUMIGEB/UNDP geochemical survey. About

2,000 ppm Zn and 1,500 ppm lead were detected in silicified tuffs at the surface. The World Bank funded the drilling of the original six boreholes. There are now 45 boreholes at the site. The entire prospect is about 750 m by 250 m in area.

Due to the volcano-sedimentary origin, the rocks were deposited with rapid facies changes. The structural deformation in the area does not permit the restoration of the stratigraphy using drill holes. Mineralized tuff beds dip to the west at approximately 70°. There is a barren silicified-weathered cap zone about 50 m thick. From the bottom to the top, the mineral-bearing zones are:

1. Brecciated facies with rock fragments cemented by sulfides (pyrrhotite, pyrite, and sphalerite enriched in copper and gold).
2. Massive facies with pyrite and sphalerite, the main ore zone.
3. Banded facies with pyrite, sphalerite, and barite.
4. Chert beds.
5. Disseminated sulfide zone.

Only the first three zones constitute ore.

Initial estimates of the reserves of the Perkoa Deposit indicate about 4.63 million tons of ore available at 18.48% Zn (Table Burkina Faso 8). Of this total, 4.45 million tons at 17.43% Zn was considered recoverable.

A prefeasibility study was conducted by the French group Penarroya (1986). Penarroya recommended the open-stoping method of mining and the following beneficiation treatment:

1. Preconcentration (by cycloning of crushed ore at 12 mm).
2. Primary grinding to 140 µm followed by a secondary grinding to 40 µm.
3. Flotation.

A second prefeasibility study performed by a Swedish group, Boliden International (Anonymous, 1989), also recommended a stoping method and an ore rilling plan. One favorable factor for developing the deposit is that the Ouagadougou-Abidjan railway is located less than 40 km to the south of the mine site. The zinc sulfide concentrate would be shipped by rail to the port of Abidjan and processed at another location.

Pyrite beneficiation was investigated. Barite ($BaSO_4$) beneficiation was also studied because the ore can assay 22% $BaSO_4$. The sulfides and sulfates rejected in sphalerite concentration might be used to produce sulfuric acid. Approximately 40,000 to 45,000 tpy of sulfuric acid could be produced over a 10-year period if all the pyrite is used for sulfuric acid production.

Further exploration by airborne magnetics, ground magnetics, and electromagnetics delineated several other anomalies (perhaps 10) in the general area that have geophysical characteristics similar to the Perkoa Deposit. These anomalies are the size of the Perkoa or larger. With the discovery of additional deposits, several mines could be developed in the area.

In 2004 Snowden Mining Industry Consultants of Australia was hired to recalculate resources at the Perkoa Deposit (Bermúdez-Lugo, 2004). The recalculated inferred mineral resource at Perkoa was reported to be 7.06 million tons at grades of 17.7% Zn and 37.8 g/ton silver (at a 10% Zn cutoff grade).

Occurrences of pyrite have been reported northeast of Pilimpikan at Dacola and Pouny in the Batango area (Gorodiski, 1949). Bituminous beds containing sulfides are reported in the Volta Depression and west of the Niger River.

Table Burkina Faso 8. Total and Recoverable Reserves of the Perkoa Deposit

Type	Categories	Tonnage (Total)	Tonnage Zn	Percent Zn
		(tons)		
Total Reserves				
Principal	P1	3,195,000	613,500	19.20
Principal	P2	619,000	122,800	19.83
Secondary	P2	814,000	119,100	14.63
Total		4,628,000	855,400	18.48
Recoverable Reserves				
Principal	P1 & P2	3,679,000	668,000	18.17
Secondary	P2	779,000	108,700	13.96
Total		**4,458,000**	**776,700**	**17.43**

Source: Anonymous (1989).

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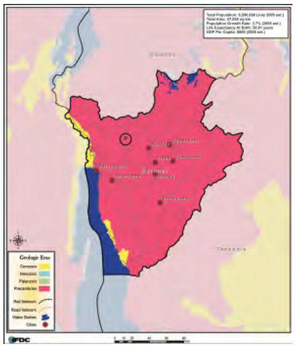
BURUNDI



The Republic of Burundi (Figure Burundi 1) is bordered to the north by Rwanda, to the east and south by Tanzania, and to the west by the Democratic Republic of the Congo. Total area is 27,830 km² and approximately 35.6% of the land is arable. The population was estimated in mid-2005 as approximately 8.1 million inhabitants (World Factbook, 2006). Agriculture occupies about 94% of the labor force.

The transportation network comprises 1,028 km of paved roads and 13,452 km of unpaved roads. There is one airport with a paved runway and seven airports with unpaved runways. Lake Tanganyika is essentially the only navigable waterway, and Bujumbura is the main port.

Over 97% of the rocks exposed in Burundi are Precambrian in age (Figure Burundi 1). Archean and early Proterozoic age hornblende-biotite gneisses, amphibolites, and quartzites occur in three complexes or areas—the Mugere Complex in the west, Yikuka in the south, and the Mugera in the east. Middle Proterozoic geosynclinial deposits underlie most of central and western Burundi. The metamorphosed sediments consist of phyllites, quartz-phyllites, graphitic schists, andalusite schists, and intercalations of dolomitic limestones. The Upper Proterozoic Malagarasian Sequence occurs in a narrow strip in the southeast of the country. This sequence consists of basal conglomerates, schists, quartzitic schists, and quartzites. Dolomitic limestones and several basalt flows are found within this sequence.

Tertiary and Quaternary lacustrine-fluviatile rift and basin-filling sediments are found in limited areas along the Nile River and in southwestern Burundi in basins extending inland from Lake Tanganyika.

Nitrogen Resources

Burundi has no identified resources of coal, natural gas, or oil. The state-owned Office National de la Tourbe produced and distributed peat for domestic consumption. Peat production was 4,643 tons in 2004 (Yager, 2004). Resources of peat are estimated at 35 million tons, most of which is located in the Atanyara Valley near Buyongwe. It is not known if this peat is suitable for gasification.

Phosphate Resources

The Matongo Deposit is the only significant phosphate deposit known in Burundi. The general features of the Matongo area, summarized from Tack et al. (1984), are discussed in the following paragraphs. The Matongo area is located within the Upper Ruvubu Plutonic Alkaline Complex (URPAC) (Figure Burundi 2). The magmas and fluids associated with this complex discordantly intruded various formations of Kibarian age (Burundian). The complex is bordered to the west by various types of metasediments—phyllites, metaquartzites, and interbedded metavolcanics. These metamorphic rocks of the green schist and amphibolite facies are part of an extensive belt of Burundian formations, which occupy most of the northwestern part of Burundi.

In the immediate vicinity of Kayanza, in the north and northeast of the URPAC, the Burundian sequence is intruded by a granitic batholith. The Kayanza Granite is calc-alkaline, tourmaline rich, slightly foliated, and generally porphoritic. The Rb-Sr dating method gave a l,330±30 Ma age for the granite. The URPAC is composed of three units:

1. An older unit in which rocks vary considerably in composition and texture.

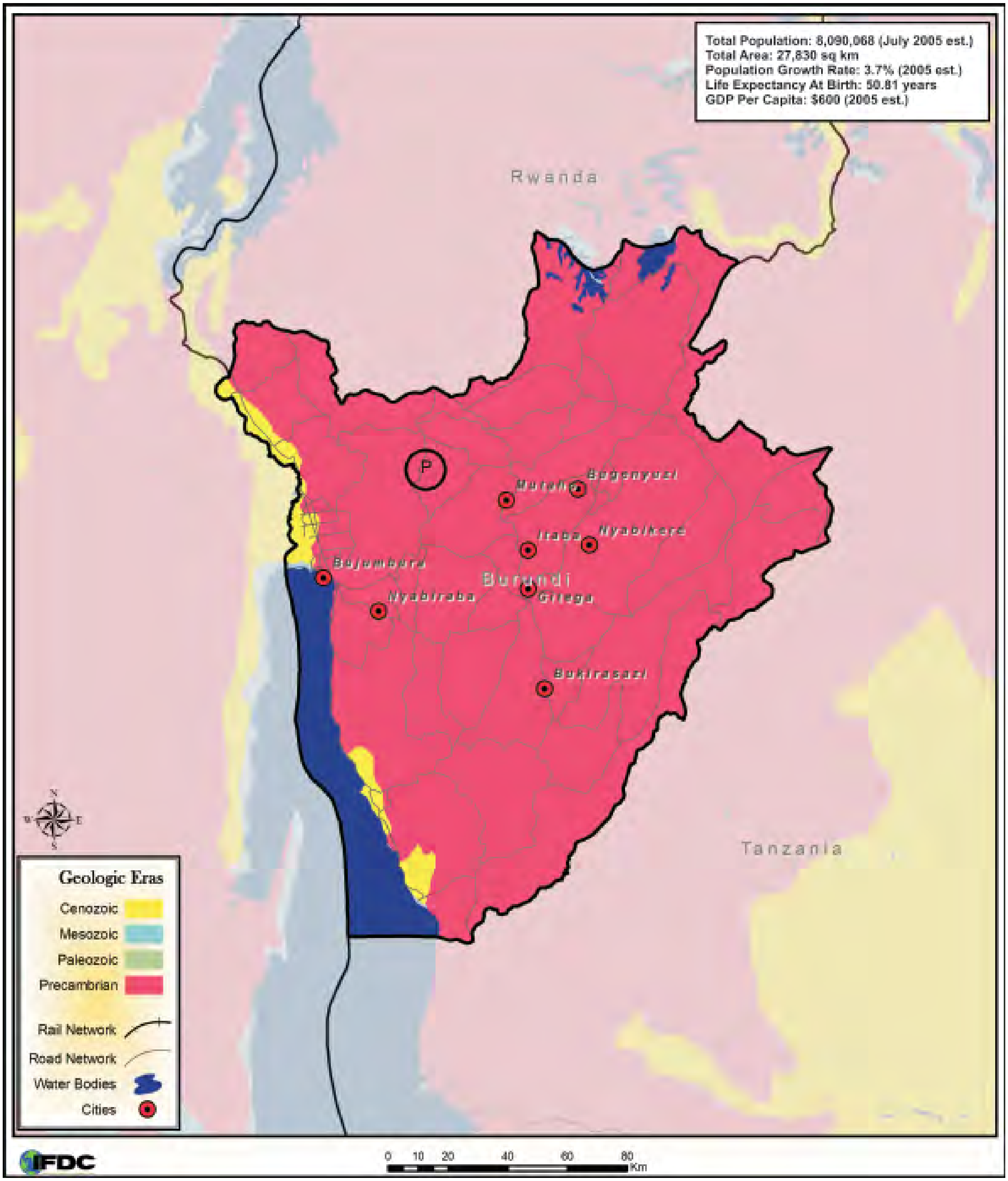


Figure Burundi 1. Geology, Major Cities, and Transportation Network

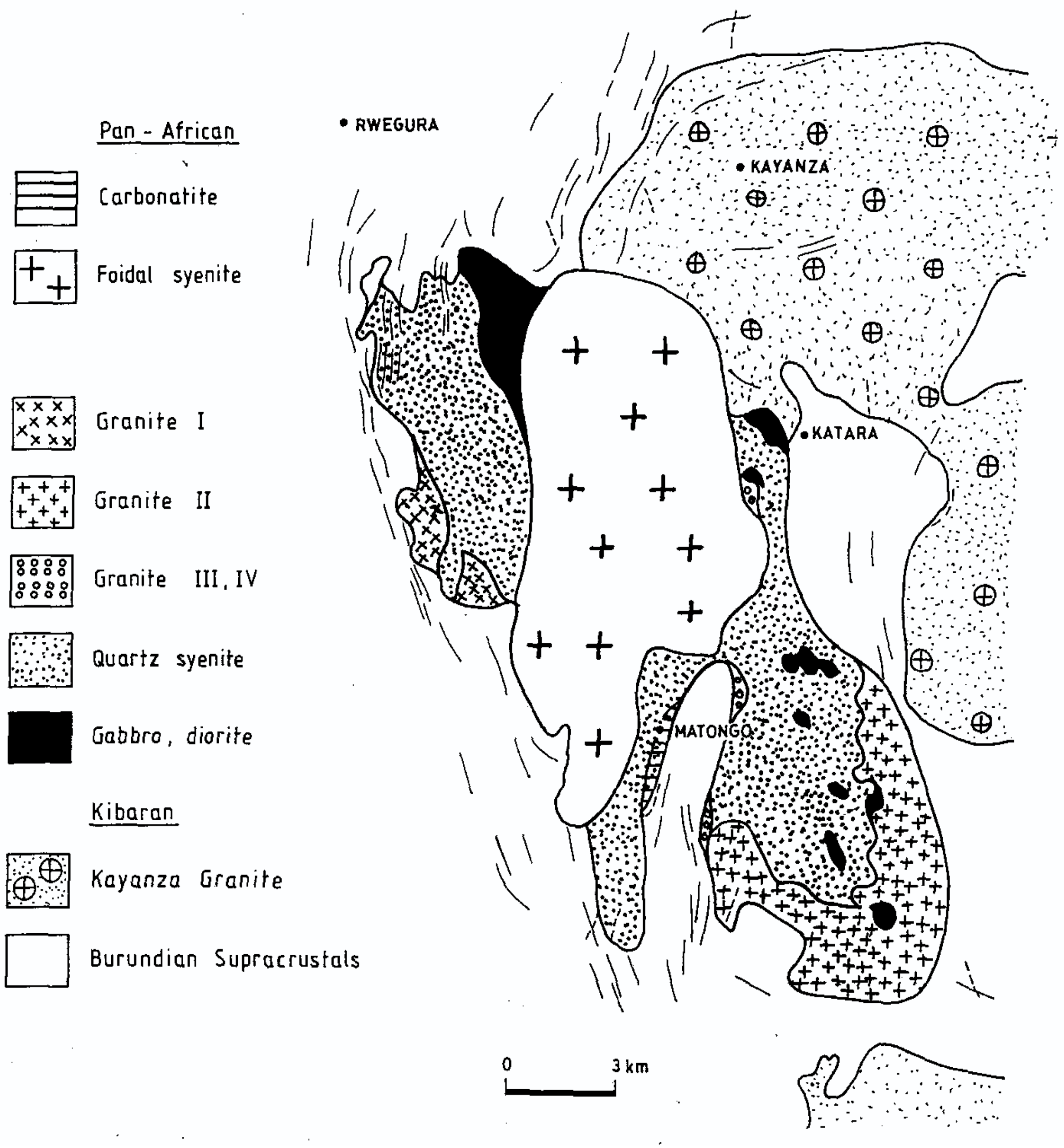


Figure Burundi 2. Geology of the Upper Ruvubu Alkaline Complex (Modified from Tack et al., 1984)

2. A central unit of younger foidal syenite.
3. A deep carbonatite intrusive body, known by drilling, which probably constitutes the most recent intrusive episode of the URPAC.

Structurally, the Kayanza Granite is an antiform, whereas the surrounding metasediments constitute a synform. The Burundian metasediments are characterized by an S1 foliation parallel to the S0 bedding of the original sediments. In the Kibarian granites and basic rocks, an S1 foliation is locally developed, systematically concordant with the S1 foliation of the sediments. These structures strike approximately north-south in the Matongo area.

The Matongo Deposit is located at the contact between the foidal syenite, forming the core of the URPAC with Burundian metasediments. Phosphate mineralization occurs within various types of altered metasediments. The metasediments are intruded by a carbonatite body that forms a narrow band (±0.30 x 2.5 km) striking approximately north-south. The phosphate mineralization generally occurs above and around the carbonatite body; therefore, the known extension of the carbonatite intrusion indicates the approximate boundaries of the phosphate deposit.

The Matongo Deposit was discovered by two aerial geophysical surveys performed in 1971 and 1975 by Hunting Geology and Geophysics Ltd. The 1971 survey was a helicopter-borne gamma ray spectrometry survey, which covered 5,500 km^2 that included the Matongo area. The main purpose of this survey was to locate areas of possible uranium (U) mineralization and supplement geological knowledge of the area. In 1975 Hunting Geology and Geophysics carried out a helicopter-borne gamma-ray spectrometry and proton magnetometry survey.

A project funded by the United Nations Development Programme (UNDP) followed up the aerial geophysical surveys with an extensive geochemical survey and field mapping. These surveys subsequently led to a drilling and trenching program.

During the geochemical survey, a considerable amount of soil sampling was carried out over an area of 1 km^2 at Matongo-Bandaga on approximately east-west traverses on a 300 m x 50 m grid. The soil samples were analyzed for U, P_2O_5, niobium, lead, molybdenum, and occasionally for copper, zinc, thorium, ruthenium, tungsten, gold, beryllium, and bismuth. The prospecting grid was subsequently tightened to 100 x 25 m over the anomalous area. A detailed (1/20,000 scale) geological map of the Matongo-Bandaga area was produced in 1977.

From April 1976 to August 1978, the UNDP program drilled 14 boreholes totaling 2,342 m and covering an area of 0.47 km^2. Twelve of the boreholes intersected phosphate zones. A scout hole, located 750 m south of the other boreholes, did not intersect phosphate mineralization. The 12 holes that intersected the phosphate zones were drilled along five profiles spaced from south to north as follows:

Profile	Number of Holes	Distance Between Holes	Distance to Next Profile
		(m)	
AA	3	60; 120	610
BB	2	Same location, 1 vertical, 1 inclined	160
CC	2	100	620
DD	1	–	300
EE	4	120, 60, 60, 60	–

Three trenches were excavated in the Matongo area during the UNDP program, all of which uncovered subsurface phosphate zones.

After the UNDP drilling campaign, detailed field mapping was undertaken in order to locate surficial phosphate, uranium, and carbonatite indications, and another 1/20,000-scale map of the area was produced in 1982. Geophysical work performed in the area in 1977 and 1978 included emanometry, scintillometry, gamma-ray spectrometry, and gamma borehole probes. Results from the emanometry, scintillometry, and spectrometry survey showed a strong radioactive anomaly in the region of the carbonatite. The resistivity survey showed the most distinctive and pronounced anomaly over the carbonatite with the highest resistivity readings where the carbonatite was later determined to be closest to the surface.

Following the UNDP study, a prefeasibility study was performed by the British Sulphur Corporation (British Sulphur Corporation Ltd., 1983). Twenty-five boreholes ranging from 60.86 to 228.29 m in depth and totaling 3,730.50 m were drilled from July 1982 to March 1983. The purpose of the British Sulphur study was to investigate the potential of the Matongo Deposit as a source of both phosphate ore and carbonate for fertilizer and cement production. For that reason boreholes were drilled far beyond reasonable depths for the potential open-pit mining of phosphate rock.

A program of trenching and pitting was carried out as part of the British Sulphur investigation. The three trenches previously excavated by the UNDP survey were cleaned out and resampled. Three new trenches were excavated to check rare earth and radiometric anomalies. An adit driven 10 m from an exposure on the main road at the south end of the area into a high-amplitude radiometric anomaly revealed an altered phosphate zone. Several pits to depths of about 6 m in the northern part of the deposit uncovered subsurface zones of highly altered phosphates.

After the British Sulphur study, the structure of the carbonatite intrusion, particularly its upper surface, remained unclear. Also, little had been done to investigate the hydrogeological characteristics of the deposit. For this purpose EKONO was contracted to supervise the drilling of six inclined boreholes, ranging from depths of 132.00 to 342.30 m, for structural investigations and two vertical boreholes for water pumping trials (EKONO, 1985). EKONO also reassessed the phosphate and carbonatite ore reserves. FORAKY (Belgium) carried out the drilling of 1,627.60 m of inclined and 250.40 m of vertical boreholes and hydrogeological investigations (FORAKY, 1985).

On the basis of all the previously mentioned studies, the rock types found at Matongo can be broadly divided into metasediments and intrusive rocks. Various types of schists and a clay occur in the deposit area. These schist facies vary considerably and randomly both laterally and vertically. The main types of schists can be described as follows:

1. Coarse micaschist with large mica flakes. It generally occurs near the surface where it is often weathered into a black, oxidized “crust.”
2. Yellowish, fine-grained schist with a slight schistosity.
3. Schistose rock with quartzo-feldspathic bands alternating with fine-grained micaceous bands. Locally, this type becomes more sandy. This sandy facies constitutes the best quality phosphate rock.
4. Green schist with a microfolded schistosity. The rock breaks easily into blocks following the schistosity. This feature makes it very unstable and thus difficult to excavate. A pinkish powder typical of this facies is produced by kaolinization of feldspars.
5. White compact clay, a distinctive rock type forming a narrow band striking north-south. Locally the compact clay shows a granular structure due to the presence of yellow or reddish pisoliths. The weathering of this clay has produced a high-quality clay deposit in the Inamvumvu Valley used for brickmaking. Phosphate mineralization has not been found in this lithology.

The main types of intrusive igneous rocks located in the Matongo area are carbonatite, syenite, and several types of breccias. Foid-bearing syenite occurs to the northwest of the deposit. Phosphate-rich syenite has been found within the deposit.

Varying levels of weathering have produced several types of breccia. Borehole FM-4 intersected breccia from 0.00 to 18.80 m and from 47.00 to 62.00 m. Trench TR-5 shows an intersection of similar breccia. The trench was 20 m long, 10 m high at one end, and 2 m high at the other end. The breccia is yellow, friable, and has brown oxidation “spots.” In Trench TR-5 the breccia has many microcavities with large, often fractured, feldspar crystals. The breccia is clayey in places and has inclusions of grey phyllites that are occasionally rich in sulfide minerals. The chemical composition of the breccia from Borehole FM-4 varies vertically as shown in the following table:

Depth	P_2O_5	CaO	Fe_2O_3	CaO/P_2O_5
(m)	(wt %)			
0.00–18.86	15.89	10.17	30.93	0.64
47.00–62.00	16.70	21.65	27.83	l.30

The CaO/P_2O_5 ratios indicate that the original apatite of the near-surface intersection is weathered to secondary phosphate minerals, whereas the deeper intersection has a CaO/P_2O_5 ratio near that of apatite (l.32).

Breccia found in Trench 8 (TR-8) and Pit 30 (P-30) has only been investigated near the surface where the chemical composition is similar to that of the FM-4/TR-5 breccia. However, TR-8 breccia is much harder and typically has a purplish color.

The breccia found in Borehole TS-6 is probably the ultimate stage of the weathering of the breccia. At TS-6 the breccia outcrops as a hard ferruginous “crust.” The chemical composition of the breccia in Borehole TS-6 is as follows:

Depth	P_2O_5	CaO	Al_2O_3	Fe_2O_3	CaO/P_2O_5
(m)	(wt %)				
3.30–6.40	20.60	6.01	27.8	18.9	0.29
6.40–9.00	20.70	5.96	28.3	19.5	0.28

Although the P_2O_5 content of the TS-6 breccia is above 20 wt %, the CaO/P_2O_5 ratios indicate that little of the phosphate could be present as apatite.

In May 1987 the Government of Burundi (GOB) signed a contract with IFDC to perform beneficiation and fertilizer manufacturing tests on the Matongo phosphate rock. The World Bank provided a loan to the GOB for this work. According to the contract, IFDC was to characterize several types of Matongo phosphate rock and, based on the results of these characterizations, select several sites where 30 tons of a representative sample could be excavated.

An IFDC geologist traveled to Burundi in February 1987 and sampled three sets of core samples that were provided by the Department of Geology (Figure Burundi 3). Based on the chemical and mineralogical analysis of 31 bulk samples and 70 partial analyses of screened size fractions of selected intervals of core samples from Boreholes TS-12, TS-11, and S-15, intervals from Borehole S-15 were considered the only samples suitable for beneficiation and eventual fertilizer manufacture (IFDC, 1988). Screened samples of phosphate-rich zones of Borehole TS-12 contained undesirable aluminophosphates in the size range that contained the bulk of the apatite (minus 1 mm plus 75 µm). Samples from Borehole TS-11 contained aluminophosphates and secondary carbonate-apatite (francolite) particles, which were not representative of the igneous apatite crystals of the deposit. Washed samples from Borehole S-15, at a depth of over 23 m, contained well-formed igneous apatite crystals in a suitable size range for beneficiation with a minimum of aluminophosphate contamination.

In August and September 1987, an IFDC geologist and mining engineer visited Burundi to select sites for collecting bulk samples. Pitting was already in progress at the sites of Boreholes TS-12 and TS-11. At this time, 19 samples from seven boreholes and trenches were collected, washed, and screened at minus 1 mm plus 75 µm and then petrographically and chemically analyzed (Figures Burundi 3, Burundi 4, and Burundi 5). On the basis of the previous analyses performed at IFDC and analyses performed in Burundi, sites at Boreholes S-15 and TS-6 and Trench TR-1 were selected to procure the bulk samples.

An adit driven in the wall of Trench TR-1 showed considerable variations in the grade and physical characteristics of the phosphate rock over short distances (<l m). Geologists from the Department of Geology did not consider the phosphate rock from Trench 1 representative of the deposit.

Two pits were dug at the site of Borehole S-16. Borehole data and data from washed borehole samples indicated significant phosphate mineralization at depths of 5-12 m. The initial pit at S-16 encountered significant water inflow at 4-5 m and collapsed at 10 m without intersecting significant phosphate mineralization. A second pit was dug (12 m depth) 8 m to the northeast of the borehole and failed to encounter significant phosphate mineralization.

A pit was not dug at Borehole S-15 due to the depth at which phosphate rock would be intersected (over 20 m). Approximately 100 m to the south, Pit TS-11 encountered water at 4 m, and water inflow and caving of the pit walls were a serious problem. Pitting at TS-11 was abandoned at a depth of over 8.5 m.

Figure Burundi 3. Core Sampling, Burundi Department of Geology, Bujumbura

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As a result of missions by IFDC personnel to Burundi, the following conclusions were drawn on the nature of the deposit:

1. The heterogeneity of the deposit was recognized. Structural controls of the phosphate mineralization could not be determined based on existing data. The phosphate rock occurs as very irregular bodies. The potentially economic phosphate mineralization was apparently related to the aureole of contact rocks rather than the intrusive carbonatite mass itself.
2. Portions of the deposit are highly weathered, especially near the surface. In some potential orebodies, the original igneous apatite crystals have been altered to undesirable and nonprocessable aluminophosphates (crandallite and wavellite). The phosphate of such zones may not be suitable for beneficiation by any means. The total P_2O_5 content of a given phosphate interval was not a reliable indicator of potentially recoverable apatite and resource potential of the deposit.
3. There was no one representative phosphate rock type at Matongo. There are several rock types and all variations between these rock types.
4. In some potential orebodies, apatite crystals occur in a natural size range (minus 1 mm plus $\cong$75 µm) that is readily processable by conventional means (washing, screening, flotation, and/or magnetic separation). Significantly, grinding of the run-of-mine (ROM) ore or washed ore would not be required to process the apatite that naturally occurred in this size range.
5. The hydrogeological characteristics of the area may have a profound influence on mine design. Water inflow and caving were serious problems during pitting. A comprehensive study of the shallow hydrogeologic characteristics of the area was recommended.

Figure Burundi 4. Pitting Operation, Matongo Deposit

Figure Burundi 5. Trench Intersecting an Apatite-Bearing Zone, Matongo Deposit

Realizing the heterogeneity and other complexities of the deposit, an IFDC geologist traveled to Burundi in February 1988 and outlined a program with the Department of Geology of the Ministry of Energy and Mines (MEM) to undertake a comprehensive augering, pitting, and trenching program that lasted from March 1988 to April 1989. The aim of the program was to locate potential orebodies near the surface and select sites to collect representative bulk phosphate rock samples for the IFDC test work.

The previously surveyed area was divided into three zones—the southern, central, and northern zones. In the southern zone, 16 closely spaced (20-25 m) auger holes ranging from 5 to 20 m in depth failed to discover any significant subsurface phosphate rock bodies. In the central and northern areas, a total of 30 holes were augered and 25 pits ranging from 7 to 23 m were excavated. Three trenches were also excavated in the northern zone. This survey confirmed the perceived heterogeneity of the deposit. Some of the near-surface phosphate zones were highly weathered, whereas others contained phosphate rock that was potentially processable.

Five sites corresponding to five different rock types were selected for sampling. One of the sample sites was eventually rejected.

As a result of the IFDC study (IFDC, 1990), a total of approximately 42.5 tons of raw Matongo ore was scrubbed and washed onsite producing 11.7 tons of preconcentrate, which was shipped to the United States and further beneficiated to produce 1.7 tons of 39.3 wt % P_2O_5 concentrate (Samples 1 and 2), 1 ton of 37.9 wt % P_2O_5 concentrate (Sample 3), and 0.2 ton of 40.7 wt % P_2O_5 concentrate (Sample 4).

Concurrent characterization studies of four ROM Matongo phosphate rock (Tables Burundi 1-4) and four attrition scrubbed and screened samples (Tables Burundi 5-8) (minus 1 mm plus 75 µm) determined the mineralogical residence of chemical constituents. The X-ray diffraction (XRD) analysis indicated the unit cell a-values ranged from 9.374Å to 9.385Å. The range of unit cell a-values indicates the phosphate rocks contain an almost pure fluorapatite to a fluorapatite variety with a minor amount of hydroxyl substitution.

With attrition scrubbing and screening, the apatite contents of the samples increased between 49.8% and 97.9% (Table Burundi 9). The feldspar contents of three samples were increased between 39.0% and 51.9% with attrition scrubbing and screening. The contents of undesirable aluminophosphates, clays and mica, and iron oxides were significantly reduced by attrition scrubbing and screening. In the original samples, 30% to 53% of the total P_2O_5 present was in the form of aluminophosphates. Aluminophosphate contents were decreased between 34.2% and 58.1% with attrition scrubbing and screening. Iron oxide contents of three samples were decreased as much as 57.4%. The iron oxide content of sample four actually increased 8.9%. With three samples, the clay and mica contents were reduced to nonquantifiable levels, and the clay and mica content of the fourth sample was reduced 77.7%.

Detailed laboratory and pilot plant beneficiation tests were conducted. The beneficiation processes used to produce the phosphate concentrates involved washing and sizing, attrition scrubbing and sizing, flotation, and magnetic separation. Three different beneficiation pilot plant configurations were used to prepare bulk concentrate samples. In order to produce concentrates suitable for single superphosphate (SSP) manufacture, all of the samples required treatment by flotation and magnetic separation. Even with these rather sophisticated types of beneficiation processes, all of the concentrates produced had low CaO/P_2O_5 ratios (1.24-1.27) (Table Burundi 10), indicating some of the phosphate present was not apatite ($CaO/P_2O_5 \cong 1.32\text{-}1.33$).

Relatively low NAC P_2O_5 solubility values (Table Burundi 10) are indicative of the nature of igneous apatite. Phosphate rocks with such low NAC P_2O_5 solubility analyses are not recommended for direct application.

The concentrates were processed into SSP by a process used at the SSP plant at Sukulu Hills, Uganda. This plant used a novel process with wet rock feed and undiluted sulfuric acid (98%) for acidulation. The most significant feature of this process is that the phosphate concentrate from the beneficiation plant does not require drying before

Table Burundi 1. Chemical Analyses and Approximate Mineralogical Modal Analysis, ROM Matongo Sample 1, Burundi

Chemical Analyses		Apatite[a]	Alumino-phosphates[b]	Fe-Oxides[c]	Feldspars[d]	Clay and Mica[e]	Unassigned
(wt %)							
P_2O_5	16.2	11.10	5.10				
CaO	15.8	14.56	1.03			0.20	0.01
F	1.0	1.0					
SiO_2	18.2				10.12	8.08	
Al_2O_3	11.4		5.5		2.88	3.02	
Fe_2O_3	23.8			23.12		0.68	
Na_2O	0.1					0.06	0.04
MgO	0.3					0.27	0.03
K_2O	3.3				2.64	0.66	
TiO_2	0.8					0.1	0.7
SrO	0.8		0.8				
BaO	1.5		1.5				
ZnO (ppm)	430						430
CuO (ppm)	20						20
MnO	1.1						1.1
Cr_2O_3 (ppm)	430						430
V_2O_5	0.4						0.4
NiO (ppm)	105						105
La_2O_3	0.2						0.2
CO_2	0.5						0.5
S	0.02						0.02
$C1^{-1}$ (ppm)	140						140
Free H_2O[f,g]	0.7						
LOI[f,h]	7.6						
	95.42	26.66	13.93	23.12	15.64	13.07	3.05
–O≡F[i]	0.42	0.42					
	95.0	26.24	13.93	23.12	15.64	13.07	3.05
+H_2O[j]	5.86		2.27	2.61		0.98	
	100.86	26.24	16.20	25.73	15.64	14.05	3.05

a. Fluorapatite composition.
b Crandallite group aluminophosphates.
c. Hematite and goethite as Fe_2O_3.
d. Potassium feldspar.
e. Illite and phlogopite composition.
f. Not included in totals.
g. Free H_2O = weight loss, 105°C, 1 h.
h. LOI = loss on ignition, weight loss, 1000°C, 1 h.
i. Fluorine correction, 2 F^- substitute for 1 O^{2-}.
j. Combined water in mineral structures, calculated.

Table Burundi 2. Chemical Analyses and Approximate Mineralogical Modal Analysis, ROM Matongo Sample 2, Burundi

Chemical Analyses		Apatite[a]	Alumino-phosphates[b]	Fe-Oxides[c]	Feldspars[d]	Clay and Mica[e]	Unassigned
				(wt %)			
P_2O_5	8.9	6.19	2.71				
CaO	9.0	8.12	0.51			0.37	
F	0.6	0.56					0.04
SiO_2	35.6				22.37	13.23	
Al_2O_3	14.9		2.92		6.36	4.3	1.32
Fe_2O_3	15.0			13.77		1.23	
Na_2O	0.1					0.1	
MgO	1.1					0.48	0.62
K_2O	7.1				5.84	1.19	0.07
TiO_2	0.6					0.19	0.41
SrO	0.5		0.5				
BaO	0.8		0.8				
ZnO (ppm)	235						235
CuO (ppm)	30						30
MnO	0.2						0.2
Cr_2O_3 (ppm)	640						640
V_2O_5	0.6						0.6
NiO (ppm)	150						150
La_2O_3	0.2						0.2
CO_2	0.2						0.2
S	0.03						0.03
$C1^{-1}$ (ppm)	160						160
Free H_2O[f,g]	1.0						
LOI[f,h]	5.4						
	95.43	14.87	7.44	13.77	34.57	21.09	3.69
–O≡F[i]	0.25	0.23					0.02
	95.18	14.64	7.44	13.77	34.57	21.09	3.67
+H_2O[j]	3.62		1.2	1.07		1.35	
	98.80	14.64	8.64	14.84	34.57	22.44	3.67

a. Fluorapatite composition.
b. Crandallite group aluminophosphates.
c. Hematite and goethite as Fe_2O_3.
d. Potassium feldspar.
e. Illite and phlogopite composition.
f. Not included in totals.
g. Free H_2O = weight loss, 105°C, 1 h.
h. LOI = loss on ignition, weight loss, 1000°C, 1 h.
i. Fluorine correction, 2 F^- substitute for 1 O^{2-}.
j. Combined water in mineral structures, calculated.

Table Burundi 3. Chemical Analyses and Approximate Mineralogical Modal Analysis, ROM Matongo Sample 3, Burundi

Chemical Analyses		Apatite[a]	Alumino-phosphates[b]	Fe-Oxides[c]	Feldspars[d]	Quartz (SiO_2)	Clay and Mica[e]	Unassigned
				(wt %)				
P_2O_5	22.3	14.17	8.12					0.01
CaO	18.7	18.60					0.1	
F	1.2	1.2						
SiO_2	9.0				3.33	1.98	3.69	
Al_2O_3	10.9		8.75		0.95		1.2	
Fe_2O_3	25.0			24.66			0.34	
Na_2O	0.1						0.03	0.07
MgO	0.3						0.13	0.17
K_2O	1.2				0.87		0.33	
TiO_2	0.9		0.9				0.05	0.85
SrO	0.9		0.9					
BaO	1.2		1.2					
ZnO (ppm)	170							170
CuO (ppm)	20							20
MnO	0.05							0.05
Cr_2O_3 (ppm)	430							430
V_2O_5	0.6							0.6
U_3O_8 (ppm)	310							310
NiO (ppm)	80							80
La_2O_3	0.2							0.2
CO_2	0.2							0.2
S	0.08							0.08
C1^{-1} (ppm)	150							150
Free H_2O[f,g]	1.3							
LOI[f,h]	9.6							
	93.03	33.97	18.97	24.66	5.15	1.98	5.87	2.43
–O≡F[i]	0.51	0.51						
	92.52	33.46	18.97	24.66	5.15	1.98	5.87	2.43
+H_2O[j]	7.75		5.59	1.78			0.38	
	100.27	33.46	24.56	26.44	5.15	1.98	6.25	2.43

a. Fluorapatite composition.
b. Crandallite group aluminophosphates.
c. Hematite and goethite as Fe_2O_3.
d. Potassium feldspar.
e. Illite and phlogopite composition.
f. Not included in totals.
g. Free H_2O = weight loss, 105°C, 1 h.
h. LOI = loss on ignition, weight loss, 1000°C, 1 h.
i. Fluorine correction, 2 F^- substitute for 1 O^{2-}.
j. Combined water in mineral structures, calculated.

Table Burundi 4. Chemical Analyses and Approximate Mineralogical Modal Analysis, ROM Matongo Sample 4, Burundi

Chemical Analyses		Apatite[a]	Alumino-phosphates[b]	Fe-Oxides[c]	Feldspars[d]	Quartz (SiO_2)	Clay and Mica[e]	Unassigned
					(wt %)			
P_2O_5	22.0	10.37	11.63					
CaO	15.4	13.6	1.72				0.08	
F	0.9	0.9						
SiO_2	8.6				0.97	4.88	2.75	
Al_2O_3	13.7		12.53		0.28		0.89	
Fe_2O_3	26.2			25.94			0.26	
Na_2O	0.1						0.02	0.08
MgO	0.1						0.10	
K_2O	0.5				0.25		0.25	
TiO_2	0.4						0.04	0.36
SrO	1.2		1.2					
BaO	1.3		1.3					
ZnO (ppm)	220							220
CuO (ppm)	25							25
MnO (ppm)	700							700
Cr_2O_3 (ppm)	625							625
V_2O_5	0.9							0.9
U_3O_8 (ppm)	190							190
NiO (ppm)	60							60
La_2O_3	0.4							0.4
CO_2	0.3							0.3
S	0.03							0.03
$C1^{-1}$ (ppm)	250							250
Free H_2O[f,g]	1.1							
LOI[f,h]	10.8							
	92.00	24.87	28.38	25.94	1.31	4.88	4.39	2.04
–O≡F[i]	0.38	0.38						
	91.62	24.49	28.38	25.94	1.31	4.88	4.39	2.04
+H_2O[j]	9.13	0.03	6.68	2.14			0.28	
	100.75	24.52	35.06	28.08	1.31	4.88	4.67	2.04

a. Fluorapatite composition.
b. Crandallite group aluminophosphates.
c. Hematite and goethite as Fe_2O_3.
d. Potassium feldspar.
e. Illite and phlogopite composition.
f. Not included in totals.
g. Free H_2O = weight loss, 105°C, 1 h.
h. LOI = loss on ignition, weight loss, 1000°C, 1 h.
i. Fluorine correction, 2 F^- substitute for 1 O^{2-}.
j. Combined water in mineral structures, calculated.

Table Burundi 5. Chemical Analyses and Approximate Mineralogical Modal Analysis, Washed Matongo Sample 1, Burundi

Chemical Analyses		Apatite[a]	Alumino-phosphates[b]	Fe-Oxides[c]	Feldspars[d]	Clay and Mica[e]	Unassigned
(wt %)							
P_2O_5	24.2	21.43	2.43				0.34
CaO	29.1	28.14	0.96				
F	1.9	1.9					
SiO_2	17.3				15.42	1.88	
TiO_2	0.6						0.6
Al_2O_3	7.0		2.61		4.39		
Fe_2O_3	12.6			12.6			
Na_2O	0.1						0.1
MgO	0.2						0.2
K_2O	3.9				3.9		
CO_2	0.2						0.2
$C1^{-1}$ (ppm)	50						50
LOI[f,g]	2.5						
	97.10	51.47	6.00	12.6	23.71	1.88	1.44
–O≡F[h]	0.80	0.80					
	96.3	50.67	6.00	12.6	23.71	1.88	1.44
$+H_2O$[i]	2.52	0.02	1.08	1.42			
	98.82	50.69	7.08	14.02	23.71	1.88	1.44

a. Fluorapatite composition.
b. Crandallite group aluminophosphates.
c. Hematite and goethite as Fe_2O_3.
d. Potassium feldspar.
e. Illite and phlogopite composition.
f. Not included in totals.
g. LOI = loss on ignition, weight loss, 1000°C, 1 h.
h. Fluorine correction, 2 F^- substitute for 1 O^{2-}.
i. Combined water in mineral structures, calculated.

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further processing. Due to the poor setting characteristics of the acidulated Matongo concentrates, the addition of potassium chloride (KCl) was required to produce SSP with suitable processing and physical characteristics. A partially acidulated phosphate rock (PAPR) product could not be produced with wet rock feed and strong sulfuric acid because of an unfavorable water balance. PAPR was produced by granulating run-of-pile (ROP)-SSP with 75% solids concentrate slurry.

The quality of the SSP produced from the Matongo concentrates under these conditions was similar to that of SSP from Araxa phosphate rock (igneous), which is used commercially in Brazil. The grade of Burundi SSP was 0-22.5-0 while the grade of Araxa SSP is 0-22-0. The water-soluble P_2O_5 content of the Matongo ROP-SSP, after a 21-day curing period, was 18.2 wt % P_2O_5, and the available P_2O_5 was 90.3% of total P_2O_5. The grade of the PAPR produced from the 75% concentrate slurry was 0-28.2-0, and the available P_2O_5 was 51.8% of the total P_2O_5.

Because the phosphate ore reserves at Matongo have not been delineated with adequate prospecting, it was necessary to assume that the bulk samples selected by the Department of Geology and utilized by IFDC to produce the fertilizer products for a preliminary prefeasibility study were representative

Table Burundi 6. Chemical Analyses and Approximate Mineralogical Modal Analysis, Washed Matongo Sample 2, Burundi

Chemical Analyses		Apatite[a]	Alumino-phosphates[b]	Fe-Oxides[c]	Feldspars[d]	Clay and Mica[e]	Quartz (SiO_2)	Unassigned
					(wt %)			
P_2O_5	13.9	12.24	1.66					
CaO	16.8	16.07	0.65				0.08	
F	1.1	1.1						
SiO_2	35.8				31.15	1.71	2.94	
TiO_2	1.5						0.04	1.46
Al_2O_3	11.6		1.79		8.85		0.96	
Fe_2O_3	6.4			6.13			0.27	
Na_2O	0.1						0.02	0.08
MgO	0.7						0.11	0.59
K_2O	8.4				8.14		0.26	
CO_2	0.3							0.3
$\mathrm{C1}^{-1}$ (ppm)	75							75
LOI[f,g]	1.4							
	96.60	29.41	4.10	6.13	48.14	1.71	4.68	2.43
–O≡F[h]	0.46	0.46						
	96.14	28.95	4.10	6.13	48.14	1.71	4.68	2.43
$+H_2O$[i]	1.26		0.74	0.22			0.30	
	97.40	28.95	4.84	6.35	48.14	1.71	4.98	2.43

a. Fluorapatite composition.
b. Crandallite group aluminophosphates.
c. Hematite and goethite as Fe_2O_3.
d. Potassium feldspar.
e. Illite and phlogopite composition.
f. Not included in totals.
g. LOI = loss on ignition, weight loss, 1000°C, 1 h.
h. Fluorine correction, 2 F^- substitute for 1 O^{2-}.
i. Combined water in mineral structures, calculated.

of ores that will be mined at Matongo in the future (IFDC, 1990). Inspection of prospect logs and other data indicated ores of similar quality and character at Matongo, but the deposit was quite unpredictable because of the sporadic mineralization. Therefore, the term "preliminary prefeasibility study" was used.

The total fixed capital cost estimate for a manufacturing complex at Matongo that can produce 24,000 tpy of ROP-SSP or granular SSP, or 20,692 tpy granular PAPR-50 was US $24,528,000 (Table Burundi 11). This cost includes the mine, processing units, power, highway relocation, and infrastructure. In order to keep costs as low as possible, the mine was not mechanized other than use of a conveyor system to the beneficiation plant. Hand labor was assumed to actually mine the ore.

The lowest cost fertilizer that can be produced at Matongo, using the premises assumed and conditions imposed on the study, was ROP-SSP. Using a totally subsidized scheme (capital costs equal sunk cost), the manufacturing cost per ton of ROP-SSP would be US $170.67 and US $147.51 at 90% utilization of 24,000-tpy and 48,000-tpy capacities, respectively (Table Burundi 12). Using a commer-

Table Burundi 7. Chemical Analyses and Approximate Mineralogical Modal Analysis, Washed Matongo Sample 3, Burundi

Chemical Analyses		Apatite[a]	Alumino-phosphates[b]	Fe-Oxides[c]	Feldspars[d]	Quartz (SiO_2)	Unassigned
(wt %)							
P_2O_5	29.1	24.92	3.61				0.57
CaO	32.7	32.7					
F	2.2	2.2					
SiO_2	7.8				4.98	2.82	
TiO_2	0.4						0.4
Al_2O_3	5.3		3.88		1.42		
Fe_2O_3	15.7			15.7			
Na_2O	0.1						0.1
MgO	0.2						0.2
K_2O	1.3				1.3		
CO_2	0.2						0.2
$C1^{-1}$ (ppm)	45						45
LOI[e,f]	3.7						
	95.0	59.82	7.49	15.7	7.7	2.82	1.47
–O≡F[g]	0.93	0.93					
	94.07	58.89	7.49	15.7	7.7	2.82	1.47
$+H_2O$[h]	3.63	0.03	2.84	0.76			
	97.70	58.92	10.33	16.46	7.7	2.82	1.47

a. Fluorapatite composition.
b. Crandallite group aluminophosphates.
c. Hematite and goethite as Fe_2O_3.
d. Potassium feldspar.
e. Not included in totals.
f. LOI = loss on ignition, weight loss, 1000°C, 1 h.
g. Fluorine correction, 2 F^- substitute for 1 O^{2-}.
h. Combined water in mineral structures, calculated.

cially financed scheme at 10% interest with a 15-year plant life, the cost per ton of ROP-SSP was estimated to be US $287.84 and US $248.15 at 90% utilization of 24,000-tpy and 48,000-tpy capacities, respectively.

The option of granulation of ROP-SSP added production costs. Under a totally subsidized scheme, the cost per ton of granular SSP would be US $208.23 and US $185.07 at 90% utilization of 24,000-tpy and 48,000-tpy capacities, respectively. Under a commercially financed scheme, the manufacturing cost per ton of granular SSP would be US $355.63 and US $315.98 at 90% utilization of 24,000-tpy and 48,000-tpy capacities, respectively.

The capacity of the entire plant would be reduced if it is used to manufacture granular PAPR-50. The total capacity of the mine, beneficiation plant, and rock grinding and slurry preparation section was 14,851 tpy of concentrate. From this total about 44% of the concentrate was used to produce 12,375 tons of ROP-SSP, and the remaining 8,317 tons of concentrate was fed directly to the SSP-PAPR granulation unit. Therefore, the total capacity of PAPR-50 was 20,692 tpy versus

Table Burundi 8. Chemical Analyses and Approximate Mineralogical Modal Analysis, Washed Matongo Sample 4, Burundi

Chemical Analyses		Apatite[a]	Alumino-phosphates[b]	Fe-Oxides[c]	Feldspars[d]	Quartz (SiO_2)	Unassigned
				(wt %)			
P_2O_5	23.7	15.54	8.61				
CaO	21.6	20.39	1.21				
F	1.6	1.4					0.2
SiO_2	6.0				0.38	5.62	
TiO_2	2.0						2.0
Al_2O_3	8.9		8.79		0.11		
Fe_2O_3	28.6			28.6			
Na_2O	0.1						0.1
MgO	0.2						0.2
K_2O	0.1				0.1		
CO_2	0.3						0.3
C1^{-1} (ppm)	50						50
LOI[e,f]	7.0						
	93.1	37.33	18.16	28.6	0.59	5.62	2.80
–O≡F[g]	0.67	0.59					0.08
	92.43	36.74	18.16	28.6	0.59	5.62	2.72
+H_2O[h]	6.89		4.92	1.97			
	99.32	36.74	23.08	30.57	0.59	5.62	2.72

a. Fluorapatite composition.
b. Crandallite group aluminophosphates.
c. Hematite and goethite as Fe_2O_3.
d. Potassium feldspar.
e. Not included in totals.
f. LOI = loss on ignition, weight loss, 1000°C, 1 h.
g. Fluorine correction, 2 F^- substitute for 1 O^{2-}.
h. Combined water in mineral structures, calculated.

Table Burundi 9. Summary of Mineralogical Characteristics of ROM and Washed Matongo Samples 1–4, Burundi

	Apatite	Alumino-phosphates	Fe-Oxides	Feldspars	Clays and Micas	Quartz (SiO_2)
ROM Sample 1, wt %	26.2	16.2	25.7	15.6	14.0	
Washed Sample 1, wt %	50.7	7.1	14.0	23.7		1.9
Increase/decrease with washing, %	+93.5	–56.2	–45.5	+51.9		
ROM Sample 2, wt %	14.6	8.6	14.8	34.6	22.4	
Washed Sample 2, wt %	28.9	4.8	6.3	48.1	5.0	1.7
Increase/decrease with washing, %	+97.9	–44.2	–57.4	+39.0	–77.7	
ROM Sample 3, wt %	33.5	24.6	26.4	5.1	6.2	2.0
Washed Sample 3, wt %	58.9	10.3	16.5	7.7		2.8
Increase/decrease with washing, %	+75.8	–58.1	–37.5	+51.0		+40.0
ROM Sample 4, wt %	24.5	35.1	28.1	1.3	4.7	4.9
Washed Sample 4, wt %	36.7	23.1	30.6	0.6		5.6
Increase/decrease with washing, %	+49.8	–34.2	+8.9	–53.8		+14.3

Table Burundi 10. Chemical Analyses of the Ground Phosphate Concentrates of Matongo Phosphate Ores

Ingredients	Sample 1[a]	Sample 2[a]	Sample 3[b]	Sample 4[b]
	(wt %)			
P_2O_5	38.2	38.6	38.2	40.3
NAC soluble P_2O_5[c]	1.6	1.7	1.4	2.4
CaO	47.3	48.6	47.8	51.1
Fe_2O_3	3.0	2.3	1.0	0.7
Al_2O_3	1.8	1.4	2.2	1.2
MgO	0.4	0.3	<0.1	<0.1
SiO_2	3.0	3.2	4.1	1.1
Na_2O	0.3	1.1	0.2	0.2
K_2O	0.6	0.7	0.8	0.2
F	3.1	3.1	3.3	3.4
Cl[d]	60.0	60.0	30.0	30.0
Organic	0.1	0.1	0.1	0.1
CO_2	0.3	0.1	0.3	0.4
LOI[e]	21.9	21.7	2.5	1.1
Oven H_2O	21.1	21.3	0.1	0.1
CaO/P_2O_5 weight ratio	1.24	1.26	1.25	1.27
NAC P_2O_5	1.6	1.7	1.4	2.4

a. Wet ground in a rod mill to 70% by weight passing 0.045-mm screen opening.
b. Dry ground in a Patterson ball mill with ceramic balls to 70% by weight passing 0.075-mm screen opening.
c. By definition of the Association of Official Analytical Chemists, the neutral ammonium citrate (NAC) soluble phosphorus is the phosphorus that is soluble after extraction of 1 g of material with 250 mL of water and subsequently with 100 mL of NAC.
d. Expressed as parts per million (ppm).
e. Loss on ignition.

24,000 tpy as an SSP plant. The capacity of PAPR-50 in the 48,000-tpy SSP plant was 41,384 tpy.

Under a totally subsidized scheme, the manufacturing cost per ton of PAPR-50 would be US $194.46 and US $164.10 at capacities of 20,692 tpy and 41,384 tpy, respectively (Table Burundi 12). Under the commercially financed scheme, the manufacturing cost of PAPR-50 per ton would be US $348.38 and US $300.77 at capacities of 20,692 tpy and 41,384 tpy, respectively.

Table Burundi 11. Matongo, Burundi, Total Capital Cost—Estimate Summary Commercially Financed[a]

Item	US $ x 1,000
Mine	481
Scrubbing and sizing	1,865
Flotation	695
Magnetic separation	2,033
Sulfuric acid plant	2,900
Rock grinding, slurry preparation and ROP-SSP plant	9,364
SSP granulation plant	4,954
Power	1,108
Highway	400
Infrastructure	728
Total Capital Cost	**24,528**

a. All items include interest during construction, 1990 U.S. dollars.

Table Burundi 12. Summary of Manufacturing Costs for ROP-SSP and Granular SSP at 24,000 tpy and 48,000 tpy Total Capacities and Granular PAPR-50 at 20,692 tpy and 41,384 tpy Capacities Using Totally Subsidized and Commercially Financed Schemes[a,b,c]

	24,000 tpy	48,000 tpy
	(cost/ton, US $)	
ROP-SSP		
Totally subsidized	170.67	147.51
Commercially financed	287.84	248.15
Granular SSP		
Totally subsidized	208.23	185.07
Commercially financed	355.63	315.98
	20,692 tpy	41,384 tpy
	(cost/ton, US $)	
Granular PAPR		
Totally subsidized	194.46	164.10
Commercially financed	348.38	300.77

a. ROP-SSP and granular SSP calculated at 90% of total capacities.
b. PAPR-50 capacity at 100% of mine, beneficiation plant, and rock-grinding and slurry-preparation section.
c. All costs in 1990 U.S. dollars.

Discounted cash flow analyses were performed for the production of ROP-SSP and granular SSP based on the capital and manufacturing cost estimates and a 15-year market projection. In order to realize a 10% internal rate-of-return (IRR) for the project, ROP-SSP must be sold at the equivalent of US $320/ton over the 15-year life of the project at the level of market projections. In order to realize a 10% IRR for the project, granular SSP must be sold at the equivalent of US $400 for the 15-year life of the project at the level of market projections.

At the time of the study it was estimated that granular triple superphosphate (TSP) (46% P_2O_5) could be imported to Matongo for approximately US $300/ton. On a P_2O_5 unit basis, ROP-SSP produced locally at Matongo and sold for US $320/ton (22% P_2O_5) would be about 122% more expensive (more than double the cost) than imported granular TSP.

It was estimated that ROP-SSP (18% P_2O_5) could be imported to Matongo for US $231/ton. On a P_2O_5 unit basis, ROP-SSP produced at Matongo and sold for US $320/ton (22% P_2O_5) would be about 12% more expensive than imported ROP-SSP. Although the economics of the production of Matongo ROP-SSP or granular SSP are not favorable when compared with imported high-analysis phosphate products, the production of ROP-SSP at Matongo appeared to be approaching economic viability when compared to the importation of ROP-SSP. The study concluded that in a subsequent detailed feasibility study, it may be possible to reduce capital and manufacturing costs whereby the costs of producing ROP-SSP at Matongo are comparable to the cost of importing ROP-SSP.

IFDC recommended that the Matongo Deposit should be explored in detail to further identify and quantify the various types of ore and the physical distribution of orebodies in the deposit. Detailed mining plans could only be made when the quality, quantity, and physical distribution of orebodies were relatively well known. Samples from this exploration effort should be bench-scale processed to produce apatite concentrates. Bench-scale processing data would give an indication of the ratios of concentration to be expected in processing the ore and help to determine the design of a beneficiation plant. Based on the results of further exploration, one or more large unwashed ore samples should be subjected to the entire beneficiation sequence in pilot-plant scale. Detailed chemical analysis of concentrates produced by bench-scale and pilot-scale processing would provide an indication as to the amenability of the reserves for the production of fertilizers and details for the final design of fertilizer product facilities.

IFDC also indicated that further hydrological investigations should be conducted to accurately assess the quantity of water inflow to be expected in developing an open-pit mine, relative to increases in mine pit depth. Tests completed by FORAKY could provide a good basis from which to proceed, but assessment at shallow depths and within each minable area of the deposit was deemed essential.

The rock-grinding and slurry-preparation circuit in the conceptual SSP plant design (included in the IFDC report) would require testing to arrive at a suitable combination of equipment and configuration to ensure the supply of 75% solids rock slurry to the acidulation step. In the conceptual Matonga SSP plant design, a centrifuge and batch-mixing tanks were considered. In the SSP plant at Sukulu Hills, hydrocyclones were used to dewater wet-ground concentrate prior to acidulation. Limited data indicate that these hydrocyclones did not perform satisfactorily, and apparently the dryer in the SSP plant in Uganda was used to remove excess water.

IFDC recommended that, when the various uncertainties of mining Matongo phosphate rock, beneficiation requirements, and processing options were resolved, the next feasibility study should reassess capital and manufacturing costs in greater detail. A detailed discounted cash flow analysis should be performed on the basis of this information. An environmental impact study for the mining of Matongo ore and converting it to fertilizer should be included in the next study.

The Matongo phosphate ore reserves were calculated successively by the UNDP, British Sulphur, and EKONO studies. An assessment of potential minable reserves was made on the basis of the Department of Geology survey exploration program.

The reserve calculation by UNDP was based on the total P_2O_5 content of samples from a total of 12 boreholes located on five profiles. Because of the wide spacing of the boreholes (60-120 m between boreholes; 160-620 m between profiles), the reserves calculated were considered probable. The reserves were calculated by the conventional cross-sectional method at a 7% P_2O_5 cutoff grade using an empiric specific gravity of 2.5. A total of about 5.0 million tons of ore with an average P_2O_5 content of 13% was estimated.

British Sulphur defined an area of probable and possible ore reserves in the northern part of the deposit where most of the drilling took place. The ore reserves were calculated by assuming horizontal continuity of phosphate zones between widely spaced boreholes and using geostatistical methods. The British Sulphur estimate, similar to the UNDP estimate, was based on the total P_2O_5 content. For all phosphate intersections ≥l.5 m in thickness from the top to the bottom of each borehole, ore reserves were calculated as follows:

Cutoff Grade	Estimated Total Tonnage	Average P_2O_5 Content
Cross-Sectional Method (Probable + Possible)		
7%	9,297,175	13.3%
5%	13,716,350	11.5%
Geostatistical Calculation		
7%	13.2 million	12.6%
5%	17.3 million	11.0%

In addition to the l,878 m of boreholes drilled under their supervision, EKONO based their reserve calculation on British Sulphur's boreholes. The geostatistical method used by EKONO indicated a total of 9.71 million tons of ore with an average of 9.32% P_2O_5 at a cutoff grade of >5% P_2O_5.

An assessment of potential minable phosphate ore reserves was presented in a technical report by Songore and Nahigombeye (1989). Based on 11 deep boreholes from the British Sulphur and EKONO survey and 14 shallow pits of the Department of Geology survey, two potential ore-bearing areas were delineated—the northern area and the central area. These two potential orebodies cover an area of approximately 0.082 km^2.

The main criteria used to restrict the extent of the potential orebodies were a maximum mining depth of 40 m and a stripping ratio of ≤2.5. Due to a lack of data, assumptions had to be made regarding the vertical and horizontal continuity of phosphate zones. The Department of Geology estimate was based on the amount of recoverable apatite, using the ratio of concentration of the ore developed by IFDC beneficiation test work (5:1). Using these criteria, the resulting reserves are calculated as 3,167,387 tons of ore, which contains 633,500 tons of recoverable apatite concentrate. The overall stripping ratio was determined to be 0.6.

Following the IFDC study, the Ministry of Energy and Mines contracted McKay and Schnellmann to perform a feasibility study (McKay and Schnellmann, 1993). McKay and Schnellmann reviewed previous work and performed three phases of exploratory drilling. The drilling program was completed in February 1993; 84 boreholes were drilled for a total of 3,935.34 m. The initial phase of drilling focused on the central zone of the deposit where previous work indicated the most potential for reserves near the surface. The second phase was performed to define the southern and western limits of the central zone. After the results of the first two phases indicated that the potential reserves in the central zone would be insufficient for industrial development, drilling was continued in the southern and northern zones.

On the basis of the drilling program and previous investigations, a model of structural controls on phosphate mineralization was developed. It was theorized that during early stages of deformation carbonate and phosphate rocks were emplaced in elongate or platey pods and lenses primarily confined to a layer in a 45° southeast-dipping deformation zone. Continuing thrust movement toward the northwest gave rise to anticlinal stacking on fold hinges. Apatitic fluids and other fluids circulated and infilled areas of low fluid pressure in the fold hinges. During the later stages of formation, fault zones appear to have remained active, giving rise to deformation, fracturing, and brecciation of earlier formed deposits.

The area of rich phosphate mineralization in the northern zone was interpreted as a complex anticlinal dome formed by anticlinal stacking in a thrust zone.

It appears there was an anticlinal stacking feature in the central zone, but it was largely eroded. Phosphate values in the southern area did not exceed values considered background for the shear zone, and detailed investigations were not considered any further for this area. McKay and Schnellmann (1993) performed limited laboratory-scale batch beneficiation tests.

The results of the McKay and Schnellmann study indicated that insufficient high-grade material was present to support a superphosphate plant (Songore, 1996). As a result of the McKay and Schnellmann study, further exploration efforts in the Matongo area for phosphate were discontinued (Songore, 1997, Personal Communication).

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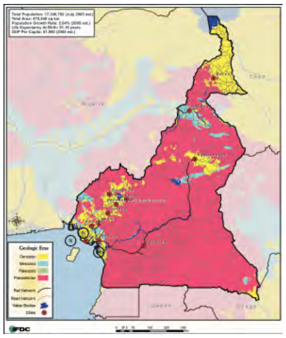
CAMEROON



The Republic of Cameroon (Figure Cameroon 1) is bordered by Nigeria to the north and west; Chad to the north and east; the Central African Republic to the east; the Republic of the Congo, Gabon, and Equatorial Guinea to the south; and the Atlantic Ocean to the west. Total area is 475,440 km^2 and arable land is approximately 12.5% of the total. The population was estimated at 17.3 million inhabitants in mid-2005 (World Factbook, 2006). Agriculture occupies approximately 70% of the labor force.

The transportation network comprises 5,398 km of paved roads, 75,534 km of unpaved roads, and 1,008 km of 1.0-m-gauge railway. There are 11 airports with paved runways and 36 airports with unpaved runways. Navigation on the Benue River is limited to the rainy season. Douala and Simboh Terminal are the main ports. There is a 90-km gas pipeline, a 9-km liquid petroleum line, and 1,120 km of oil pipeline from Chad.

Precambrian rocks outcrop over much of the country and mainly consist of schists, gneisses, amphibolites, quartzites, and migmatites. The Middle Proterozoic can be divided into a metamorphic sequence and a less metamorphosed volcano-sedimentary sequence. Upper Proterozoic rocks consisting of sandstones and limestones outcrop in southeastern Cameroon. There are no known occurrences of Paleozoic rocks in Cameroon.

Cretaceous age sediments unconformably overlie Precambrian rock. In northern Cameroon fluvio-continental sandstone, conglomerates, and mudstones are intercalated with marine marls and limestones. The Cretaceous sequence in the Coastal Basin begins with conglomerates and sandstones that are overlain by marls and limestones deposited in marine environments. Continental Tertiary sediments predominate at the surface onshore. A zone of volcanics transverses Cameroon with a northeasterly trend. Quarternary clastic sediments predominate to the south of Lake Chad. Offshore Cameroon, and in the northwestern coastal area, is the prograding Niger Delta sequence with rocks and sediments that range in age from the Upper Cretaceous to the Pleistocene.

Nitrogen Resources

The Republic of Cameroon is the sixth largest oil producer in sub-Saharan Africa (EIA, 2004). Reserves are located offshore in the Rio del Rey Basin (Niger Delta), offshore and onshore in the Douala/Kribi-Comp basins, and onshore in the northern part of the country in the Logone-Birni Basin. Most of the offshore oil and gas is found in Upper Miocene to Pliocene age sands (Bruso et al., 2004).

The Ministry of Energy and Mines regulates the oil industry through the Société Nationale des Hydrocarbures (SNH). In 2004 Cameroon produced about 35 million barrels of oil (Bermúdez-Lugo, 2004). Total Exploration and Production Cameroon and Pecten Cameroon Co. are the major operating companies. Oil is produced from 21 oil fields. All the production is exported. Petroleum reserves are indicated as 400 million barrels (Bermúdez-Lugo, 2004; MBendi, 2005).

Cameroon natural gas reserves are indicated to be 55.22 billion m^3 (Index Mundi, 2005) or may be as high as 110 billion m^3 (Bermúdez-Lugo, 2004). There is no commercial gas use in Cameroon. It has been suggested that some of the onshore fields could be developed to provide electrical power for all

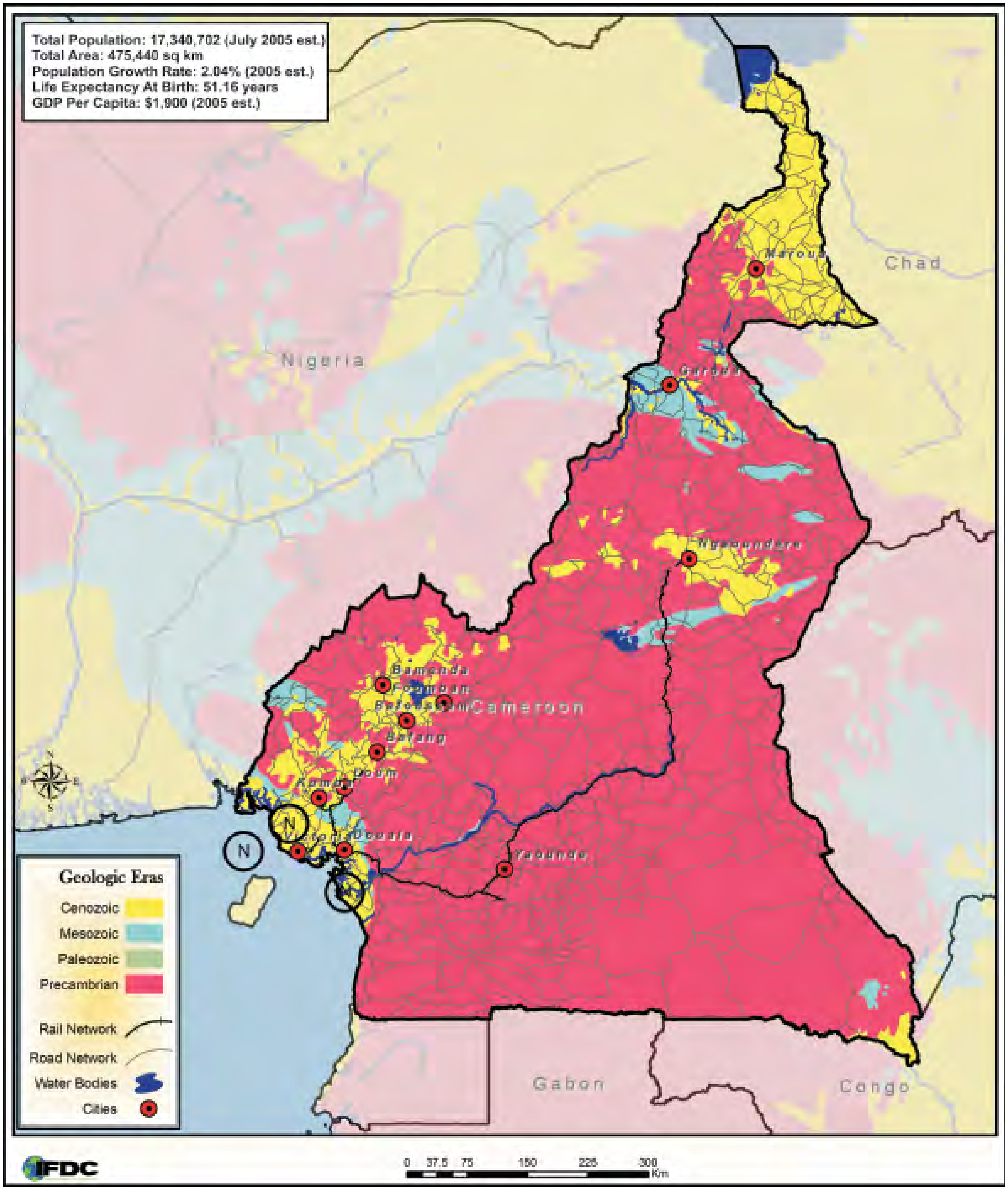


Figure Cameroon 1. Geology, Major Cities, and Transportation Network

Cameroon (Tafu, 2006). Five gas fields could supply electricity to Cameroon for 400 years (based on a 100-MW plant consumption at 50% load factor). In 2004, Euroil, Ltd. (Scotland) and Syntroleum Corporation (Oklahoma, U.S.A.) announced plans to develop the 17 billion m^3 Sanga Sud Field offshore Cameroon.

The only refinery in Cameroon is located in the port city of Simbe and operated by the Société Nationale de Raffinage. The production capacity is 42,000 barrels per day (bpd) utilizing oil from Nigeria and Equatorial Guinea as feedstock (Bermúdez-Lugo, 2004).

The Cameroon segment of the Chad-Cameroon Pipeline began operating in late July 2003 (ChevronTexaco, 2003). Production of 225,000 bpd is expected when all the development work is completed. In 2004, average daily production was about 200,000 bpd. The pipeline in Cameroon is operated by Cameroon Oil Transportation Company S.A. in a partnership with Esso Exploration and Production Chad Inc. The pipeline runs from the Doba Basin in Chad to a marine terminal near Kribi in Cameroon.

Phosphate Resources

Siliceous phosphatic nodules containing 12% to 18% P_2O_5 have been found in the Bongue River Valley near Kompina, 50 km north-northwest of Douala. The nodules occur in the lower part of the Série de Bongue in black sandy clays. At the bottom of the Séries, the nodules are associated with thin limestones (Visse, 1953; McClellan and Notholt, 1986). Appleton (2001) pointed out that these occurrences are probably not of economic interest even though they do occur in Eocene strata.

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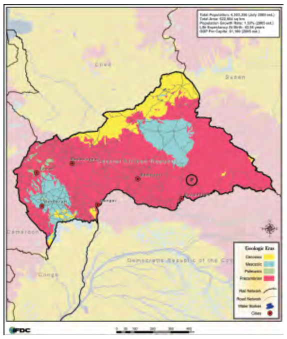
CENTRAL AFRICAN REPUBLIC



The Central African Republic (Figure Central African Republic 1) is bordered by Chad to the north; Sudan to the north and east; the Republic of the Congo and the Democratic Republic of the Congo to the south; and Cameroon to the west. The Central African Republic is a totally landlocked country. Total area is 622,984 km^2 and only 3.1% of this land is arable. The population was estimated in mid-2005 as 4.3 million inhabitants (World Factbook, 2006).

The transportation network comprises 23,810 km of roadways and 2,800 km of waterways, mainly on the Oubangui and Sangha Rivers. The main ports are Bangui, Nola, Salo, and Nzinga. There are no railroads within the country. There are 3 airports with paved runways and 47 airports with unpaved runways.

Precambrian rocks outcrop over more than 60% of the surface of the Central African Republic. The central and eastern areas of the country are composed of Archean schists and gneisses intruded by granites. Maps of the western area of the country indicate mainly undifferentiated Precambrian rocks in that the geology of much of the area is not well known (Boss et al., 1996). Proterozoic age rocks consist of gneisses, quartzites, dolomites, and other metasediments.

Continental Mesozoic sediments occur in the southwest, northern, and central parts of the country. Cretaceous detrital sediments, red clay beds, and limestones were deposited over karst topography developed on the Upper Proterozoic Bakouma Dolomite. Undifferentiated Cenozoic continental sediments overlie older rocks in the north of the country. Granites that intrude the Yade Massif in the extreme northwest of the country are indicated in Figure Central African Republic 1 to be of Paleozoic age. Boss et al. (1996) indicates that these intrusions may be of Tertiary age.

Phosphate Resources

Phosphatic lenses reaching thicknesses of 20-25 m occur at depths of up to 35 m in Eocene clays of the M'Patou Formation at Bakouma, about 480 km east of Bangui (McClellan and Notholt, 1986). The deposits were discovered during the course of uranium exploration during the 1960s. The deposits are apparently the result of the infilling of the karst topography on the Upper Proterozoic Bakouma Dolomite. Grades of 9% to 35% P_2O_5 and up to 0.25% U_3O_8 were recorded (Bigotte and Bonifas, 1968). The phosphate rock in these deposits contains francolite; because the deposits are highly weathered, they contain significant amounts of aluminum phosphates.

The deposits were subsequently studied by OECD/NEA (1980) and Miauton (1980, as quoted in van Straaten, 2002). Miauton indicates the deposits are of continental origin. There are no resource estimates for these deposits.

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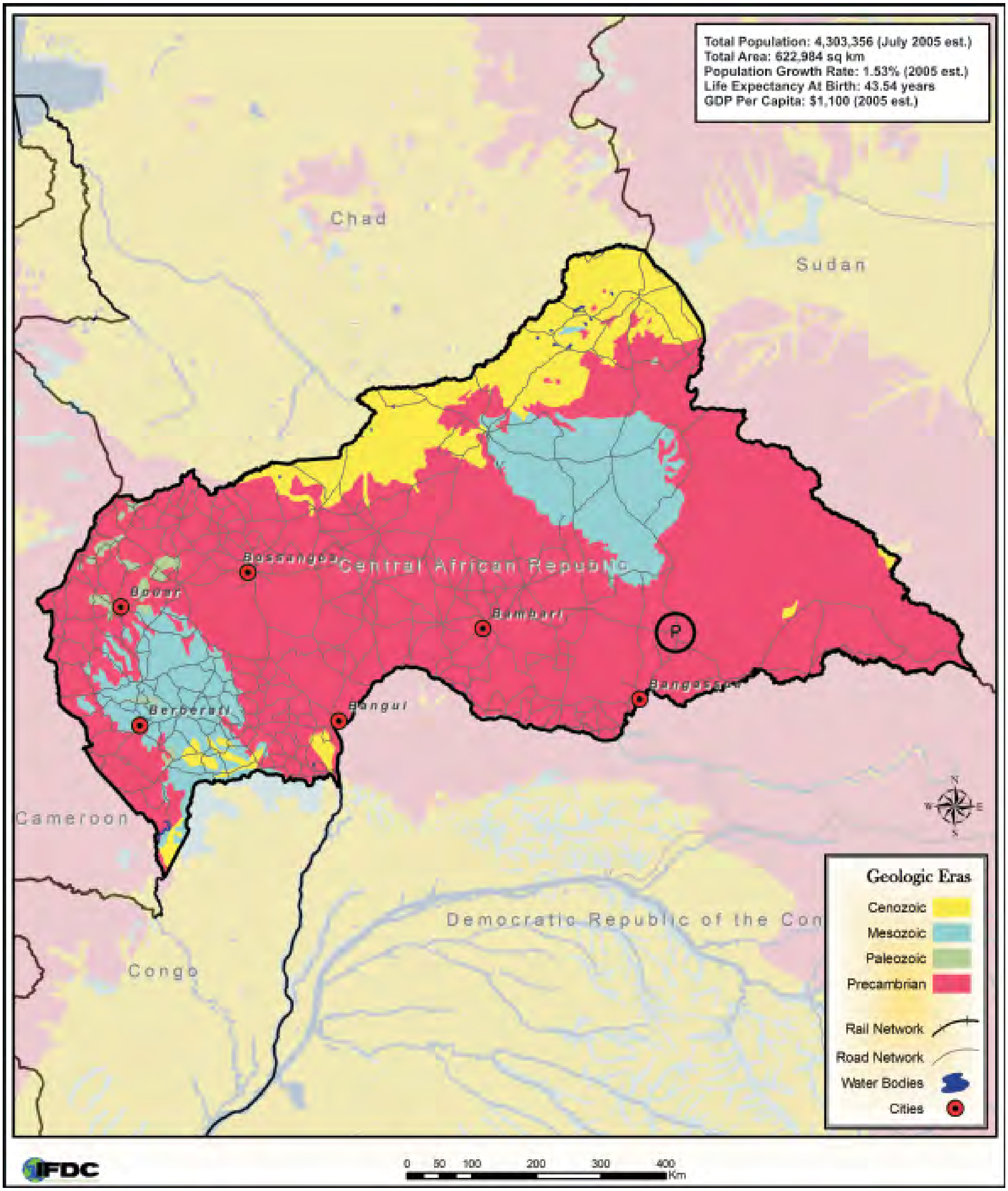

Figure Central African Republic 1. Geology, Major Cities, and Transportation Network

Rohstaffe und de Geologischen Landesämtern in der Bundesrepublik Deutschland, Herstellung: Kölle-Druck GmbH, 32361 PrèuBisch Oldendorf.

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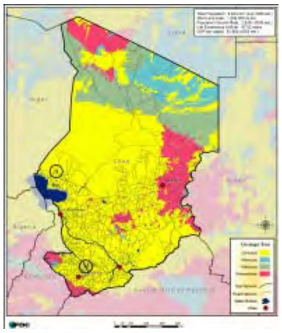
CHAD



The Republic of Chad (Figure Chad 1) is bordered to the north by Libya; to the east by Sudan; to the south by the Central African Republic; and to the west by Niger, Nigeria, and Cameroon. Chad is a totally landlocked country. Total area is 1,284,000 km^2 and arable land is 2.8% of the total land area. The population was estimated in mid-2005 as approximately 9.9 million inhabitants (World Factbook, 2006). Agriculture occupies more than 80% of the labor force.

The transportation network includes 267 km of paved roads and 33,133 km of unpaved roads. There are no railroads. There are 7 airports with paved runways and 44 airports with unpaved runways. Chad has 205 km of oil pipeline, which continues through Cameroon to the coast. Within Chad, the Chari and Logone Rivers are navigable only in the wet season.

Precambrian rocks occur in the northwest in the Tibesti Mountains, the eastern central area, and the extreme south of Chad. In the north of the country, lower Paleozoic sandstones overlie the Precambrian basement. The Lower Paleozoic sandstones in the Kufra Basin (extending from Libya) are overlain by the Nubian Sandstone. Cretaceous continental clastics overlie the Precambrian basement in the south of the country and extend into the Chad Basin, thickening to several thousand meters. During the upper Cretaceous, there was a marine incursion, which was followed by another continental sequence. Paleocene continental sandstones occur in southern Chad.

The extensive and thick lacustrine Chad Formation was deposited during the Pleistocene. Dune sands overlie the Chad Formation throughout the Chad Basin. Miocene to Recent volcanic flows cover areas in the Tibesti Mountains.

Nitrogen Resources

Oil exploration began in Chad in the 1970s, and discoveries were made in both the Lake Chad Basin and the Dobra Basin in southern Chad by a consortium composed of Chevron, Conoco, Exxon, and Shell (MBendi, 2005). Exploration and development was suspended due to the civil war in 1979. Conoco withdrew from Chad in 1981. Exxon took over operations and discovered the Bolobo Field in 1989. EssoChad, a venture of ExxonMobil Corp. (40% equity interest), Petronas Carigali Overseas Sdn Bhd of Malaysia (35%), and Chevron Overseas Petroleum (25%) started production from the Miandoum Oil Field in 2003 (ChevronTexaco, 2003).

ChevronTexaco (2003) announced the startup of pipeline fill activities on July 28, 2003. The pipeline was completed 1 year ahead of schedule. The pipeline is 1,070 km long and ends at an export terminal at Kribi, Cameroon. Project construction began in October 2000. The pipeline was expected to transport 225,000 barrels of oil per day by 2005 (Mobbs, 2004). The consortium's investment in oil fields and the pipeline was reported as US $4.7 billion (EssoChad, 2006).

Production started from the Komé Field in the first quarter of 2004 and from the Bolobo Field in the third quarter of 2004. In 2005 EssoChad continued exploration of the Moundouli and Nya Fields and continued exploration of the Selanga, Mangara, and the M'Bikou Prospects (Mobbs, 2004).

Crude oil from the Bolobo, Komé, and Miandoum Fields is blended at EssoChad's central

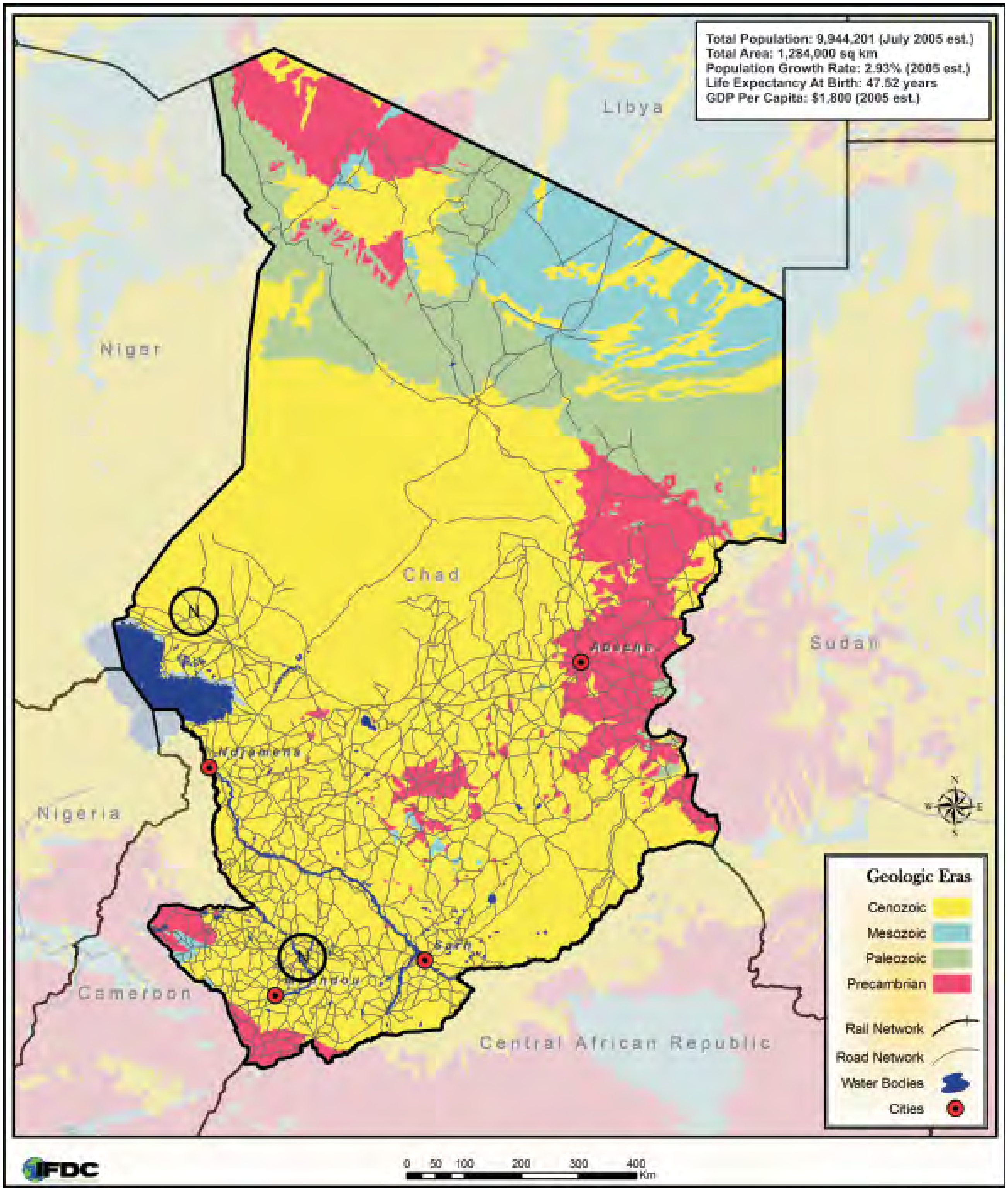


Figure Chad 1. Geology, Major Cities, and Transportation Network treating facility at Komé. Analysis of the oil places it in the heavy, sweet, high-acid category that has some marketing problems. Most refineries in China and Europe are designed to process light crudes (Mobbs, 2004). The oil from Chad is sold at a discount under light crudes (minus US $8-$16/barrel in 2004).

Other oil companies that are active in Chad include EnCana Corp. of Canada, Cliveden Petroleum Co. Ltd. (British Virgin Islands), Citic Resources Holdings (a subsidiary of China International Trust and Investment Corp.), Trinity Energy Resources (United States), and Energem Petroleum Chad Ltd. (a subsidiary of Energem Resources Inc., Canada). In 2004 Energem Petroleum Chad Ltd. was awarded the Chari West (8,200 km^2) concession in the Doba Basin and the Largeau concession (251,000 km^2) in northern Chad.

Proven recoverable oil reserves are estimated at approximately 1 billion barrels (MBendi, 2005). There is no information to indicate that there are any gas reserves. There is no information to indicate gas is being flared within the oil fields. At the present time there is no oil refinery in Chad.

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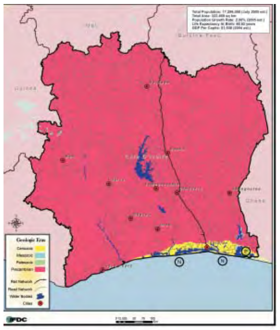
CÔTE D'IVOIRE



Côte d'Ivoire is bordered by the Atlantic Ocean to the south, Ghana to the east, Liberia and Guinea to the west, and Burkina Faso and Mali to the north (Figure Côte d'Ivoire 1). Total area is 322,460 km^2; 9.75% of the land is arable cropland. The population was estimated as 17.3 million inhabitants in mid-2005 (World Factbook, 2006). Annual population growth is 2.06%.

Côte d'Ivoire has been among the world's largest producers of coffee, cocoa beans, and palm oil. Roughly 68% of the population is dependent on agriculture and related activities.

The transportation network consists of 50,400 km of roads, of which 4,889 km is paved, and 660 km of railway. An additional 622 km of the railway extends into Burkina Faso. Côte d'Ivoire has 980 km of navigable rivers, canals, and coastal lagoons.

The geology of Côte d'Ivoire is dominated by Precambrian igneous rocks as well as sequences of Birimian metasediments (conglomerates, sandstones, and slates) with subordinate metavolcanics (Figure Côte d'Ivoire 1). No Neoproterozoic or Paleozoic age rocks have been found in Côte d'Ivoire. Sediments of Cretaceous and Quaternary age are found in a narrow east-west coastal strip and extend at depth offshore.

Nitrogen Resources

Petroleum was first discovered in the early 1970s off the coast near Jacqueville, west of Abidjan. A second field was discovered off Grand-Bassom, east of Abidjan. The initial two fields, Espoir and Bélier, were relatively small, geologically complex, and located in deep water. The Espoir Field (Phillips Petroleum) began operations in 1982. The Bélier Field (Exxon) began producing in 1986. By 1988 production from Bélier was halted and Exxon capped its wells.

A consortium of Canadian, British, and Ivorian companies produces gas from the East Espoir Oil Field. The company developed the Baobab Oil Field, expecting the first production by mid-2005 at a rate of 27,000 barrels per day (bpd) to reach 35,000 bpd by 2006 (World Factbook, 2006). The company holds several exploration blocks offshore and planned to continue its exploration program in 2006.

The San Pedro prospect (Block CI-112) was to be drilled in 2005 by a consortium of American, Indian, Chinese, and Ivorian companies. Oil production (2004) was estimated at 29,300 bpd (World Factbook, 2006). Oil consumption, within the country (2001), was estimated at 32,000 bpd. Proven oil reserves were estimated in 2004 as 220 million barrels (World Factbook, 2006).

Gas reserves are both nonassociated and associated with oil fields. Proven reserves are estimated at 14.87 billion m^3 (World Factbook, 2006). The gas is utilized for power generation. The government purchased four large gas-powered turbines in 1983/84. Apparently the prospect of producing fertilizer was assessed at that time. Natural gas production (2001 estimate) was 1.35 billion m^3 and gas consumption for the same year was 1.35 billion m^3. Côte d'Ivoire meets its own energy requirements and exports energy to surrounding countries.

The refinery at Vvidi, operated by Sociéte Ivoirienne de Raffinage was commissioned in 1965

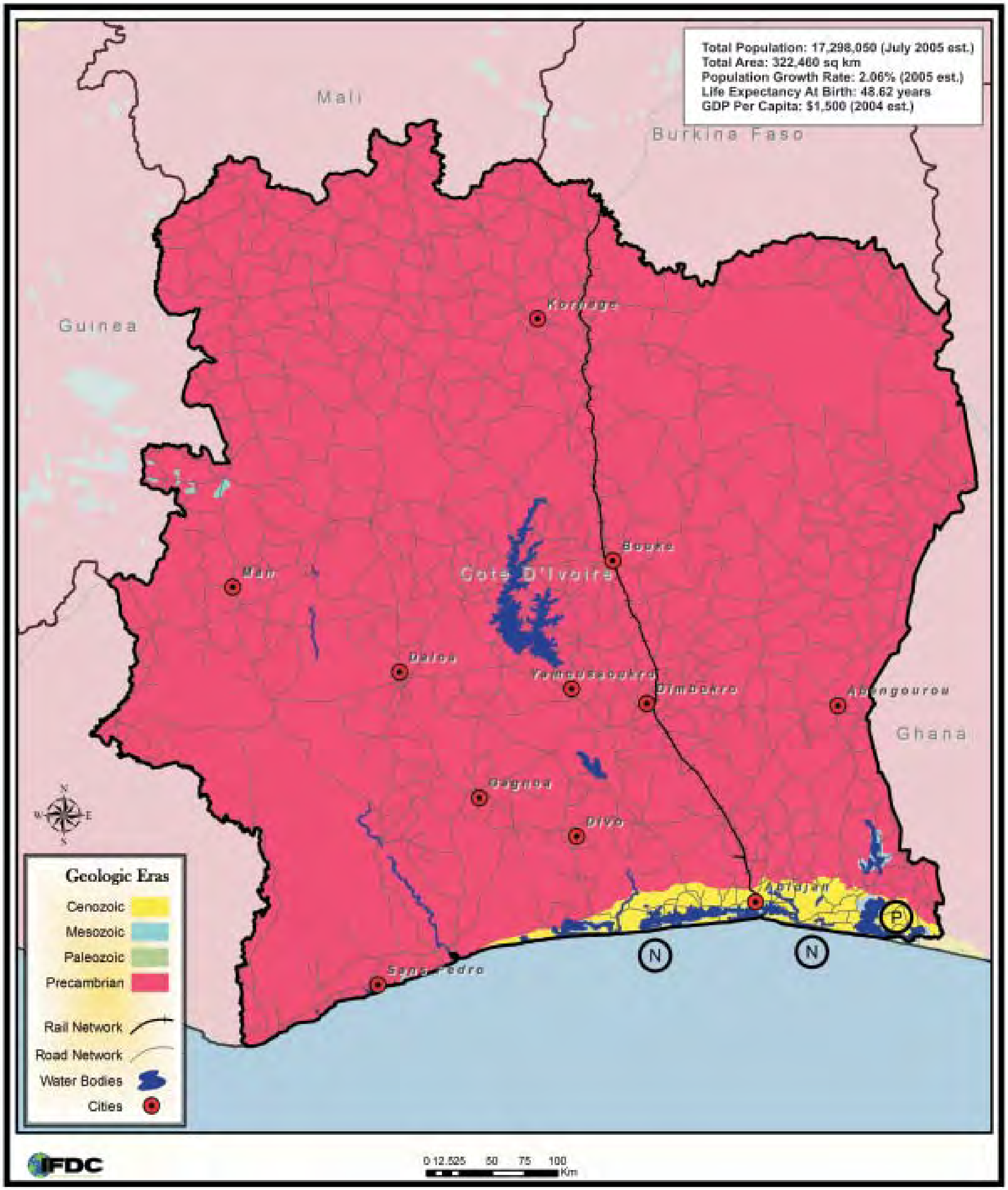


Figure Côte d'Ivoire 1. Geology, Major Cities, and Transportation Network with a capacity of 700,000 tpy. In 1986 capacity was increased to 3.2 million tons. The refinery is mainly used to process oil from other African countries (principally Nigeria). Within the country there are three pipelines (condensate, 107 km; gas, 223 km; oil, 104 km).

Phosphate Resources

An occurrence of phosphate rock was noted by Dian (1977) in the coastal sediments of Côte d'Ivoire. The phosphates occur as nodules in Paleocene to Eocene sediments near Eboinda at depths of 3-9 m. Phosphate values as high as 30% P_2O_5 were reported. Apatite and aluminum phosphates (wavellite, crandallite, and variscite) were reported from the same locality (Tagini and Gobert, 1981). No further work has been reported.

Sulfur Resources

There is no reported sulfur production from Côte d'Ivoire. Sulfur is often a byproduct from oil refining; there is no information to suggest sulfur is produced from oil or natural gas in Côte d'Ivoire.

Sulfuric acid is often produced as a byproduct from sulfide smelting. There is no production of metal from sulfides currently in Côte d'Ivoire.

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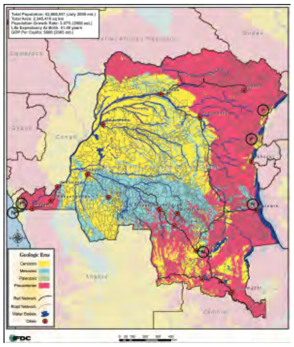
DEMOCRATIC REPUBLIC OF THE CONGO



The Democratic Republic of the Congo (DRC) (Figure Democratic Republic of the Congo 1) is bordered to the north by the Central African Republic and Sudan; to the east by Uganda, Tanzania, Rwanda, and Burundi; to the south by Zambia and Angola; and to the west by the enclave of Cabinda, the Republic of the Congo, and the Atlantic Ocean. Total area is 2,345,410 km^2 and approximately 2.9% of this land is arable. The population was estimated in mid-2005 as approximately 62.7 million inhabitants (World Factbook, 2006). Subsistence farming provides a livelihood for 57% of the population (Link2exports, 2006).

The transportation network consists of 157,000 km of roadways; 5,138 km of railways (3,987 km of 1.067-m gauge, 125 km of 1.000-m gauge, and 1,026 km of 0.600-m gauge); and 15,000 km of waterways. Major waterways include the Congo, Lualaba, Kasai, and Obangui Rivers. Banana, Boma, Bukavu, Bumba, Goma, Kalemie, Kinshasa, Kisangani Matadi, and Mbandaka are the main ports. The coastline is 37 km long on the Atlantic Ocean. There is a gas pipeline 54 km long and an oil pipeline 71 km long.

The overall geology of the DRC can be simply described as being formed by the sedimentary Congo Basin surrounded by Precambrian basement rocks and bounded by the Rift Valley system on the eastern border. Archean gneisses, magmatites, and metamorphosed Middle Proterozoic age sediments, all intruded by granite, form the basement. Upper Proterozoic sediments, including conglomerates, shales, tillites, sandstones, and carbonates, unconformably overlie the basement. Many of these formations are slightly to moderately metamorphosed.

Karroo (or Karoo) sediments of Carboniferous to Triassic age unconformably overlie the Precambrian basement in southern DRC and much of the Congo Basin. Karroo sediments consist of a basal tillite, coals, shales, and sandstones. Most of the rim of the Congo Basin is composed of continental Cretaceous age rocks. In the southern part of the country, vast areas are overlain by Kalahari sands. The center of the Congo Basin is filled with a thick sequence of mudstones.

In the coastal region Cretaceous and Tertiary sediments are found in a narrow band and extend offshore. This area can be considered a part of the Cabinda-Gabon Basin or a part of the Congo River Delta, which extends offshore at depth for a considerable distance.

In the east considerable thicknesses of sediments may be found in the grabens of the Rift Valley. These sequences also contain significant amounts of volcanics.

Nitrogen Resources

Petroleum—Exploration for oil and gas began in the 1960s along the Atlantic Ocean coastline. By 1983, 41 wells had been drilled (MBendi, 2002). From this activity, five oil fields and one gas field were discovered. The Mibale Field, discovered by Chevron in 1978, contains almost half of the recoverable oil reserves. The gas field has not been exploited. A consortium comprising Congo Gulf Oil (ChevronTexaco) (50%), Teikoku Oil of Japan (32%), and Union Oil of California (18%) operates the offshore concession. An onshore concession in the Congo River estuary was operated by a consortium known as Congo P.

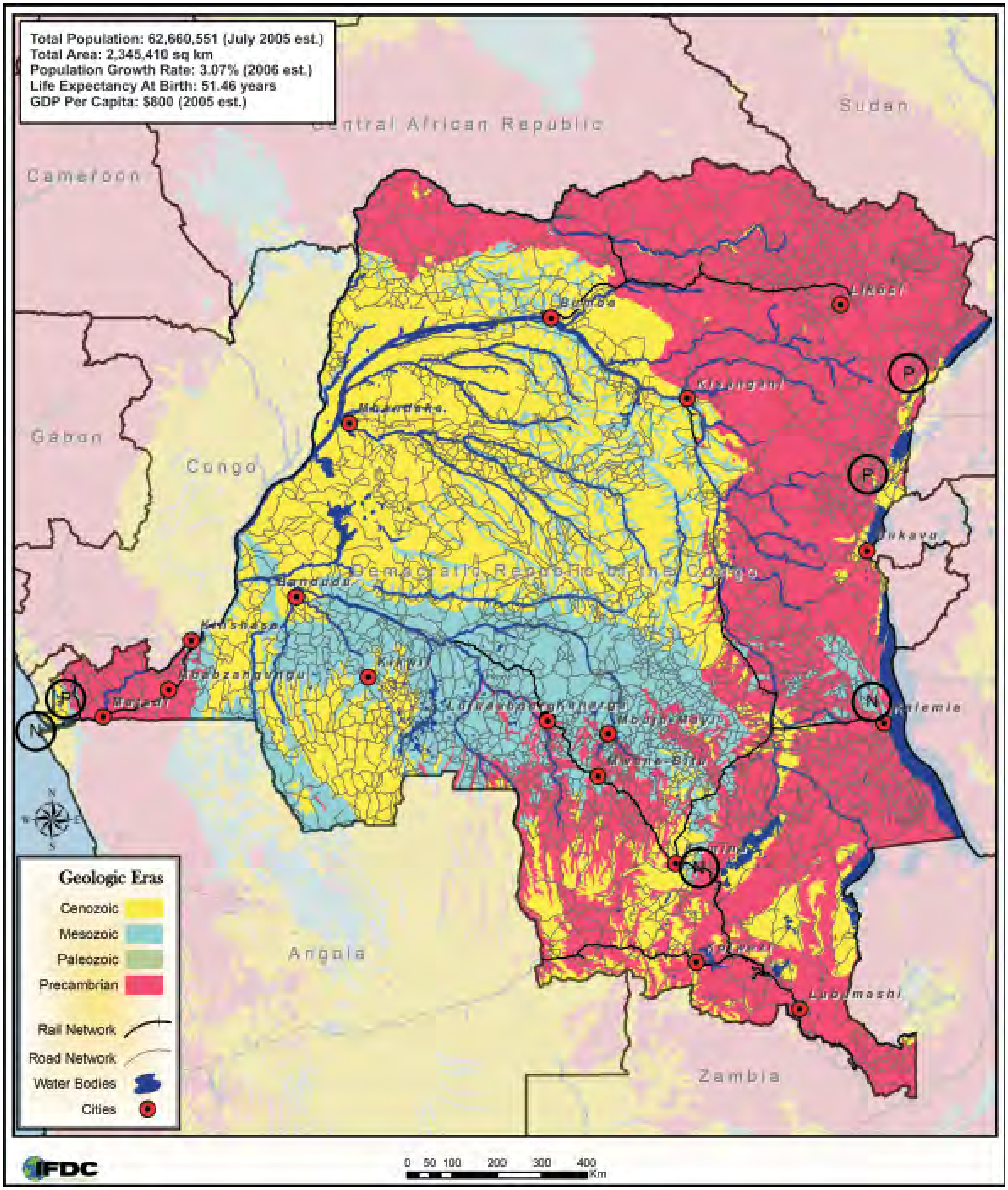


Figure Democratic Republic of the Congo 1. Geology, Major Cities, and Transportation Network

The last known onshore drilling in the western DRC was in 1988 by Zairep (a subsidiary of Petrofina). Drilling is occurring offshore in the western DRC. In the Rift Valley, Heritage Oil Corporation (Canada) has been drilling in the Lake Albert area since 2002 (Link2exports, 2006).

Oil production in 2003 was estimated as 8,300 barrels per day (bpd) or about 3.03 million barrels per year (bpy) (World Factbook, 2006). Proven oil reserves are estimated at 1.538 billion barrels. (January 2002) (World Factbook, 2006). Proven oil reserves are quoted by another source (Link2exports, 2006) as 185 million barrels in 2003. Proven reserves of natural gas are indicated as 991.1 million m^3 (January 2003) (World Factbook, 2006).

There is a petroleum refinery at Muanda at the mouth of the Congo River. Coakley (2003) reports a capacity of 17,000 bpd but lists zero product from the refinery as of 2002. The refinery operated on imported oil.

Coal—Coal is found in the eastern DRC. Coal was mined at the Luena Coal Mine by La Générales de Carrières et des Mines (Gécamines) for operations in the Congo copper belt, use in the cement industry, and use by the railroad. Annual capacity was 800,000 tpy. Coal production essentially ended sometime in the early 1990s. Coakley (2003) listed 1,000 tons of coal production for 2001, 2002, and 2003. Link2exports (2006) reports that a smaller coal mine was operated by Charbonage du Tanganyika near Kalemie. Link2exports (2006) also reports that remaining coal reserves were estimated at 87.9 million tons. This figure could not be verified.

Phosphate Resources

Sedimentary Phosphate Deposits—The only known sedimentary deposits in the DRC are in the small coastal basin area at the mouth of the Congo River. The United Nations Development Program (UNDP) conducted exploration work on phosphate deposits in Cabinda between 1969 and 1971. These deposits were known to continue on into the DRC from the border to the valley of the Congo River. Between 1978 and 1980, the UNDP conducted exploration in the DRC, drilling 30 boreholes and sinking 54 pits and focusing on the area of Fundu Nzobe, Vuangu, and Kangi (Barry, 1981; as summarized by van Straaten, 2002).

Exploration at Fundu Nzobe near the Cabinda border indicated five phosphate beds 5.1 to 20 m thick with 11.5% to 31.0% P_2O_5. Apparently the overburden in the area was quite thick, and structural deformation in the area precluded the possibility of mining. Resources were not estimated for this area.

At Kanzi near the mouth of the Congo River, one phosphate-bearing bed 8-10 m thick containing 14% P_2O_5 is covered by sandy overburden. Twelve boreholes were drilled in the area at a total length of 1,460 m. The phosphate resources at Kanzi were estimated at 20-28 million tons in situ and 5-7 million tons of concentrate. Zellar-Williams Co. (Florida, U.S.A.) performed beneficiation studies, which indicated that concentrates up to 34% P_2O_5 could be produced utilizing flotation techniques.

This project was undertaken with the goal of establishing a small- to medium-scale phosphoric acid-based fertilizer plant nearby. Apparently there were concerns over the technical and economic feasibility of the project, and no follow-up studies were performed.

One phosphate sample from the Mankao area in the coastal basin of the DRC has been analyzed at IFDC (Table Democratic Republic of the Congo 1). The sample contained 34.2% P_2O_5 with relatively high levels of Al_2O_3 (6.4%) and Fe_2O_3 (2.9%). The R_2O_3 (Fe_2O_3+Al_2O_3)/P_2O_5 ratio of the sample (0.27) is far above a level considered suitable for chemical processing (0.10).

X-ray diffraction (XRD) analysis indicated the presence of francolite, wavellite ($Al_3(OH)_3(PO_4)_2 \bullet 5H_2O$), and quartz. The measured unit cell a-value of the apatite was 9.352±0.001Å, indicating a francolite with about 2.2 wt % CO_2 substitution. The measured NAC P_2O_5 solubility indicates the rock is of medium reactivity. The apatite composition and chemistry are very similar to that of samples obtained from deposits in Cabinda (see Angola section).

Igneous Deposits—The DRC has at least five known carbonatite deposits, and two of those deposits contain apatite.

Bingu—The Bingu Carbonatite Deposit is located about 80 km south of Lake Edward. The carbonatite was prospected by the Société Minière de Lueshe (formed by the Congo government and Union

Table Democratic Republic of the Congo 1. Phosphate Rock Sample From the Mankao Area

Chemical Analyses	wt %
P_2O_5	34.2
CaO	38.6
F	2.9
SiO_2	5.7
Al_2O_3	6.4
Fe_2O_3	2.9
Na_2O	0.09
MgO	0.1
K_2O	0.22
S	0.08
Cl (ppm)	<50.0
CO_2	1.6
SrO	0.08
BaO	0.03
MnO	0.64
Free H_2O[a]	5.6
LOI[b]	12.7
NAC P_2O_5[c]	3.8

a. Free H_2O = weight loss, 105°C.
b. Loss on ignition, 1,000°C.
c. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).

Carbide) in the 1960s (Savage, 1987). Proven resources of niobium are indicated at 2.3 million tons averaging 3.6% Nb_2O_5. No phosphate resources are listed although the area was indicated to contain an enormous reserve of phosphate prior to the Société Minière de Lueshe investigation.

Lueshe Carbonatite—The Lueshe Complex is located in the Lueshe Valley about 40 km south of Lake Kivu. It is a circular complex with a pyrochlore-aegerine-carbonatite core. Two samples of carbonate indicate analyses of 3.65% and 4.67% P_2O_5. Pitting and trenching carried out by the Société Minière de Nyambuki indicated about 30 million tons of pyrochlore ore at 1.34% Nb_2O_5 in the mantle produced by weathering. A 2-tph pilot plant was operated in 1984 (Savage, 1987). A byproduct phosphate concentrate sample showed the following analysis:

	(%)
P_2O_5	41.3
CaO	55.0
SrO	0.8
SiO_2	0.9
CO_2	0.2
F	4.1
Cl	0.05
H_2O	0.12

The chemical analysis indicates that the sample is almost pure fluorapatite. Maravic et al. (1983) estimated the P_2O_5 contents of the lateritic residual soils as 5%-9%. A pilot plant to extract pyrochlore was built in 1986 and was worked until 1993 when security in the area degraded (van Straaten, 2002).

Sulfur Resources

Coakley (2003) reported 80,000 tons of sulfuric acid production in the Democratic Republic of the Congo in 2003. Gécamines has a sulfuric acid plant at Kolwezi. It is assumed that all the production is consumed in the copper industry.

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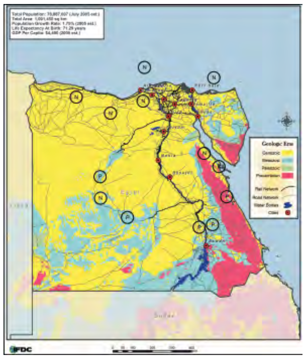
EGYPT



The Arab Republic of Egypt is bordered to the south by Sudan, the west by Libya, the east by the Red Sea, and the north by the Mediterranean Sea (Figure Egypt 1). Total area is 1,001,450 km^2. Approximately 2.9% of the land is arable. Most of the arable land is located in the Nile Valley and the Nile Delta. The population was estimated in mid-2005 as 78.9 million inhabitants (World Factbook, 2006). Agriculture occupies 32% of the labor force.

The transportation network consists of 49,984 km of paved roads, 14,016 km of unpaved roads, and 5,063 km of 1.435-m-gauge railway. There are 72 airports with paved runways and 15 airports with unpaved runways. Waterways (3,500 km) include the Nile River, Lake Nasser, Alexandria-Cairo Waterway, numerous small canals in the Delta, and the Suez Canal. The main ports are Alexandria, Damietta, El Dekheila, Port Said, Suez, and Zest. Pipelines as of 2004 include gas (6,115 km); condensate/gas (94 km); condensate (289 km); liquid petroleum gas (852 km); oil (5,032 km); oil/water/gas (36 km); and refined products (246 km).

Precambrian age igneous and metamorphic rocks, including granodiorites, gabbro and doleritic intrusions, gneisses, migmatites, chlorite schists, metagraywackes, phyllites and conglomerates, and volcanics such as rhyolites, diorite, basalts, and ignimbrites outcrop along the west coast of Egypt and in the Sinai. Precambrian age rocks also outcrop to the west of the Nile River in southern Egypt and to the west near the borders with Sudan and Libya.

Limited outcrops of Paleozoic age rocks occur in southwestern Egypt, near the Gulf of Suez and in the Sinai. Paleozoic age rock types include clastic sediments, granites, and volcanics.

Jurassic age marine and near-shore sediments occur in southwestern Egypt, the west bank of the Gulf of Suez, and the northern Sinai. The Cretaceous Nubian Sandstone outcrops over wide areas in southern Egypt. Undivided, Cretaceous age shales, marls, limestones, dolomites, chalks, interbedded sandstones, and red beds overlie the Nubian Sandstone. These undivided, Cretaceous age sediments are found in middle to southern Egypt across the Nile Valley to the south of the Luxor area, continue to the east and north, and occur along the western side of the Precambrian age rocks that form the mountains along the Red Sea. Near the Red Sea these sediments also occur as isolated erosional remnants within Precambrian age rocks. These Cretaceous age sediments contain the phosphate beds associated with Abu Tartur, the Nile Valley, and the Red Sea coast deposits.

Paleocene age sediments consist of limestones and shales. Lower Middle and Upper Eocene rocks are characterized by limestones of varying purities. Fluvial and lacustrine sediments characterize the Oligocene.

Miocene age rocks are composed of a basal clastic unit with overlying carbonates. Miocene rocks form most of the outcrops north of latitude 29° west of the Nile Valley. In the Red Sea area, the Miocene contains a thick section of evaporates in the subsurface. The Pliocene is composed of fossiliferous limestones, calcareous sandstones, and gravels along the Nile Valley and in the northwestern part of the country. Quaternary cover includes beach deposits, coral reefs, gravel terraces along rivers, and sand dunes.

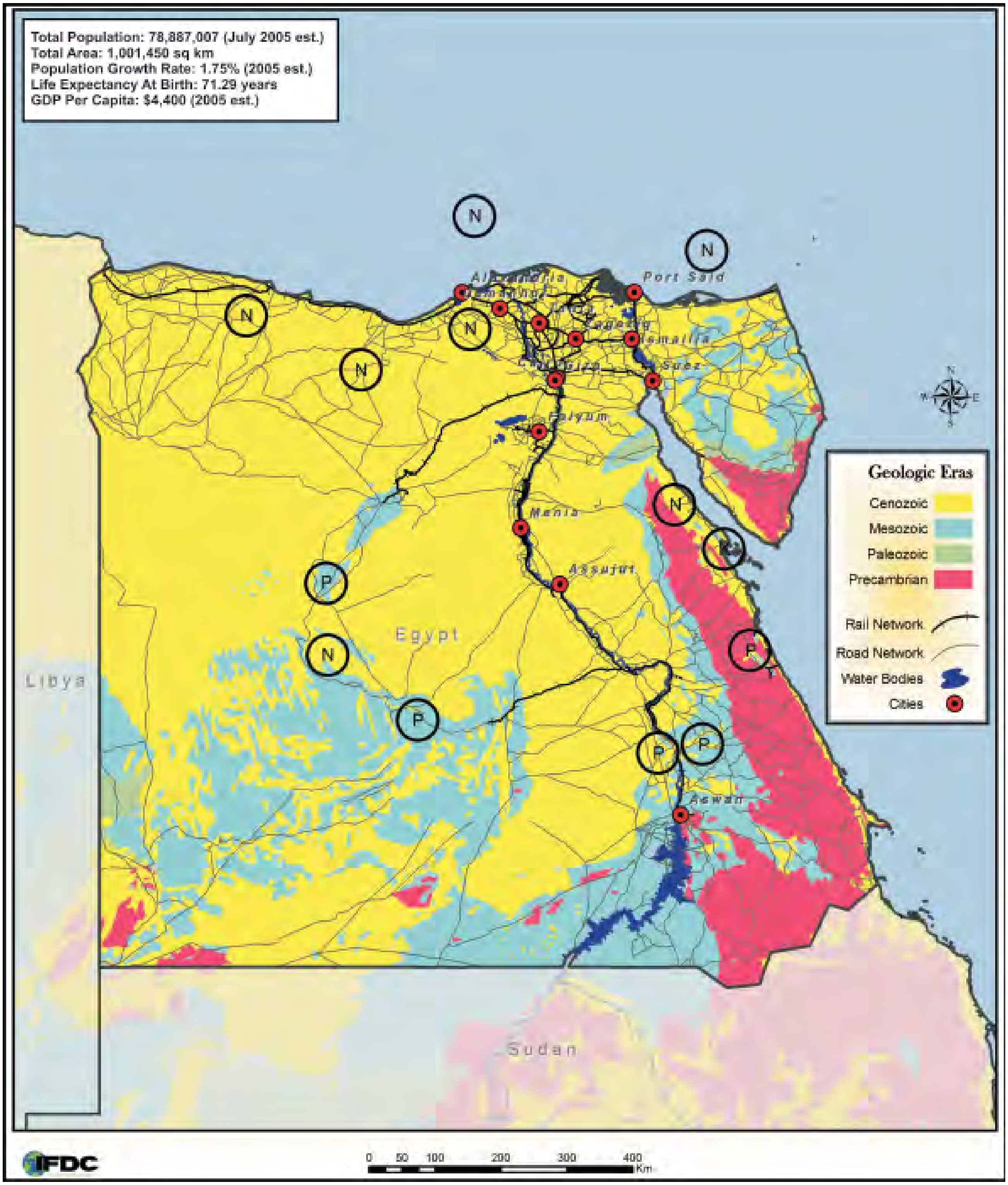


Figure Egypt 1. Geology, Major Cities, and Transportation Network

Nitrogen Resources

The Energy Information Administration (EIA) noted that Egypt's crude oil production averaged about 594,000 barrels per day (bpd) in 2004, down from a peak of 922,000 bpd in 1996 (EIA, 2005). Egyptian oil production comes from four areas: the Gulf of Suez; the Western Desert; the Eastern Desert; and the Sinai Peninsula. Increased production of condensates, which averaged about 114,000 bpd in 2004, has offset some of the declines in oil production. Most of the declines in production are from Gulf of Suez fields, which produce about 50% of Egypt's oil. Oil from the Suez Basin is mostly produced by the Gulf of Suez Petroleum Company (GUPCO) under a production-sharing agreement between British Petroleum (BP) and the Egyptian General Petroleum Corporation (EGPC). Petrobel is Egypt's second largest producer (a joint venture between EGPC and Agip of Italy). Other major oil companies in Egypt include Badr el-Din Petroleum Company (EGPC and Shell), Suez Oil Company (EGPC and Deminex), and the El Zoafarana Oil Company (EGPC and British Gas). It is hoped that enhanced recovery techniques and new discoveries, particularly in the Western Desert and Upper Egypt, will stem declining production. Significant deep-water exploration is ongoing at this time.

Egypt's natural gas sector is rapidly expanding. In the early 1990s, foreign oil companies began actively exploring for natural gas deposits and located deposits in the Nile Delta, offshore from the Nile Delta, and in the Western Desert. Natural gas production in Egypt averaged about 10.2 million m^3 per day in 2004. Production is expected to rise to about 15.3 million m^3 per day by 2007 with much of the increased production to be exported as liquefied natural gas (LNG).

Natural gas demand in Egypt grew rapidly as power plants switched from oil to gas. EIA notes that power plants account for 65% of Egypt's total gas consumption (EIA, 2005). In late 1999 the Egyptian government stated that natural gas reserves were more than sufficient for domestic needs and thus firms producing gas in Egypt should seek export customers. An export pipeline to Jordan began operation in July 2005. Egyptian firms were responsible for building the pipeline to Aqaba in Jordan. The Jordanians were responsible for the pipeline through Jordan; eventually the pipeline may extend to Turkey.

Two LNG projects are underway. The Spanish firm, Union Fenosa, shipped its first cargo in January 2005 upon completion of the first LNG train at Damietta. The second LNG export project at Idku is being built by British Gas (BG) in partnership with Petroliam Nasional Berhad (PETRONAS), based on BG's Simian/Sienna fields. The first train began production in March 2005, and the second train was to be operational by late 2005. Gaz de France is the main customer for the first train. The LNG from the second train will be delivered initially to the Lake Charles import terminal for the U.S. market (EIA, 2005). BP and Shell are also contemplating LNG projects in Egypt.

Proven oil reserves are listed as 2.7 billion barrels (2005 estimate) (World Factbook, 2006) to 3.7 billion barrels (January l, 2005, estimate) (EIA, 2005). Based on figures released by the Egyptian government, proven natural gas reserves (2003 estimate) were estimated as 1.8 trillion m^3 and probable reserves as about 3.4 trillion m^3 (Bermúdez-Lugo, 2003). A 2005 natural gas estimate indicates 1.9 trillion m^3 of proven reserves (World Factbook, 2006).

Nitrogen Fertilizer Production—Egypt has a well-developed ammonia industry based on natural gas. Table Egypt 1 lists the ammonia producing companies, the name of the plant, locations, and status. Note that ammonia is used for a variety of applications and not all the capacity listed is for fertilizer applications. The total capacity for 2005/06 is 2,263,000 tpy. The projected total capacity for ammonia in 2009/10 is 5,563,000 tpy (IFDC, 2006a).

Based on a substantial proportion of the ammonia production, Egypt has a well-developed urea industry. Table Egypt 2 lists the urea producing companies, the names of plants, locations, and status. Total Egyptian urea plant capacity in 2005/06 was 2,245,000 tpy. The projected total capacity for urea in 2009/10 is 5,420,000 tpy (IFDC, 2006b) based on plants under construction or in the planning stages.

Phosphate Resources

Sedimentary Deposits—The phosphate deposits of Egypt are a part of an Upper Cretaceous to Lower Tertiary sedimentary sequence widely distributed in the Eastern Desert (Red Sea area), the Nile Valley, and Western Desert areas. At Abu Tartur, in the Nile Valley, and in the Red Sea area, the

Table Egypt 1. Egypt—Ammonia Plant Capacities

Region/Country Company/Location	Plant Status[a]	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	Indefinite
	(tons x 1,000)									
Africa/Egypt										
Abu Qir Fertilizers and Chemical Industries Co. (AFC)										
Abu Qir I, Alexandria	OPR	330	330	330	330	330	330	330	330	330
Abu Qir II, Alexandria	OPR	330	330	330	330	330	330	330	330	330
Abu Qir III, Alexandria	OPR	396	396	396	396	396	396	396	396	396
Company Total		1,056	1,056	1,056	1,056	1,056	1,056	1,056	1,056	1,056
Al Mansora Fertilizer Company										
Talkha	PLN	–	–	–	–	–	396	396	396	396
Alexandria Fertilizer Company (AlexFert) (Subsidiary of Abu Qir Fertilizers)										
Abu Qir (Near Alexandria) (2006)	UCT	–	–	–	–	396	396	396	396	396
El Amria	PLN	–	–	–	–	–	–	660	660	660
Company Total		0	0	0	0	396	396	1,056	1,056	1,056
Al-Nasr Co. for Coke & Basic Chemicals										
El-Tabbin, Helwan	OPR	33	33	33	33	33	33	33	33	33
Egyptian Basic Industries Co. (EBIC)										
Ain Sukhna	UCT	–	–	–	–	–	–	660	660	660
Egyptian Company for Chemical Industries (KIMA)										
Aswan	OPR	126	126	126	126	126	126	126	126	126
Egyptian Fertilizer Company (EFC)										
Ain Sukhna I (near Suez)	OPR	400	400	400	400	400	400	400	400	400
Ain Sukhna II (near Suez)	UCT	-	-	-	-	396	396	396	396	396
Company Total		400	400	400	400	796	796	796	796	796
El Delta Company for Fertilizers and Chemical Industries, Talkha-Dakahlia										
Talkha I	OPR	120	120	120	120	120	120	120	120	120
Talkha II	OPR	396	396	396	396	396	396	396	396	396
Company Total		516	516	516	516	516	516	516	516	516
El Nasr Company for Fertilizers and Chemical Industries, Attaka-Suez "Semadco"										
Suez II	OPR	132	132	132	132	132	132	132	132	132
Company Total		132	132	132	132	132	132	132	132	132
Helwan Fertilizers										
Helwan (2007)	UCT	–	–	–	–	–	–	396	396	396
Misr Oil Processing Company (MOPCO)										
Damietta (2008)	UCT	–	–	–	–	–	–	396	396	396
Egypt Total		2,263	2,263	2,263	2,263	3,055	3,451	5,563	5,563	5,563

a. OPR = Operating; PLN = Planned; UCT = Under construction.

phosphate-bearing formation is known as the Duwi Formation. At the Bahia Oasis north of Abu Tartur the equivalent formation is the El-Hefuf Formation. The Duwi Formation is subdivided into the Lower, Middle, and Upper Members. The Lower Member of the Duwi Formation is the most important member at Abu Tartur, where the beds form a single seam averaging 12 m thick (Baioumy, 2002). In the Nile Valley and the Red Sea areas, the Upper Member of the Duwi Formation contains the economically exploitable beds.

Red Sea Area—The sedimentary rocks in which the phosphate deposits occur in the Red Sea area have been subjected to considerable structural deformation. The phosphate-bearing beds are found in basin-like structures surrounded by Precambrian granites and other rock types, except around Wadi Gasus where the sedimentary sequence extends to the coast.

A group of mines was located in the Safaga area, about 20-30 km south and southeast of the port of Safaga. Phosphate product was shipped to Safaga over a 27.5-km-long, 1-m-gauge railway. In the Safaga area three basin-like depressions are known as the Um El Huetat, Mohammad Rabah, and Wasif. Up to three phosphate beds, from 1.3 to 2.0 m thick,

Table Egypt 2. Egypt—Urea Plant Capacities

Region/Country Company/Location	Plant Status[a]	Type[b]	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	Indefinite
	(tons x 1,000)										
Africa/Egypt											
Abu Qir Fertilizers and Chemical Industries Co. (AFC)											
Abu Qir I, Alexandria	OPR	P	465	512	512	512	512	512	512	512	512
Abu Qir III, Alexandria	OPR	G	600	578	578	578	578	578	578	578	578
Company Total			1,065	1,090	1,090	1,090	1,090	1,090	1,090	1,090	1,090
Al Mansora Fertilizer Company											
Talkha	PLN	G	–	–	–	–	–	635	635	635	635
Alexandria Fertilizer Company (AlexFert) (Subsidiary of Abu Qir Fertilizers)											
Abu Qir (Near Alexandria) (2007)	UCT	G	–	–	–	–	635	635	635	635	635
Egyptian Fertilizer Company (EFC)											
Ain Sukhna I (near Suez)	OPR	G	635	635	635	635	635	635	635	635	635
Ain Sukhna II (near Suez)	UCT	G	–	–	–	–	635	635	635	635	635
Company Total			635	635	635	635	1,270	1,270	1,270	1,270	1,270
El Nasr Company for Fertilizers and Chemical Industries, Attaka-Suez (Semadco)											
Talkha	OPR	P	520	520	520	520	520	520	520	520	520
Helwan Fertilizers											
Helwan, Egypt (2007)	UCT	G	–	–	–	–	–	–	635	635	635
Misr Oil Processing Company (MOPCO)											
Damietta (2008)	UCT	G	–	–	–	–	–	–	635	635	635
Egypt Total			2,220	2,245	2,245	2,245	3,515	4,150	5,420	5,420	5,420

a. OPR = Operating; PLN = Planned; UCT = Under construction.
b. P = prilled; G = granular.

were mined in the Safaga area (Savage, 1987). The P_2O_5 content of the beds ranged from 20% to 28% (Savage, 1987). The phosphate beds could dip up to 30°.

Mining began in 1911 in the Safaga area under the British-owned Egyptian Phosphate Co. In 1956 the mines were nationalized and operated by the Safaga Phosphate Co., a subsidiary of the Egyptian General Organization for Mining and Geological Research. In 1975 the mines in the Red Sea area were reorganized under the Red Sea Phosphate Co.

All mining was performed underground by room and pillar and short-wall systems. Part of the output was sundried at the mine. After crushing and screening, the entire output was shipped to Safaga where it was finally dried in an oil-fired rotary furnace. The product was sold as Saphos. A partial analysis of the product was given as 29.30% P_2O_5, 9.84% $CaCO_3$, 1.38% Fe_2O_3+Al_2O_3, and 4.00% SiO_2 (Savage, 1987).

The Quseir (or Kosseir) group of mines was located inland of the port of Quseir about 80 km south of Safaga. Seven mines were based on ore bodies separated by intrusions and erosion. The economically exploitable deposits were located in synclinal or monoclinal deposits with beds dipping at up to 20°. The P_2O_5 content of the mined ore was generally in the range of 20%-30%; however, the P_2O_5 content could reach 37% (Savage, 1987).

The Quseir Deposits were worked between 1912 and 1953 by Stá. Eqiziana per l'Estrazoine ed il Commercio dei Fosfati. In 1951 the Egyptian government acquired a 50% interest, and after nationalization the Quseir Phosphate Company was formed. The Red Sea Phosphate Company took over operations in 1975. Savage (1987) reported that additional reserves at Abu Shegela were under development to replace dwindling reserves.

All mines were underground operations using the room and pillar method. The ore was crushed, screened, and dried at the mine and transported to the port of Quseir. Some of the material was washed with seawater and dried. The product was typically about 30% P_2O_5.

The Hamrawein Deposit is located 40 km south of Safaga, and the Hamrawein Beneficiation Complex is located on the Red Sea coast 20 km north of Quseir. Two beds of the Upper Member of the Duwi Formation are workable in this area. These beds vary in thickness from 0.5 to 0.8 m and have a range of P_2O_5 contents from 12.5% to 20% (Savage, 1987). Reserves were originally estimated at 40 million tons.

Development was initiated by the Safaga Phosphate Company, and Industrial Export of Romania was to supply assistance for the establishment of a mine. Production commenced in 1978. Original planned capacity, 600,000 tons of concentrate per year, was never achieved. There was a plan to increase run-of-mine ore production from 180,000 tpy to 1.2 million tpy by the late 1980s.

All mining was by underground methods. The ore was railed to Hamrawein for crushing, sizing, washing, and drying. Two grades of rock were produced, 26% P_2O_5 and 28%-29% P_2O_5.

In 2000 the Red Sea Phosphate Company and the Hamrawein operations were merged with the El Nasr Phosphate Company, and the name was changed to the El Nasr Mining Company (ENMC). ENMC indicates there are five deposits with 1.6 million tons of reserves remaining in the Red Sea area (ENMC, 2006). The minimum P_2O_5 specification for Red Sea phosphate rock is 27% with 1.8% Fe_2O_3, 0.44% Al_2O_3, 5%-7% CO_2, and 6%-8% SiO_2.

Abu Tartur Deposit—The Abu Tartur Phosphate Deposit was discovered in 1961 during the course of a geologic survey (Savage, 1987). In 1969 a drilling program with detailed mapping was conducted by the Geological Survey of Egypt. Technical aid was provided by the U.S.S.R. in 1973, and Sofremines of France and Alusuisse became involved in 1976. Technical studies indicated the ore could be concentrated by flotation. The World Bank approved a US $11 million loan in 1979 for a feasibility study. In 1980 the first phase of an underground mine was developed by the Ministry of Industry and Technology of Egypt. Currently the owner and operator is the Egyptian General Executive Organization for the Industrial and Mining Complexes (IMC).

The Abu Tartur Plateau lies between the Dakhla and Kharga Oases about 50 km west of El Kharga City, capital of New Valley Governorate. The plateau is roughly oval in outline with an area of 112 km^2. The plateau is bounded by scarps on all sides but the northwest. The phosphate beds outcrop on the scarp that faces southeast. The Lower Member of the Duwi Formation is particularly well developed in the Abu Tartur area. Phosphate beds also occur near Dakhla and Kharga Oases; however, they are not as well developed in terms of thickness, and they have lower P_2O_5 contents.

At Abu Tartur the Lower Member of the Duwi Formation averages about 3.9 m in thickness and is a single flat-lying bed with minimal structural deformation and faulting. The phosphate content of the bed averages about 25% P_2O_5 to a maximum of about 30% P_2O_5 (Table Egypt 3) (Savage, 1987).

IFDC characterized samples of Abu Tartur matrix and concentrate in 1980. The samples were provided by IMC. Chemical analyses (Table Egypt 4) indicate that the matrix sample contained 27.34 wt % P_2O_5, 2.97 wt % Fe_2O_3, and 0.77 wt % Al_2O_3.

Table Egypt 3. Abu Tartur, Chemical Analyses of Phosphate Ore[a]

Ore	Average Grade	Maximum Grade
	(%)	
P_2O_5	25.07	29.78
CaO	41.07	45.70
Al_2O_3	1.76	9.59
Fe_2O_3	2.64	7.72
MgO	1.68	5.54
SiO_2	6.35	14.05
SO_3	3.12	15.00
CO_2	6.97	19.32
H_2O	2.14	11.20
LOI[b]	8.78	15.03
Insoluble residue	6.72	17.66

a. Source: Savage (1987).

b. Loss on ignition = weight loss, 1 h, 1000ºC.

Table Egypt 4. Chemical Composition of Abu Tartur Phosphate

Constituent	Wt %		
	Matrix[a]	Concentrate[a]	Product[b]
CaO	45.98	47.68	42.1-45.7
P_2O_5	27.34	31.31	27.7-29.6
F	2.58	3.28	NA[c]
CO_2	5.17	NA	NA
Na_2O	0.79	0.90	0.6-0.7
K_2O	0.11	0.04	0.1-0.3
MgO	1.69	0.56	0.8-1.2
Fe_2O_3	2.97	2.55	2.9-4.3
Al_2O_3	0.77	0.14	0.3-0.5
SiO_2	4.59	1.49	NA
Total S	2.83	2.21	NA
Sulfate S	1.89	1.50	5.6-9.5
Sulfide S	0.94	0.71	NA
Organic C	0.56	NA	
SrO	0.19	NA	
As (ppm)	45	–	1-3
TiO_2	0.133	NA	
Cl	0.017	NA	
Cd (ppm)	2	NA	1.5-4.1
NAC-soluble P_2O_5[d,e]	3.5	NA	

a. IFDC analyses.
b. Current Abu Tartur Product (IMC, 2006).
c. NA = not analyzed.
d. Neutral ammonium citrate-soluble P_2O_5.
e. Determined on a sample free of dolomite.

Mineralogical analysis indicated the matrix was composed of francolite (69.3 wt %), gypsum (11.8 wt %), dolomite (6.7 wt %), smectite clay (3.0 wt %), goethite (2.7 wt %), pyrite (2.1 wt %), glauconite (2.0 wt %), quartz (1.3 wt %), and a trace of sphalerite.

The beneficiation process upgraded the ore to 31.31 wt % P_2O_5 and reduced the iron and aluminum contents (2.55 wt % Fe_2O_3 and 0.14 wt % Al_2O_3). Mineralogical analysis indicated the beneficiated concentrate was composed of francolite (85-86 wt %), quartz (2 wt %), gypsum (5-6 wt %), pyrite (2-3 wt %), goethite (2-3 wt %), dolomite (1-2 wt %), smectite clay (1-2 wt %), and a trace of orthoclase feldspar.

The X-ray diffraction (XRD) analysis of the francolite in the two samples indicated a unit cell a-value of 9.347 Å ± 0.001. This corresponds to a francolite with a maximum P_2O_5 content of 38.49 wt % and a hypothetical CO_2 content of 2.9 wt %. The matrix sample had a neutral ammonium citrate (NAC)-soluble P_2O_5 value of 3.5%. Significantly, the cadmium content was very low at 2 ppm. Chemical analyses of current product (Table Egypt 4) indicate P_2O_5 contents of 27.7-29.6 wt % P_2O_5.

The Abu Tartur Mine is an underground mine utilizing a fully mechanized long wall technique. Each mining panel has an average length of 1,100 m (IMC, 2006). One panel is being produced and another panel is ready for exploitation. Each panel has a mining system with a design capacity of 1.2 million tpy. The maximum height of a working seam is 3.4 m. The minimum seam thickness is 1.8 m. There is a hard dolomitized roof over the phosphate seam. If the hard bed is absent, 0.4 m of phosphate ore will be left in the roof. Ore with more than 3% MgO and/or 5% green clay will not be extracted.

Beneficiation consists of crushing, washing, screening, thickening, attrition scrubbing, hydroclassifying, screen filtering, magnetic separation, and dewatering (IMC, 2006). The beneficiation plant was constructed to house three lines. The capacity of each line is 1.3 million tpy of run-of-mine ore to produce 730,000 tpy of concentrate. One beneficiation line has been installed in the Abu Tartur Beneficiation Plant. Coarse and fine concentrates are produced and stored outdoors in piles. Concentrates are dried in a rotary dryer. There are two loading stations for trains. The rail line has been completed to the mining area. Current production is between 500,000 tpy (IMC, 2006) and 600,000 tpy (*Fertilizer International*, 2006) of concentrate ranging from 28% to 30% P_2O_5. The concentrate is used by the Abu Zaabal Chemical and Fertilizer Company to produce single superphosphate (SSP) and triple superphosphate (TSP), and by the Egyptian Financial and Industrial Company (EFIC) to produce SSP.

Indicated reserves in the Abu Tartur Mine area are 715 million tons with an average bed thickness of

3.5 m. The current license area for the mine (14 km^2) has reserves of 65 million tons of unoxidized ore and 20 million tons of oxidized ore which can be extracted by open-pit mining.

In the 1990s the Egyptian government invested over US $45.0 million in the Abu Tartur project (*Fertilizer International*, 2006). This included development of facilities for water, power, and a 600-km rail link. Original plans were for concentrate production at 2 million tpy. Additional plans were for phosphoric acid, monoammonium phosphate (MAP), diammonium phosphate (DAP), and SSP production. The project was reevaluated in 2000 (*Fertilizer International*, 2000), and private funding was sought for further development. The government invited bids on the project in 2003. There have been no significant developments on the project since 2003.

Nile Valley Area—In the Nile Valley, there are deposits on both the west bank and the east bank of the river. IFDC was involved in a project in the area in 2005.

El Nasr Phosphate Company (ENPC) was established in 1960 to mine the Cretaceous age, sedimentary phosphate deposits on the east side of the Nile Valley between Luxor and Aswan. As noted, in 2000 the Red Sea Phosphate Company merged with the ENPC, and the name was changed to El Nasr Mining Company (ENMC). In 2001 the phosphate mines of the Abu Zaabal Fertilizer and Chemical Company on the west side of the river were merged with ENMC.

The main offices of ENMC are at the East Sebaiya (or Sabaiya) area about a 1.5-h journey to the south from Luxor on a generally well-paved road that parallels the main rail line in the Nile Valley. At the present time, ENMC produces about 2 million tpy of phosphate rock; about half of the production is exported. Each day a trainload of phosphate rock from the Nile Valley operations is delivered to the Safaga Port. There are two dedicated trains. Apparently, there is not enough rolling stock because tandem trucks with capacities of 70-75 tons and single dump trucks are also used to transport the material to Safaga (400-450 km). It is approximately 400 km to the harbor and approximately 800 km to the local companies (located near Cairo) that purchase phosphate rock. The rock is transported by truck, barge, and rail to the in-country customers.

There are four crushers in the ENMC main office and production area (Figure Egypt 2). A three-story washer plant has not been used since 1996 (Figure Egypt 3). A 32%-33% P_2O_5 product could be produced, but total P_2O_5 recovery was only about 50%. In the present beneficiation/processing scheme, the material is jaw crushed and then milled with impact crushers (hammer mills) or Raymond Mills (cone crushers). The minus 5-mm fraction can range from 30% to 33% P_2O_5 with 70% P_2O_5 recovery. Depending on the mine, the middling (>5 mm to <10 mm) can range from 24% to 27% P_2O_5 (15% of total P_2O_5). Oversize material (amounting to 15% of the total P_2O_5) with 15%-20% P_2O_5 is rejected and stockpiled. The ENMC laboratory is located in the washer plant. The laboratory functions as a quality control laboratory; it is certified by the International Standards Organization (ISO). The sun drying and dispatch area where the trucks and trains are loaded is located to the south of the washer plant and main office complex.

The current ENMC mines are located about 40-45 km into the interior. There are 11 mines in the area and 10 are being worked. The producing phosphate bed in the area is 1 to 2.5 m thick (Figure Egypt 4). The overburden can range from practically nothing to 25 m thick. Mining is very selective, using mainly power shovels and large front-end loaders (Figure Egypt 5). Blasting is employed when needed. There is one drag line in use, and another drag line had been ordered in 2005. Trucks in the mines generally range from 25- to 30-ton capacity. Tandem dump trucks generally haul the ore to the plants. Some of the trucks are owned by ENMC, and many are contracted haulers.

The one mine in the area that has not been worked contains ore at 24% P_2O_5. The ore and product across the area are very consistent in quality with respect to grade and impurities. A combined product with an average of about 30%-31% P_2O_5 is expected across the area.

These Cretaceous age sedimentary phosphates are lightly to moderately indurated. The mines may be termed small- to medium-scale mines. Relatively

Figure Egypt 2. East Sebaiya Area, Small Crusher, ENMC Office Area

Figure Egypt 3. East Sebaiya Area, Washer Plant, ENMC Office Area

Figure Egypt 4. Phosphate Ore Bed, Open Pit, East Sebaiya Area

Figure Egypt 5. Open Pit Mine, East Sebaiya Area small-scale, highly mobile equipment is needed to mine the thin ore beds under the structural conditions of the area. Many small faults are apparent in the strata of the mines, and the ore beds undulate, pinch, and thicken.

The 10 mines extend in a belt about 10-15 km to the east. Exploration is continuing toward the east. There is a crushing/grinding operation associated with one group of mines.

The ore at West Sebaiya occurs under the water table in the flood plain of the River Nile. A flotation plant at the ENMC site was built in 1988 by G.E. Technologies, England; however, operations ceased in 1994. The high cost of reagents was cited as the reason for closure. Only the scrubbing section of the beneficiation plant is presently used. A product containing 28%-29% P_2O_5 at 50%-65% recovery is marketed for export.

In 2005 the flotation plant was apparently in remarkably good condition, considering it had not been used for over 10 years. Corrosion was not apparent. It appeared that the Wemco flotation cells and other equipment could be restarted.

The main portion of the product at West Sebaiya is produced by dry crushing and grinding (Figure Egypt 6). The minus 5-mm product from two crushers assays about 27% P_2O_5. The middling size assays about 24% P_2O_5. The 27% P_2O_5 product is marketed in Egypt.

In the 48-km^2 mining area at West Sebaiya, there were 30 contractors operating small mines in 2005 (Figure Egypt 7). Typically, the overburden to ore ratio is about 2:1. There are two phosphate rock layers. The upper layer is 0.8 m thick. There is a middle layer of limestone, and the lower phosphate bed is 1.2 m thick. West Sebaiya produced about 375,000 tpy of all products in 2005.

Low-grade and high-grade samples of East Sebaiya phosphate rock have been characterized at IFDC. Chemical and mineralogical data were equated using a linear programming technique to

Figure Egypt 6. West Sebaiya Area, Crushing and Grinding Unit (Note Phosphate Rock Sun Drying in the Foreground)

Figure Egypt 7. West Sebaiya Area, Small Contractor-Operated Mine

develop an approximate mineralogical modal analysis for the low-grade sample (Table Egypt 5). Apatite (carbonate fluorapatite or francolite) is the most abundant mineral species (66.9 wt %). Quartz (13.6 wt %) and calcite (8.8 wt %) are the most abundant gangue minerals. Kaolinite (2.38 wt %), a clay mineral, and goethite (2.30 wt %) are present as minor components in the low-grade composite. The unit cell a-value dimensions of the francolite were determined as 9.343 ± 0.001Å. The P_2O_5 concentration of a pure francolite sample would be 37.79 wt %. The CO_2 content of a pure francolite sample would be 3.45 wt %.

Chemical and mineralogical data were equated using a linear programming technique to develop an approximate mineralogical modal analysis for the high-grade sample (Table Egypt 6). Francolite is the most abundant mineral species (81.1 wt %). Quartz (5.6 wt %) and calcite (4.7 wt %) are the most abundant gangue mineral species. Kaolinite (1.2 wt %) and goethite (2.0 wt %) are present as minor components in the high-grade composite.

The unit cell a-value dimension of the apatite in the high-grade composite sample was determined as 9.339 ± 0.001Å. The P_2O_5 concentration of a pure francolite sample would be 37.08 wt %. The CO_2 content of a pure francolite sample would be 3.99 wt %.

Table Egypt 5. Approximate Mineralogical Modal Analysis, Low-Grade Product, East Sebaiya Phosphate Rock Composite

Chemical Analysis		Francolite[a]	Quartz (SiO_2)	Calcite ($CaCO_3$)	Kaolinite	Goethite (FeOOH)	Unassigned
	(wt %)[b]						
CaO	41.52	36.57		4.95			
P_2O_5	24.99	24.99					
F	2.59	2.59					
Cl (ppm)	442						442
SiO_2	14.72		13.61		1.11		
Al_2O_3	0.94				0.94		
Fe_2O_3	2.07					2.07	
Na_2O	0.42	0.39					0.03
K_2O	0.05						0.05
MgO	0.39	0.20					0.19
SrO	0.17						0.17
CO_2	7.24	2.18		3.89			1.17
S (total)[c]	0.34						–
SO_4	0.95						0.95
C (organic)	0.54						0.54
Cd (ppm)	9						9
NAC1[c,d]	3.6						–
NAC2[c, d]	5.6						–
Free H_2O[c,e]	0.69						–
LOI[c,f]	10.35						–
Total	96.63	66.92	13.61	8.84	2.05	2.07	3.14
+ H_2O[g]					0.33	0.23	
Total (+ H_2O)					2.38	2.30	

a. See text for composition.

b. wt % except as noted.

c. Not included in totals.

d. NAC1 P_2O_5 = neutral ammonium citrate-soluble P_2O_5, AOAC method for fertilizers, first extraction.
NAC2 P_2O_5 = second extraction on residue of first extraction.

e. Free H_2O = weight loss, 1 h, 105°C.

f. Loss on ignition = weight loss, 1 h, 1000°C.

g. +H_2O = combined water in the mineral structure.

The first NAC-soluble P_2O_5 value for the low-grade composite sample was 3.6% P_2O_5 (Table Egypt 5). The second NAC extraction (NAC2) resulted in a value of 5.6% P_2O_5. The first extraction resulted in a low value due to the fact that free calcite suppresses the dissolution of the apatite during this analytical procedure.

The first NAC-soluble P_2O_5 value for the high-grade composite sample was a value of 4.98% P_2O_5 (Table Egypt 6). The second NAC extraction (NAC2) resulted in a value of 6.0% P_2O_5. The first extraction values were suppressed by the presence of free calcite in samples.

The total estimated resource of the phosphate deposits in the eastern desert is 1.878 billion tons (Eng. Abdel Malik Farah, 2005). The resources under the ENMC mining lease are estimated at 217 million tons. Proven reserves (as of Decem-

Table Egypt 6. Approximate Mineralogical Modal Analysis, High-Grade Product, East Sebaiya Phosphate Rock Composite

Chemical Analysis		Francolite[a]	Quartz (SiO_2)	Calcite ($CaCO_3$)	Kaolinite[a]	Goethite (FeOOH)	Unassigned
	(wt %)[b]						
CaO	46.93	44.32		2.61			
P_2O_5	29.85	29.85					
F	3.12	3.12					
Cl (ppm)	361						361
SiO_2	6.15		5.58		0.57		
Al_2O_3	0.48				0.48		
Fe_2O_3	1.77					1.77	
Na_2O	0.54	0.54					
K_2O	0.03						
MgO	0.41	0.27					0.14
SrO	0.20						0.20
CO_2	5.73	3.00		2.05			0.68
S (total)[c]	0.54						–
SO_4	1.50						1.50
C (organic)	0.32						0.32
Cd (ppm)	10						10
NAC1[c,d]	4.98						–
NAC2[c,d]	6.0						–
Free H_2O[c,e]	0.77						–
LOI[c,f]	9.25						–
Total	97.04	81.10	5.58	4.66	1.05	1.77	2.88
+ H_2O[g]					0.17	0.20	
Total (+ H_2O)					1.22	1.97	

a. See text for composition.
b. wt % except as noted.
c. Not included in totals.
d. NAC1 P_2O_5 = neutral ammonium citrate-soluble P_2O_5, AOAC method for fertilizers, first extraction.
NAC2 P_2O_5 = second extraction on residue of first extraction.
e. Free H_2O = weight loss, 1 h, 105°C.
f. Loss on ignition = weight loss, 1 h, 1000°C.
g. $+H_2O$ = combined water in the mineral structure.

ber 23, 2004, minus mined material) are about 42.5 million tons at an average P_2O_5 content of 26.9%. All figures are in-situ resources and reserves. ENMC (2006) indicates there are 24 million tons of proven resources at West Sebaiya.

Phosphate Fertilizer Production—The Abu Zaabal Fertilizer and Chemical Company has the capacity to produce 45,000 tpy of P_2O_5 as phosphoric acid (IFDC, 2006c). Capacity to produce MAP and DAP at Abu Zaabal is 45,000 tpy of P_2O_5 (IFDC, 2006d).

In 2005, ENMC announced it was establishing a joint venture with Indian Farmers Fertiliser Cooperative Ltd. (IFFCO). The new company would be called the Indo Egyptian Fertilizer Company (IEFC). IFFCO would hold a majority stake (76%) in the venture (*Fertilizer International*, 2006). Several capacities had been considered for the facility. *Fertilizer International* (2006) indicated a capacity of 500,000 tpy of P_2O_5.

The plant would be built at Edfu on the former site of ENMC operations in the area. The reported cost was estimated as US $325 million. Construction was scheduled to start in 2007 with completion in 2009/10. IFFCO and ENMC also signed an agreement wherein ENMC will supply phosphate rock for IFFCO operations in India.

The Egyptian Financial and Industrial Co. has been producing phosphate fertilizers since 1929 (*Fertilizer International*, 2006). At Kafr El Zayat, 120 km north of Cairo, EFIC produces sulfuric acid and has a 450,000-tpy powdered SSP plant. The associated granulation plant has the capacity to produce 300,000 tpy of granular SSP.

At Mahabad, Assuit, near Aswan, EFIC has two sulfuric acid plants with a combined capacity of 205,000 tpy. There is also a 450,000-tpy powdered SSP plant and a granulation unit to produce 300,000 tpy of granular product.

Potassium Resources

In 1982 a potash bed (sylvite) was discovered in oil well FF-83-2 in the Gulf of Suez area (Hite and Wassef, 1983). The potash occurrence is only known from oil well logs. The presence of potash results in a distinct signature in gamma ray logs.

The potash beds are formed in the Miocene age Zeit and South Gharib Formations. At least two potash beds can be correlated over long distances. One potash bed in the top salt bed of the Zeit Formation underlies an area of 250 km^2. A potash bed in the fifth salt bed of the South Gharib Formation underlies an area of more than 100 km^2. The average thickness of the Zeit Formation potash bed is 8 m. The thickness of the potash bed in the South Gharib Formation locally reaches more than 25 m. The thickness of the total evaporities in the Gulf may exceed 1,500 m. The potash deposits extend offshore under the Red Sea.

Interpretation of geophysical logs indicates that sylvite (KCl) and langbeinite [$K_2Mg_2(SO_4)_3$] are the dominant potash minerals. Both of these minerals are valuable potash products. A chemical analysis of a sidewall core from well FF-82-2 showed 27.60% K_2O (Hite and Wassef, 1983). Hite and Wassef (1983) pointed out that portions of the deposits are within the depth range of conventional shaft mining and the substantial thickness of the lowermost bed, when at great depth, may make it a suitable candidate for solution mining. One of the attractive features of the deposits is their location on the Red Sea coast near the southern entrance of the Suez Canal.

Michalski (1996) reported that the Egyptian government issued licenses to two companies for exploration and development of potash deposits. BHP Minerals International Exploration Inc. was granted a license for a 14,800-km^2 area near Ras Gharib on the Gulf of Suez. Bota was granted a license for a 14,000-km^2 area in the region of the Gulf of Suez and the Red Sea. Michalski (1997) reported that exploration was still in progress by the two companies.

No further references are made to exploration in these areas in continuing U.S. Geological Survey reports. No references to the Egyptian potash deposits list any resource figures.

Sulfur Resources

Approximately 4,500 tpy of byproduct elemental sulfur is produced in Egypt (Bermúdez-Lugo, 2003). The Alexandria Mineral Oil Company awarded Technip-Cofexip of France a contract for operation of an acid gas treatment plant in Alexandria. There are several occurrences of gypsum deposits in the desert west of Cairo (Bermúdez-Lugo, 2003).

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EQUATORIAL GUINEA

The Republic of Equatorial Guinea (Figure Equatorial Guinea 1) consists of a mainland area (Rio Muni Province) and several islands. The largest island, Bioko Island, is the site of the capital, Malabo. The Republic of Equatorial Guinea is bordered to the north by Cameroon and Nigeria, to the east and south by Gabon, and to the west by the Atlantic Ocean and Sao Tomé e Principe. Total area is 28,051 km^2 and arable land is approximately 4.6%. The population was estimated in mid-2005 as 540,109 inhabitants (World Factbook, 2006).

The transportation network consists of 2,880 km of roadways. There is a short section of railroad originating from Bata, the main port on the mainland. The main port on Bioko Island is Malabo. There are three airports with paved runways and one airport with an unpaved runway. There are four pipelines—gas (39 km), condensate (37 km), liquid natural gas (4 km), and oil (27 km).

Precambrian granitic, mafic, and metamorphic rocks outcrop on over 95% of the Equatorial Guinea mainland. Cretaceous marine sediments, consisting of conglomerates, sandstones, marls, and limestones outcrop in the extreme southwest of the country. Tertiary to Recent sediments form the narrow coastal plain. The island of Bioko is a Tertiary age compound volcanic cone composed of basalt flows, pyroclastics, and agglomerates (Mitchell-Thorne, 1970).

Nitrogen Resources

Although oil was first discovered in the 1960s, oil was first produced offshore by Mobil in 1991 from the Alba Field off Bioko Island (MBendi, 2005). The Zafiro Field northwest of Bioko Island was discovered in 1995 by ExxonMobil and Ocean Energy (purchased by Devon Energy in 2003) and is the largest single oil-producing field in the country (EIA, 2005). Initial production in 1995 was 7,000 barrels per day (bpd); in 2004, production was 280,000 bpd. A platform is located on the field, and a floating production, storage, and offloading (FPSO) vessel was located on the field in 2003.

The second major producing oil field in Equatorial Guinea is located offshore Rio Muni Province. The field was discovered by Triton Energy in 1999 and was brought into production in 2000. Amerada Hess Corp. acquired Triton in 2002 (Explorer, 2003). The field is estimated to contain 300-800 million barrels of oil. Additional discoveries have been made in the area.

The Alba Field continues to produce. Initial production at Alba focused on gas and condensates. Gas was mainly flared through the 1990s.

Equatorial Guinea oil production in 2003 was 371,700 bpd (EIA, 2005). Oil production in 2004 was 420,000 bpd (World Factbook, 2006). Natural gas (1.39 billion m^3, 2004) was produced from the Alba Field by a joint venture of Marathon Oil (63%), Noble Energy Equatorial Guinea Ltd. (34%), and Compañia Nacional de Petróleos de Guinea Equatorial (3%) (Mobbs, 2004). Liquefied petroleum gas (875,000 tons, 2004) was produced at Punta Europa by a joint venture of Marathon Oil Co. (52%), Noble Energy Equatorial Guinea Ltd. (28%), and Guinea Equatorial Oil and Gas Marketing Ltd. (20%) (Mobbs, 2004). Methanol (913,000 tons, 2004) was produced at Punta Europa by Atlantic Methanol Production Co. LLC (Marathon Equatorial Guinea Methanol Ltd. [45%], Samedan Methanol [45%], and Guinea Equatorial Oil and Gas Marketing Ltd. [10%]) (Mobbs, 2004).

Total Population: 540,109 (July 2006 est.)
Total Area: 28,051 sq km
Population Growth Rate: 2.05% (2005 est.)
Life Expectancy At Birth: 49.54 years
GDP Per Capita: $50,200 (2005 est.)

Figure Equatorial Guinea 1. Geology, Major Cities, and Transportation Network

A 3.8 million-tpy liquefied natural gas facility is being built on Bioko Island by Marathon Oil (75%) and Compañia Nacional de Petróleos de Guinea Equatorial (25%) (Mobbs, 2004). Output will be sold to British Gas under a 17-year agreement. The project is scheduled to be onstream in late 2007. The facility will cost US $1.4 billion (EIA, 2005).

According to the EIA (2005), gas production in 2003 (1.27 billion m^3) was balanced with gas consumption (1.27 billion m^3). The Punta Europa power plant runs on natural gas and supplies power to Bioko Island.

It is difficult to make a definite estimate of Equatorial Guinea oil reserves because reserves are being added practically on a weekly or monthly basis. Proven oil reserves are estimated at 1.28×10^9 barrels (EIA, 2005). Proven natural gas reserves are 3.68×10^{10} m^3 while probable reserves are estimated at 1.25×10^{11} m^3.

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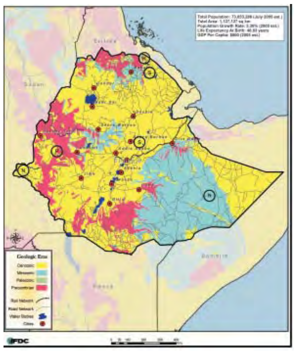
ETHIOPIA



The Federal Democratic Republic of Ethiopia (Figure Ethiopia 1) is bordered by Eritrea, Dijbouti, and Somalia to the north; Somalia to the east and south; Kenya to the south; and Sudan to the west. Ethiopia is totally landlocked. Total area of the country is 1,127,127 km^2 and 10.71% of the land is arable cropland. The population was estimated in mid-2005 as 73.0 million inhabitants (World Factbook, 2006). Annual population growth was estimated at approximately 2.4%. Agriculture and animal husbandry occupies approximately 80% of the labor force. Coffee is the principal export. The transportation network (Figure Ethiopia 1) consists of 4,367 km of paved roads, 29,489 km of unpaved roads, 681 km of 1.0-m railway, and 82 airports of which 14 have paved roads.

Ethiopia lies at the northern end of the East African Rift Valley. Thick sequences of Tertiary volcanic rocks are found along the rift valley through the middle of the country (Figure Ethiopia 1). Precambrian age rocks occur on both sides of the rift but are more prevalent in the western part of the country. Mesozoic and Tertiary sedimentary rocks underlie most of the eastern part of the country. The floor of the valley is filled with volcanics and lacustrine deposits.

Nitrogen Resources

Between 1950 and 1956 Sinclair Oil drilled two deep test wells in the Gumburo and Galadi areas of Ogaden. No discoveries were announced. However, the drilling provided the basis for establishing a stratigraphic column for the area. In 1973-74 Tenneco discovered gas in the Ogaden region.

The Ethiopian government established the Calub Gas Share Company (CGSC) to exploit these reserves of natural gas and condensate. CGSC signed an agreement with Sicor Inc. (U.S.A.) to develop the Calub and Hilala fields (Gebre-Selassie, 2000). Sicor would buy 95% of the shares of CGSC and then form Gazoil Ethiopia Share Co., which would construct a 600-km, 24-inch pipeline to transport the gas and associated liquid to Awash, 200 km east of Addis Ababa.

At Awash a cryogenic liquids plant and two gas-to-liquid process systems would be established. Either 20,000 barrels per day (bpd) of synthetic fuels or a range of petrochemical feedstock would be produced. The waste stream would be used to generate 168 MW of electricity per day. A refinery to process condensate into other products—diesel, gasoline, kerosene, etc.—was included in the project. The plant would also produce 500 tpd of ammonia for feedstock for a urea plant that would be constructed as a part of the integrated project. Total cost of the project was indicated as US $1.5 billion.

The government terminated the agreement with Sicor Inc. and the Russian-owned companies Methanol and Stroytransgas in 2003 (Yager, 2003). In 2004 it was indicated that the Ministry of Mines and Saitake International (SIL) of Jordan would develop the Calub and Hilala gas fields in the Ogaden region (Gebre-Selassie, 2004). SIL would invest up to US $1.5 billion to exploit the deposit. The project would include a gas-to-liquid conversion plant.

The reserve potential of the Calub Field has been indicated as 4 trillion ft^3 of natural gas and 13.6 million barrels of condensate (Gebre-Selassie, 2000).

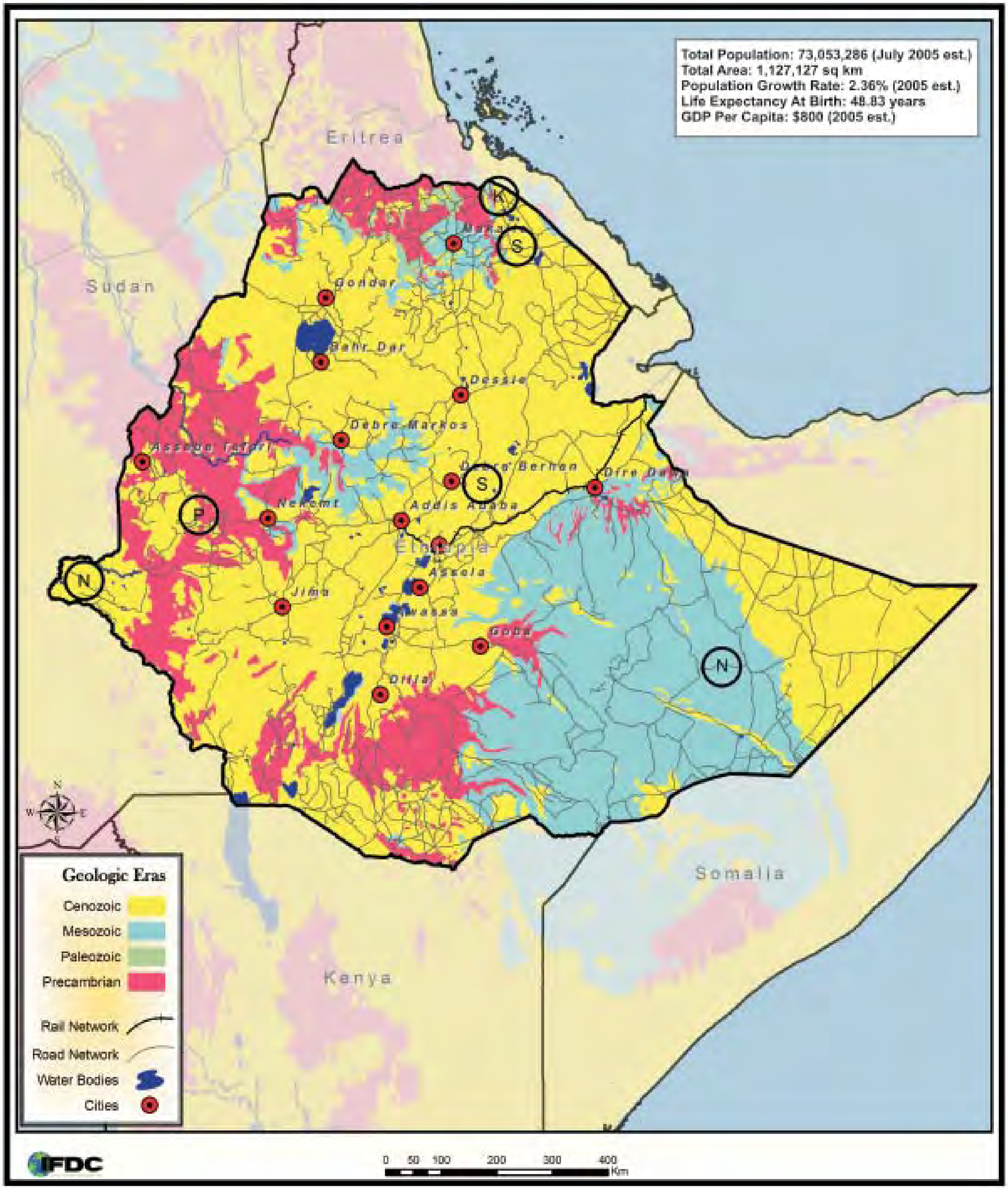


Figure Ethiopia 1. Geology, Major Cities, and Transportation Network

In 2003 the Ministry of Mines signed an exploration agreement for a 15,356-km^2 area in Gumbella State in the western part of the country near Sudan (Gebre-Selassie, 2004). Petroliam Nasional Berhad (PETRONAS) was to spend a minimum of US $5.0 million on exploration. The PETRONAS website (petronas.com) indicates the agreement was signed but offers no details on the project. PETRONAS also signed an agreement to conduct seismic surveys in the Ogaden Basin (Yager, 2003).

The Assab refinery was closed in 1997. Ethiopia has no refining capacity and is totally reliant on imports.

Phosphate Resources

Bikilal Gabbro-Anorthosite Intrusion—The Bikilal Gabbro-Anorthosite Intrusion is located 465 km west of Addis Ababa and 25 km northeast of Gimbi Town in the Welega Administrative Region (Figure Ethiopia 1). The iron ores of the Bikilal Intrusion were first discovered in 1979, and the presence of significant apatite mineralization was reported in 1986 (Assefa, 1987). Pseudostratified gabbroic rocks form an ill-defined zoned concentric structure, which is broken into a number of blocks by faults trending northwest-southeast, west northwest-east southeast, and northeast-southwest (Figure Ethiopia 2). The succession of rock types from the center of the intrusion to the periphery is (1) porphyritic olivine gabbro, (2) massive olivine gabbro, (3) leucocratic hornblende gabbro and anorthosites, and (4) hornblende gabbro (Assefa, 1987). The known north-south extent of the intrusion is about 19 km, and it ranges in width from 2.6 to 8 km, covering an area of approximately 110 km^2. Early work was concentrated in the northeastern area of the intrusion.

Apatite-magnetite-ilmenite zones appear to be restricted to the outer zone of banded hornblende gabbro. Potential ore bodies dip toward the center of the intrusion at angles of 35º-85º and range from 2 to 70 m in thickness. Chemical analyses of 97 selected samples from apatite-ilmenite-magnetite zones indicated an average of 4.56% P_2O_5 (Assefa, 1987).

One sample from Bikilal Deposit (Table Ethiopia 1) has been characterized at IFDC (IFDC, 1987). Mineralogical analysis (normalized) indicates that the rock is composed of amphiboles (53%), magnetite-ilmenite (28%), apatite (17%), and feldspar (2%). The apatite is an igneous hydroxyl-fluorapatite with a low neutral ammonium citrate (NAC) solubility. Therefore its use as a direct-application fertilizer is not normally recommended. Beneficiation is needed to upgrade the ore and remove impurities. Although the P_2O_5 content is low, the size of the well-formed igneous apatite crystals (mean diameter = 272 mm) and nature of the gangue (amphiboles, magnetite-ilmenite) indicate the sample can be beneficiated by some combination of grinding, magnetic separation, and flotation. Concentrates

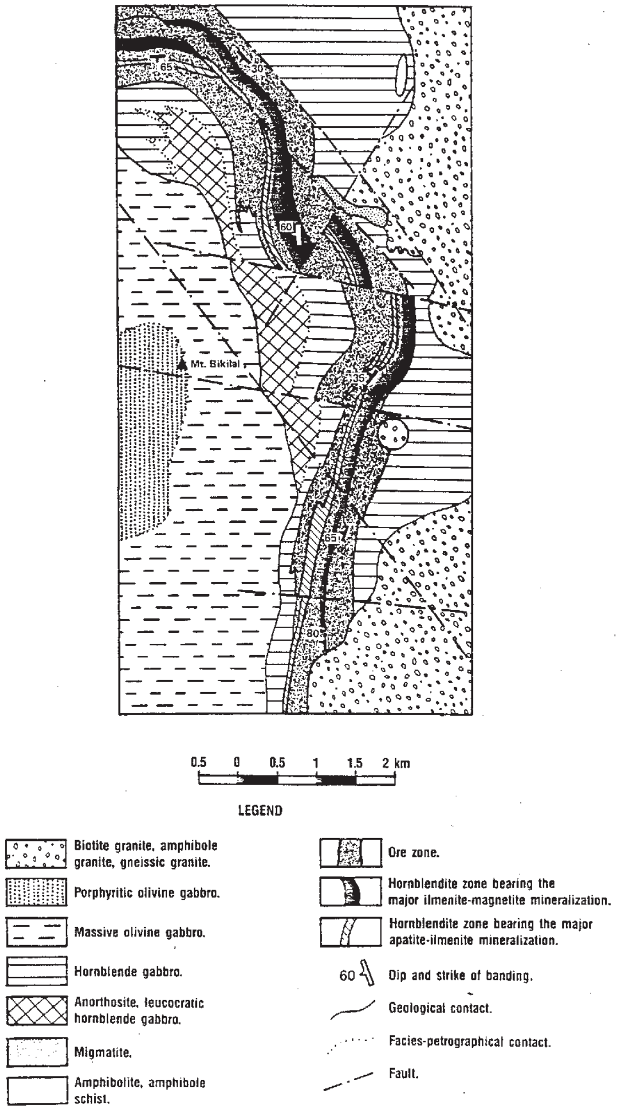


Figure Ethiopia 2. Geology of the Bikilal Apatite-Magnetite-Ilmenite Deposit (modified from Assefa, 1987)

Table Ethiopia 1. Chemical Analysis of a Sample of Bikilal Phosphate Rock

	wt %
P_2O_5	7.2
CaO	15.0
F	0.3
SiO_2	25.5
Al_2O_3	8.1
Fe_2O_3	23.9
Na_2O	1.2
K_2O	0.14
MgO	6.7
SrO	0.04
BaO	0.24
MnO	0.34
TiO_2	10.90
CO_2	0.4
S (total)	0.2
Cl^{1-} (ppm)	105
C (organic)	0.12
Free H_2O[a]	–
LOI[b]	0.4
NAC-Soluble P_2O_5[c]	0.8

a. Free H_2O = weight loss, 105°C.
b. Loss on ignition, 1,000°C
c. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).

could then be chemically treated to yield a product with agronomically available phosphate.

During the 1987 field season, a concentrated effort was made to locate naturally enriched residual phosphate zones within the deposit (Sisay Abera, Ethiopia Institute of Geological Surveys, personal communication). The viability of the prospect as a source of phosphate eventually may depend on complex mining and utilization of both the apatite and iron-titanium minerals of the deposit (Assefa, 1987).

Reported reserve estimates vary considerably. Yohannes (1994) indicated 127 million tons at 3.5% P_2O_5, 23.8% Fe_2O_3, and 7.3% TiO_2 to a depth of 200 m. Gebre-Selassie (2000) reported that the Ethiopian geologic survey verified over 200 million tons at the Gimbi locality.

Beneficiation by simple sizing and magnetic separation produced concentrates containing up to 36% P_2O_5 (as reported in van Straaten, 2002). However, the recovery rate was only 40%-58%.

Sedimentary Deposits—Sedimentary phosphorite may be present in Ethiopia in Precambrian and younger strata. The Ethiopia Institute of Geological Surveys has identified potential target areas for phosphorite exploration based on preexisting oil company well data, favorable lithologies, and favorable geologic ages (Figure Ethiopia 3). Field traversing of outcrops has been the most commonly employed technique in these areas. This technique has brought limited success in that many of the most favorable areas are mantled by thick overburden (Assefa, 1987, 1991).

Between 1950 and 1956, Sinclair Oil drilled two deep test wells in the Gumburo and Galadi areas

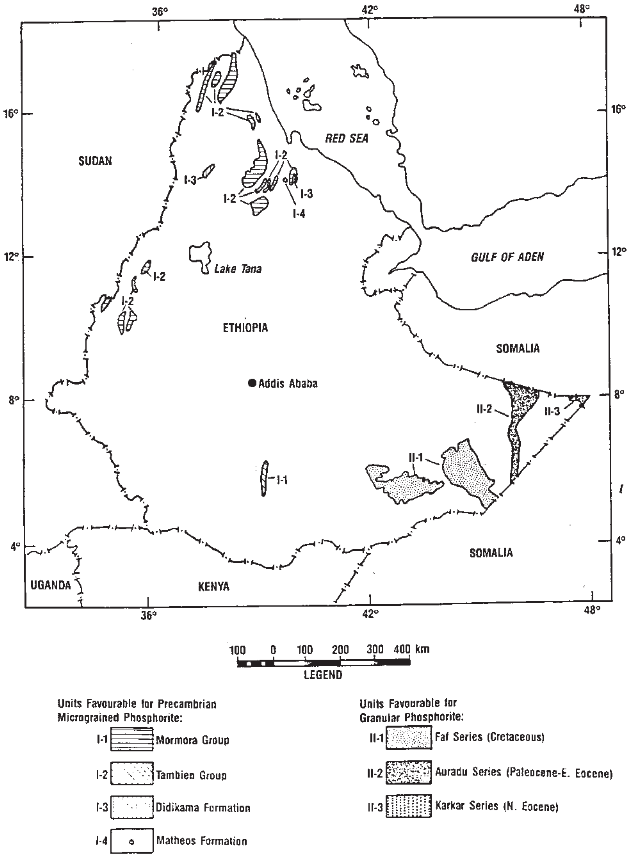


Figure Ethiopia 3. Potential Target Areas for Phosphorite Exploration (modified from Assefa, 1987) of Ogaden. Original company descriptions are not available. Sheldon (1984) gives an overview of the existing information. Phosphate layers apparently were encountered in the boreholes at depths from 792 to 829 m and from 866 to 884 m. The phosphate was reported as Eocene in age, but Sheldon pointed out that, based on geologic maps of the area, these beds should be Jurassic in age. During the 1987/88 field season, a drilling program was to be performed in the western desert near the Somalia border in an attempt to locate the buried outcrop of the beds that Sinclair Oil intersected (Sisay Abera, personal communication). The targeted area was approximately 400 km from the area where Sinclair drilled, and the beds may have less than 10-20 m of loose overburden.

Sheldon (1984) identified two other sedimentary sequences or age groups that have phosphate resource potential in Ethiopia:

1. The Auradu Series of Paleocene-Eocene age in the Central Somali-Ogaden Embayment of eastern Ethiopia.
2. Proterozoic and metasedimentary sequences that outcrop in northern, western, and southern Ethiopia.

This analysis was based on known world phosphate occurrences according to geologic age, paleogeographic settings, and lithologic associations. Sheldon concluded that the Jurassic age rocks of Ethiopia have low potential for phosphate resources. No phosphatic strata have thus far been identified from these groups (Assefa, 1987, 1991). Low-level phosphate occurrences with 1% to 5% P_2O_5 have been noted in outcrop and cuttings from exploratory oil wells in the Cretaceous Faf series (Assefa, 1987, 1991) (Figure Ethiopia 4). The potential for Precambrian occurrences may be high because Precambrian metasedimentary phosphorite has been identified in the Inda Ad Series in neighboring Somalia (Greenwood, 1982).

Potassium Resources

Thick sequences of evaporites are found in the Danakill Depression in northeastern Ethiopia. At the floor of the depression is a barren salt pan about 40 km x 8 km in size. The evaporites have been K/Ar age dated as Pleistocene in age (Abera, 1994). Exploration drilling near the center of the Depression by the R. M. Parsons Company indicated that potash-bearing strata about 50 m thick were present below 680 m of bedded halite (Holwerda and Hutchinson, 1968). The potash-bearing strata were traced updip to the western margin of the salt pan where the deposit lies beneath 50-180 m of alluvial outwash and bedded halite.

The deepest known potash-bearing bed consists of fine-grained kainite (to 74%) with halite and varies from 4 to 14 m in thickness. Above the lower kainite bed are 3-24 m of mixed carnallite salts with more kainite on the bottom and more sylvite near the top. The upper zone or sylvinite bed is a 0- to 12-m-thick interval with an abundance of sylvite near the top and increasing amounts of carnallite, polyhalite, and kainite near the base. The upper sylvinite bed also contains considerable anhydrite. A shaft was sunk to the ore body, and approximately 600 m of underground workings was cut into the sylvite-bearing beds. The mine was accidentally flooded in 1967. In 1968 the R. M. Parsons Company withdrew from the project. R. M. Parsons Company developed a flow sheet for processing that involved crushing and screening, leaching of the sylvite and carnallite ore, and a four-stage crystallization sequence. The process resulted in concentrates of up to 62.5% K_2O at 90% recovery (Ghebre, 2000).

Two ore bodies were delineated, and ore resources were calculated for the deposit (Assefa, 1985). The Cresent ore-body was considered relatively small. Total ore resources are calculated at 1.2 x 10^7 tons, of which 3.0 x 10^6 tons of potassium chloride was recoverable.

The Ethio-Libyan Mining Company (ELMICO) reevaluated the reserves of the Musley ore body in 1984. The following figures were considered generally accepted for the Musley ore body by Ghebre (2000):

Category A = Proven = 66,228,000 tons at 33.04% KCl

Category B = Proven = 32,331,000 tons at a grade of 33.96% KCl

Category C = Proven = 61,897,000 tons at a grade of 31.22% KCl

Opencast mining methods were proposed for the project. However, the project was never implemented.

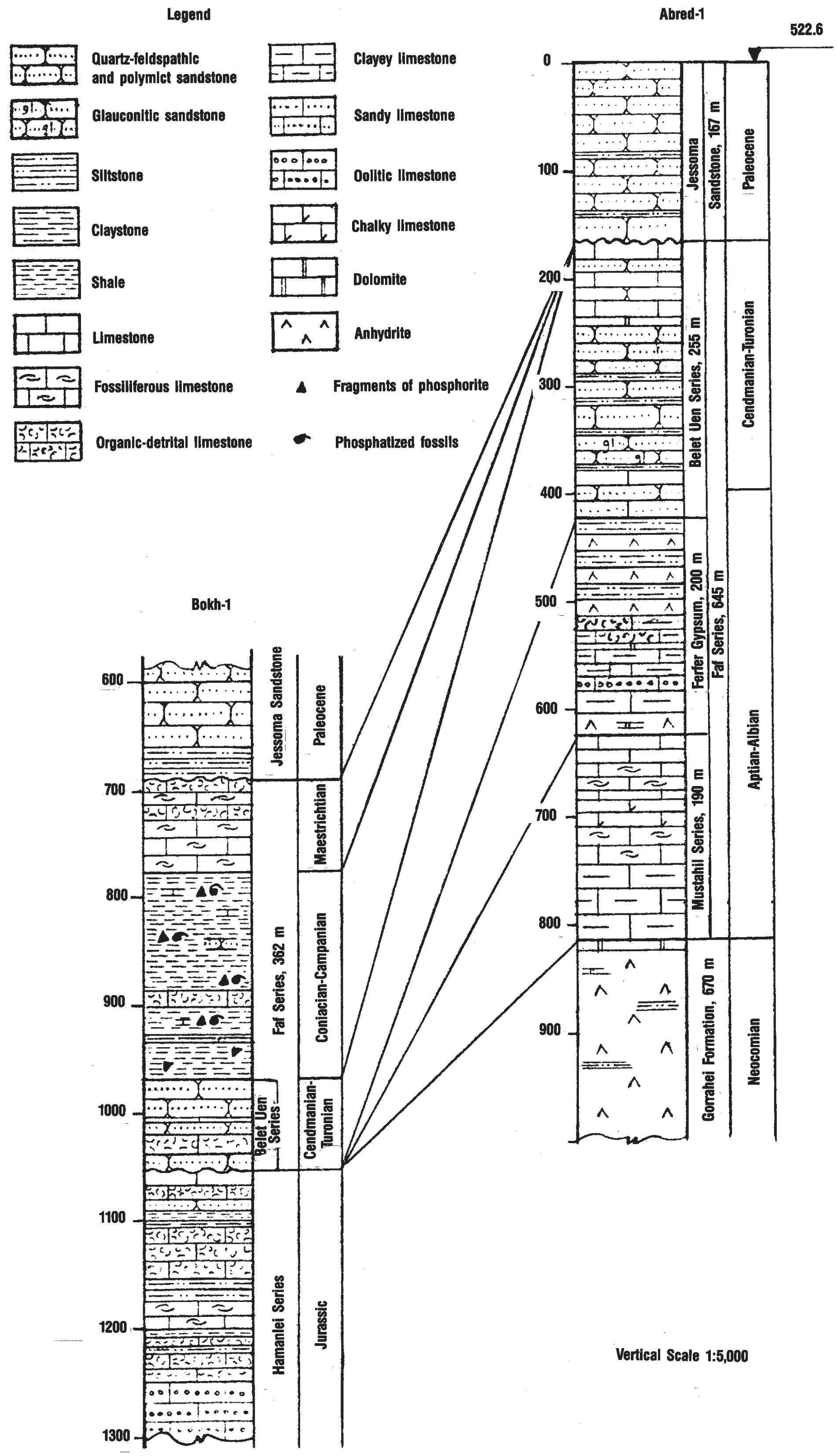


Figure Ethiopia 4. Schematic Correlation of the Faf Series (modified from Assefa, 1987)

Sulfur Resources

Small, scattered fumarole and crater sulfur deposits are found in the Rift Valley and Danakill Depression. The Dofan Crater Deposit in the Rift Valley was mined for several years until it closed down in 1973 (Assefa, 1985). Sulfur occurs at Dofan in tuffs and around fumaroles. The resources at Dofan are estimated to be 2,103 tons. At Dalol in the Danakill Depression, solfateric sulfur was produced until 1954. The resource at Dalol is estimated at 2×10^5 tons.

Native sulfur occurring in gypsum beds in the Danakill Depression was worked in surface excavations during 1944-47 and 1949-52 (British Sulfur Corporation, 1985). A decline in grade from 16%-20% to 8%-12% sulfur is said to have caused suspension of activities. Gypsum deposits occur in the Blue Nile Gorge (Central Ethiopia) and also in the Ogaden area.

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GABON

The Gabonese Republic is bordered on the north by Equatorial Guinea and Cameroon, on the east and south by the Republic of the Congo, and to the west by the Atlantic Ocean (Figure Gabon 1). Total area is 267,667 km^2 and the amount of arable land is 1.2%. The population was estimated in mid-2005 as approximately 1.42 million inhabitants. Agriculture occupies 60% of the labor force (World Factbook, 2006).

The transportation network consists of 6,247 km of paved roads, 26,086 km of unpaved roads, and 814 km of standard-gauge (1.435 m) railway. There are 11 airports with paved runways and 45 airports with unpaved runways. Within the country there is a gas pipeline (210 km) and an oil pipeline (1,385 km). Gabon has 1,600 km of waterways including 310 km on the Ogooue River. The main ports and terminals are Gamba, Libreville, Lucinda, Owendo, and Port Gentil.

Precambrian age rocks are exposed on approximately 80% of the surface of Gabon. The Early Precambrian rocks consist of granites, migmatites, and metamorphic sequences. The Middle Precambrian Franceville System occurs in the area of Franceville and Lastourville towns and contains a fluvio-deltaic sequence consisting of conglomerates, sandstones, pelites, jaspalites, and carbonates. There are also some ignimbrites associated with the Franceville System. Upper Precambrian rocks, including conglomerates, sandstones, shales, and dolomites, occur northeast of Libreville and in southwest Gabon.

Mesozoic continental sediments unconformably overlie the Precambrian in the Gabon Basin, followed by nearshore marine sediments. Evaporites of Upper Cretaceous age overlie the marine nearshore sediments. Limestones, dolomites, marls, sandstones, mudstones, and phosphates overlie the evaporites. The Mesozoic and Tertiary sequence in the Gabon Basin has an average thickness of 8,000 m (Boss et al., 1996). Tertiary and Quaternary continental sediments overlie the Precambrian basement in the east of the country on the margin of the Congo Basin.

Nitrogen Resources

Gabon is the fourth largest oil producer in sub-Saharan Africa. Ownership of oil and gas and all mineral rights are vested in the state. Exploration and production companies are licensed under the Exploration and Production Contract (ESPC) established by law No. 14/82 in 1983. The state oil company is the Société National Petroliére Gabonaise. Gabon was a member of the Organization of Petroleum Exporting Countries (OPEC) until 1996.

Oil production in 2005 was 268,900 barrels per day (bpd) (World Factbook, 2006). Gabon's largest oil field is the Shell-operated Rabi-Kounga Field with estimated reserves of 440 million barrels and production of 150,000 bpd (MBendi, 2005). The second largest field is the Gamba-Iringa Field, operated by Shell, with production rates of 10,000 to 15,000 bpd. Crude oils from Gabon are in the 30° to 35° API range, with a small amount of 25° API. Gabonese oil is mainly exported to the United States, Europe, and China.

Oil companies operating or exploring in Gabon include Shell Gabon S.A., China Petroleum and Chemical Corporation, Total Gabon S.A., PanOcean Energy Corporation Ltd. (PanOcean), VAALCO Energy Inc., Sasol Petroleum West Africa Limited,

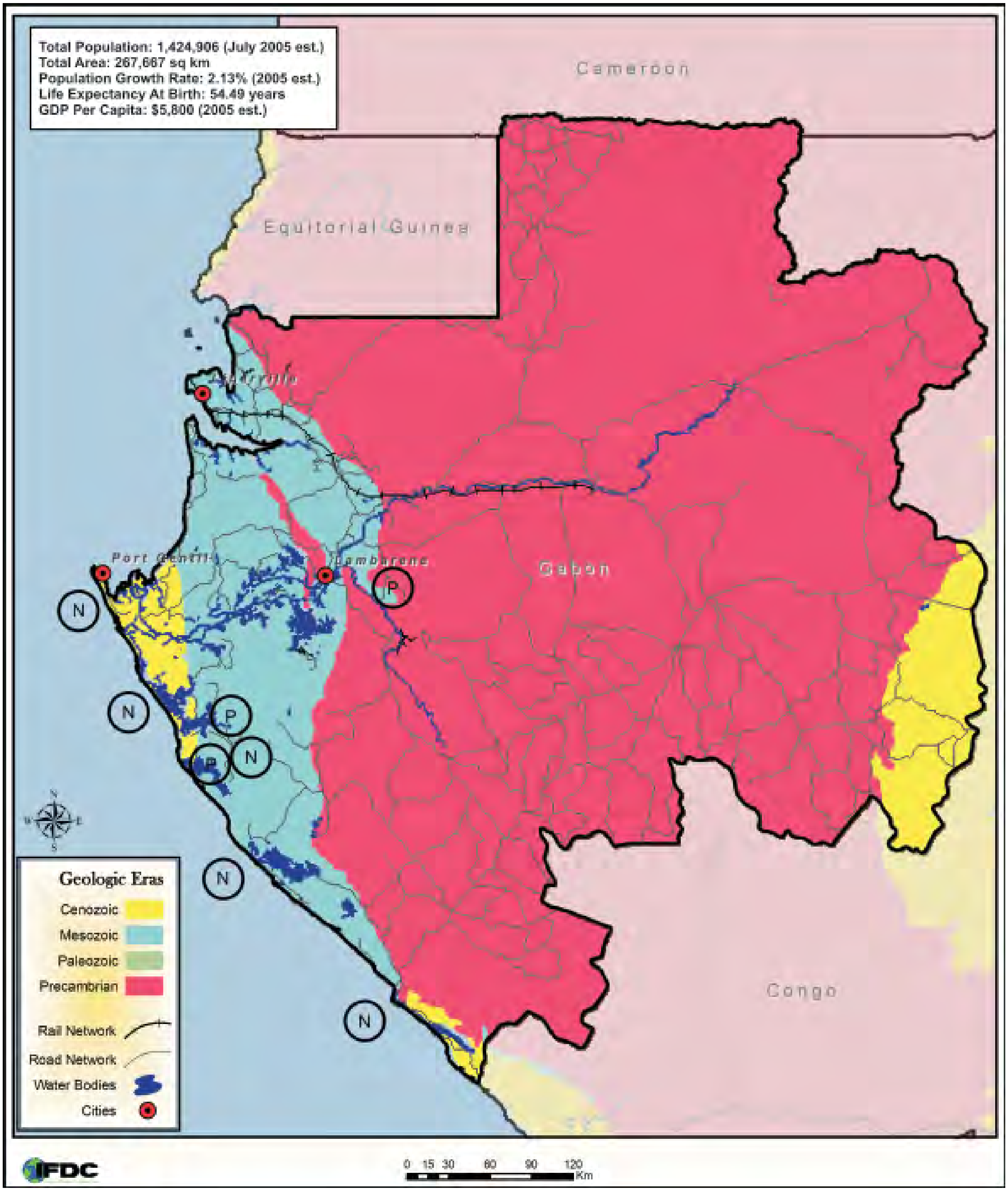


Figure Gabon 1. Geology, Major Cities, and Transportation Network

Energy Africa Gabon S.A., Energy Resources Japan Etame (Gabon) Ltd., and Petro Energy Resources Corp. (Bermúdez-Lugo, 2004).

Exploration efforts have increased in recent years to boost declining production and increase reserves. Gabon peak oil production was 371,000 bpd in 1997 (*Afrol News*, 2004).

Proven oil reserves are listed as 1.921 billion barrels by one source (World Factbook, 2006; 2005 estimate) and 2.5 billion barrels by another (Bermúdez-Lugo, 2004; 2004 estimate). Natural gas reserves are listed as 33.98 billion m^3 by one source (World Factbook, 2006; 2005 estimate) and 66 billion m^3 by another (*Nitrogen & Syngas*, 2005). Natural gas production was estimated as 90 million m^3 in 2003 (World Factbook, 2006) and is balanced by consumption.

The Sogara Oil Refinery at Port Gentil is Gabon's only oil refinery. The nameplate capacity is 21,000 bpd (Bermúdez-Lugo, 2004).

Phosphate Resources

Sedimentary Phosphate Rock—Lebedeff (1928; as quoted by Giresse, 1980) reported the presence of phosphates in Late Cretaceous age sediments along the southern coast of Gabon. Lenticular phosphate layers, said to be frequently decalcified and silicified, are exposed on the coast and the lagoons between Iguéla and Fernon Vaz. Furon (1932; as quoted by Giresse, 1980) reported that outcrops from N'Kero Lagoon in the same area contained 11% and 16% P_2O_5.

A reinvestigation of some of the occurrences north of Iguéla Lagoon was carried out by the French Bureau de Recherches Géologiques et Minières (BRGM) in 1965. Phosphate deposits were discovered in the Wara na Yeno and Ikassa areas as a result of exploratory oil drilling by the BRGM in the mid-1960s in Lower Senonian, Paleocene, Eocene, Oligocene, and Miocene Strata (Slansky, 1986) (Figure Gabon 2). Slansky indicates that the Senonian occurrences are the only beds accessible at shallow depth and are the occurrences on which most of the prospecting has been done. The best phosphate concentrations were found in the southern part of the basin, at the bottom of Conacian clay and silt, just above the Turonian carbonate beds. Slansky (1986) indicated the Gabon Basin provides a good example of where phosphorite forms and is accumulated by structural traps. The best phosphate deposits in this case appear to have developed in traps formed by two of the salt domes in the Assewe-Ikassa uplift (Figure Gabon 2).

Slansky (1986) does not provide any chemical analyses of these phosphates. Appleton (2001) indicates grades from 8% to 32% P_2O_5 for the coastal zone phosphates. McClellan and Notholt (1986) indicated that the beds had been extensively silicified and were not of economic interest.

Igneous Phosphate Rock—The Mabounie Carbonatite Complex is the only igneous phosphate deposit located in Gabon to date.

Mabounie Carbonatite—The Mabounie Carbonatite Complex was discovered as a result of an airborne geophysical survey. This survey was conducted by the Compagnie Générale de Geophysique (CGG) from 1983 to 1985 as a part of a mineral inventory of Gabon under the Direction Générale des Mines et de la Géologie (DGMG) with BRGM (France) as the principal operator (DGMG, 1989a, b).

The Mabounie Carbonatite is located about 40 km east-southeast of Lambarene. The deposit is accessible by helicopter or by a 3-h journey by river. The deposit is a ring structure and is partially covered by Cretaceous age sediments (Figure Gabon 3). In the available literature, the deposit is referred to both as a carbonatite and as an alkaline ring complex. Phlogopite from the deposit has been age dated at 660 ± 13Ma (Laval et al., 1988). The deposit has been studied as a source of iron, titanium, rare earths, niobium (as pyrochlore), and phosphate. Perhaps more emphasis has been put on its potential as a source of niobium. Numerous studies were conducted at the site during the late 1980s and into the 1990s.

There is a thick residual soil cover over the carbonatite core. This residual cover is distinctly zoned and the transitions are sharply defined (Figure Gabon 4) (Laval et al., 1988). At the surface there is a red soil zone, which may be from 2 to 16 m thick, composed of highly weathered iron oxides, crandallite, pyrochlore, quartz, and kaolinite clay.

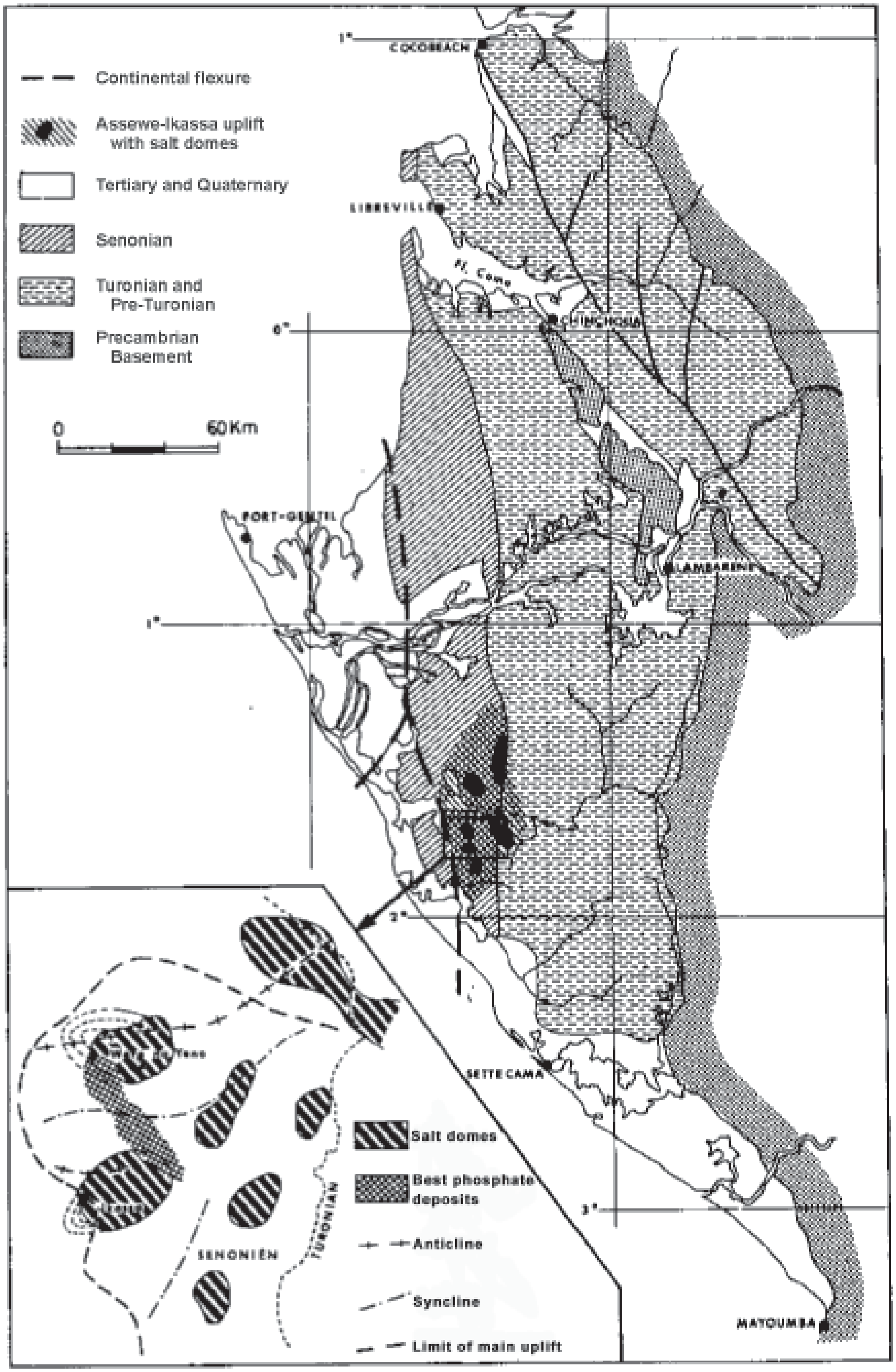


Figure Gabon 2. Location of Upper Cretaceous (Senonian) Phosphate Deposits in the Gabon Sedimentary Coastal Basin (Modified from Slansky, 1986)

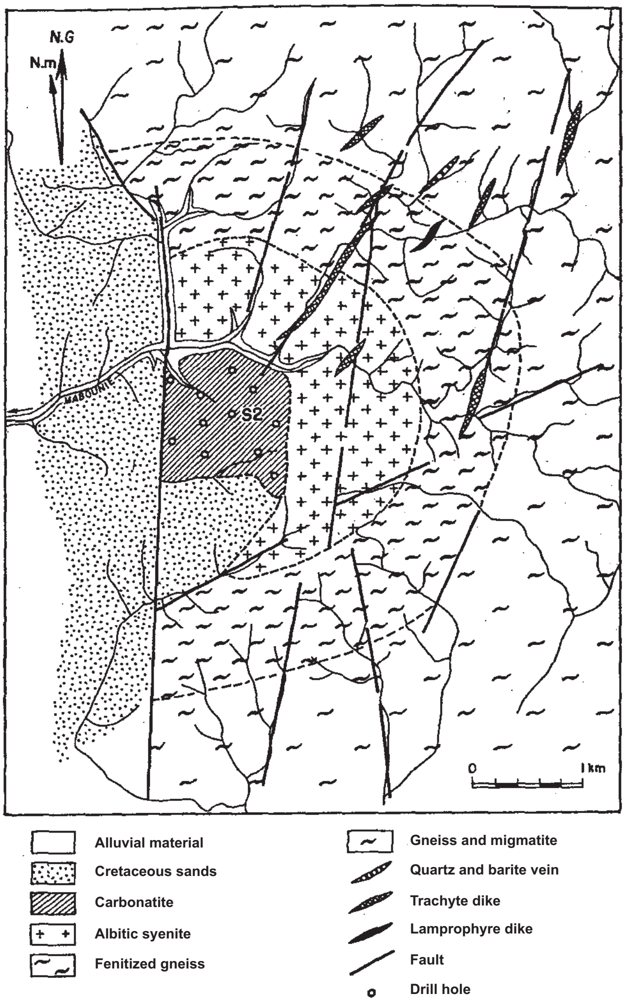


Figure Gabon 3. Simplified Geologic Map of the Mabounié Carbonatite Complex (Modified from Laval et al., 1988)

Table Gabon 1. Selected Chemical Analyses, Mabounie Carbonatite

	Carbonatite			Apatite
Sample No.	**4126**	**4134**	**4135**	**BT 28**
SiO_2, %	1.5	1.95	0.92	0.51
Al_2O_3, %	Tr	0.29	0.27	Tr
Fe_2O_3, %	7.20	17.55	10.50	22.90
MnO, %	0.29	Trace	Trace	0.28
MgO, %	18.30	15.85	17.90	Trace
CaO, %	29.94	28.80	29.55	40.40
Na_2O, %	Trace	Trace	Trace	Trace
K_2O, %	Trace	Trace	Trace	Trace
P_2O_5, %	2.82	5.05	2.90	27.90
TiO_2, %	0.14	0.42	0.07	0.60
LOI, %	36.69	30.70	38.10	2.20
Total, %	96.88	100.61	100.14	94.79
U, ppm	–	–	–	170
Th, ppm	–	–	–	75
Ce, ppm	563			1,960
Nb, ppm	700			4,965
Zr, ppm	930			815

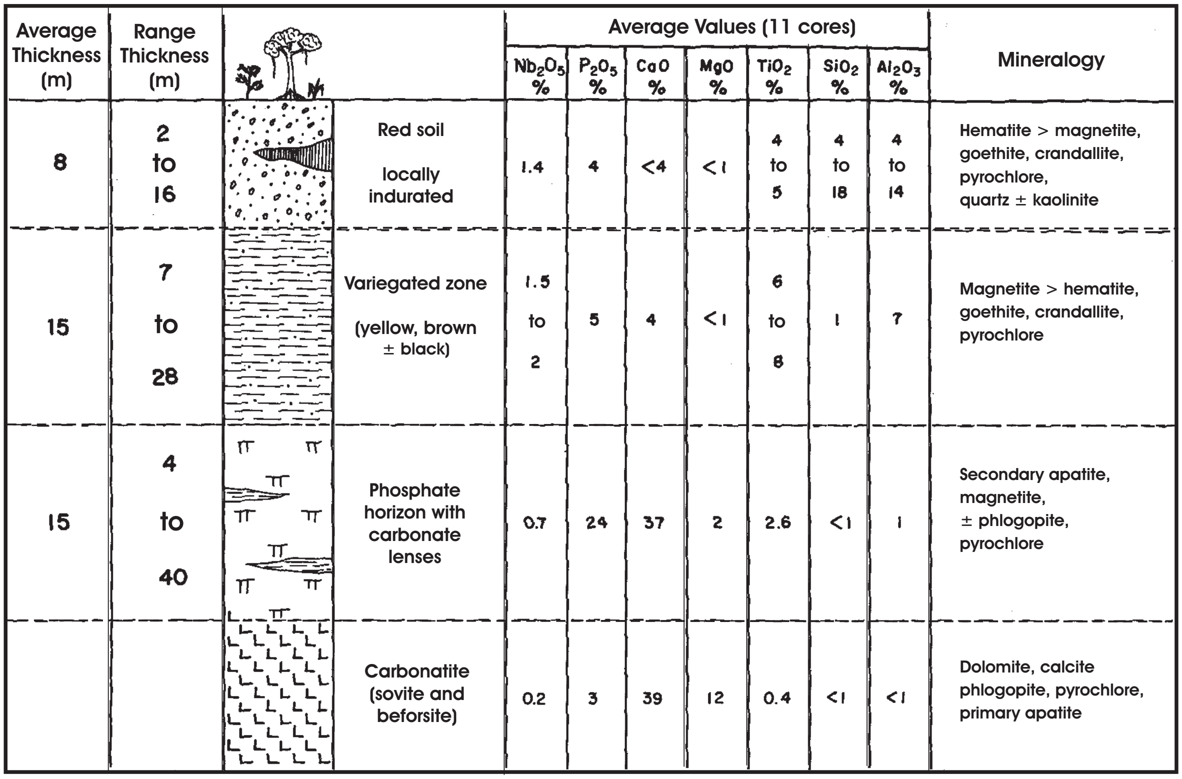
Source: Laval et al. (1988).

Below the red soil is a variegated zone (7 to 28 m thick) where the amounts of magnetite (a black to silver colored mineral) is in greater abundance than the more highly oxygenated and/or hydrated iron minerals. This zone also contains crandallite and pyrochlore.

Directly above the carbonatite plug is a phosphate horizon containing carbonatite lenses. The apatite is indicated to occur as secondary apatite. Laval et al. (1988) presents scanning electron microscope (SEM) photographs of secondary apatite crystals from this zone. The average P_2O_5 content of this zone is 24% (Laval et al., 1988; DGMG, 1989a). Table Gabon 1 contains a fairly complete analysis of a phosphate zone sample. Table Gabon 2 contains analyses of samples from 11 boreholes in the phosphate zone.

Below the phosphate zone, the carbonate zone contains primary apatite and may average about 3% P_2O_5. Table Gabon 1 contains three analyses of carbonate zone samples. The carbonate zone contains relatively high levels of magnesium, indicating high levels of dolomite. Pure dolomite contains about 22% MgO, and carbonatite samples listed in Table Gabon 1 contain from 15.85% to 18.30% MgO.

Laboratory-scale beneficiation studies included crushing, grinding, attrition scrubbing, desliming at 80 µm, heavy-liquid separation to obtain the fraction between densities of 2.9 to 3.3, washing (to remove heavy liquids) and drying, and two levels of magnetic separation using a Franz magnetic separator. The first level of magnetic separation (0.5A) was to remove iron oxides. The second level of magnetic separation (1.5A) was to remove apatite particles with inclusions of iron oxides. Heavy-liquid separa-



Average Thickness (m)	Range Thickness (m)		Nb_2O_5 %	P_2O_5 %	CaO %	MgO %	TiO_2 %	SiO_2 %	Al_2O_3 %	Mineralogy
			Average Values (11 cores)							
8	2 to 16	Red soil locally indurated	1.4	4	<4	<1	4 to 5	4 to 18	4 to 14	Hematite > magnetite, goethite, crandallite, pyrochlore, quartz ± kaolinite
15	7 to 28	Variegated zone (yellow, brown ± black)	1.5 to 2	5	4	<1	6 to 8	1	7	Magnetite > hematite, goethite, crandallite, pyrochlore
15	4 to 40	Phosphate horizon with carbonate lenses	0.7	24	37	2	2.6	<1	1	Secondary apatite, magnetite, ± phlogopite, pyrochlore
		Carbonatite (sovite and beforsite)	0.2	3	39	12	0.4	<1	<1	Dolomite, calcite phlogopite, pyrochlore, primary apatite

Figure Gabon 4. Alteration Profile of the Mabounié Carbonatite Deposit

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Table Gabon 2. Chemical Analyses, Mabounie Deposit Phosphate Zone[a]

Borehole No.	No. of Samples	Thickness	Recovery	P_2O_5	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	LOI[b]	CaO/ P_2O_5
		(m)	(%)	(%)							
1	23	40	16	29.13	1.24	1.49	17.86	39.75	1.26	4.96	1.36
2	21	41	43	24.92	2.13	2.22	24.19	32.74	1.64	5.43	1.28
3	11	22	30	27.34	1.23	1.28	16.15	39.10	2.41	8.23	1.57
4	5	6	8.50	16.68	1.25	1.33	46.46	19.90	1.15	5.49	1.18
5	9	5	19	14.70	7.17	5.54	24.62	20.79	5.58	12.02	1.66
6	7	9	25	19.14	5.98	4.50	26.80	23.67	3.87	8.00	1.21
7	8	11.50	18	23.22	1.73	2.02	31.04	29.81	1.40	8.58	1.24
8	4	5	9.50	17.26	4.72	2.81	33.03	20.86	2.49	5.64	1.19
9	12	19	7	24.34	4.92	10.95	11.73	30.60	1.22	9.15	1.06
10	5	7	30	22.60	1.00	2.57	34.38	27.43	1.00	5.28	1.20
11	3	4	4	18.34	1.50	3.35	35.63	20.98	1.24	7.42	0.92

a. Chemical analyses mainly by X-ray fluorescence.
b. LOI = Loss on ignition, conditions unknown.

Source: DGMG (1989c).

tion is often used to approximate the potential results of flotation tests.

From a head sample containing 31.3% P_2O_5 and the sequence utilizing the first level of magnetic separation, a concentrate containing 37.0% P_2O_5 with 4.81% Fe_2O_3 was obtained at 71.6% recovery. With a second magnetic separation step, a concentrate containing 38.4% P_2O_5 and 2.4% Fe_2O_3 was obtained. However, P_2O_5 recovery dropped to 33.1%. Although additional flotation studies are mentioned in one report (DGMG, 1989c), the results of any such studies were not available.

Initial studies based on 11 boreholes indicated reserves were 85 million tons at an average of 24% P_2O_5 in the weathered zone (DGMG, 1989a). Later studies by the Société Minière du Moyen-Ogoové (SOMIMO) (owned by the Government of Gabon [62%], Elf Gabon [23%], and BRGM of France) indicated 140 million tons of potential ore based on 220 cored boreholes (*Mining Annual Review*, 1998; Jones, 1996). Flotation tests produced concentrates at 39% P_2O_5. Phosphoric acid tests were performed, resulting in 52%-54% P_2O_5 acid with low impurities. It was projected that a production rate of 2 million tpy at about 39% P_2O_5 could be sustained for at least 20 years. The most likely method of transporting the materials appeared to be a slurry pipeline from Mabounie to Lambrene, then river transport to Port Gentil (Jones, 1996). The cost to perform the prefeasibility study was US $12.5 million (*Industrial Minerals*, 1996). A preliminary capital cost estimate for the mine was US $600 million. The cost of a ton of concentrate delivered to Port Gentil was estimated at US $25.

Cluff Mining acquired a 35% stake in the deposit in 2000 to become the largest shareholder, but in 2004 it was reported that Cluff Mining had been seeking to divest for some time (Leahy, 2004). Cluff Mining's primary interest in the deposit was its niobium potential. It is not known if Cluff Mining is still operating. There were no active internet sites in mid-2006. As of 2004 there was no further activity reported at the Mabounie Carbonatite Complex.

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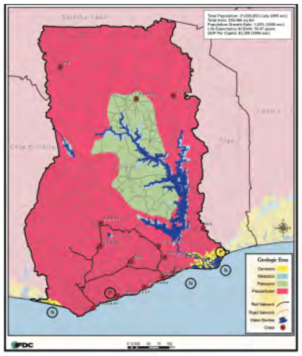
GHANA



The Republic of Ghana is bordered on the north and northwest by Burkina Faso, on the east by Togo, and on the west by Côte d'Ivoire (Ivory Coast). There is approximately 555 km of coastline along the Atlantic Ocean. Total area is 239,460 km^2; 16.3% of the land is arable cropland. The population in mid-2005 was 21.0 million inhabitants. The annual population growth rate was estimated as 1.25% (World Factbook, 2005). Most of the population is concentrated in the central and southern areas of the country. Subsistence agriculture occupies about 60% of the workforce.

The transportation network (Figure Ghana 1) includes 14,100 km of main roads, 14,200 km of secondary roads, 400 km of waterways, and about 1,000 km of railways. The main ports are Tema, Accra, and Takoradi.

Four general geological domains exist in Ghana (Figure Ghana 2). Almost 45% of the territory of Ghana belongs to the eastern margin of the Precambrian West African Shield or Craton. This shield area contains deformed metamorphosed sediments of the Birimian System deposited upon an Archean (Liberian) basement that is intruded by granitoids of the Eburnean Orogeny. Middle Proterozoic molasse-type sediments of the Tarkwaian System unconformably overlie Birimian rocks.

The Dahomeyan Mobile Belt consists of the Benin Plain Complex with the Buem and Togo Series (Atakora) formations as its fringing units. These Precambrian units continue through Togo and Benin. The Volta Basin contains flat-lying sedimentary rocks of late Precambrian to Paleozoic ages and covers almost one-third of the area of Ghana. The Voltaian System has a maximum thickness of between 3,000 and 4,000 m and rests unconformably on the Lower Proterozoic Birimian System and related granitoids and on the Middle Proterozoic Tarkwaian System. The preexisting units had been eroded to a peneplain at the time of the Voltaian transgression.

The coastal sedimentary basins of Ghana contain a variety of sediments ranging from Devonian to Recent ages. Based on two wells drilled at Atiavi (1,560 m) and Anloga (2,135 m), the Keta Basin contains sands, gravels, siltstones, limestones, shales, and clays of Devonian, Cretaceous, Paleocene, Eocene, Miocene, and Recent ages.

The Accraian Series consists of quartz sandstones, shales, and mudstones of Middle Devonian age. The beds unconformably overlie the Dahomeyan Basement Complex. The Amisian Formation outcrops at a number of places along the coast between Saltpond and Winneba. The formation consists of a series of interbedded soft pebbly sandstones, conglomerates, micaceous arkosic sandstones, and greenish gray clays. The sediments are approximately Upper Jurassic in age (Bates, 1958).

The Sekondi Series occurs in several disconnected outcrops along the coast between Cape Coast and Dixcove. With a total thickness of about 1,245-1,325 m, the series consists mainly of sandy shales with conglomerates, sandstones, and micaceous clays. The age of the Sekondi Series ranges from the Devonian to Early Cretaceous. The Tano Basin (Apollonian Formation) sediments are composed of Cretaceous-Eocene marine beds of alternating sandy clays and limestones.

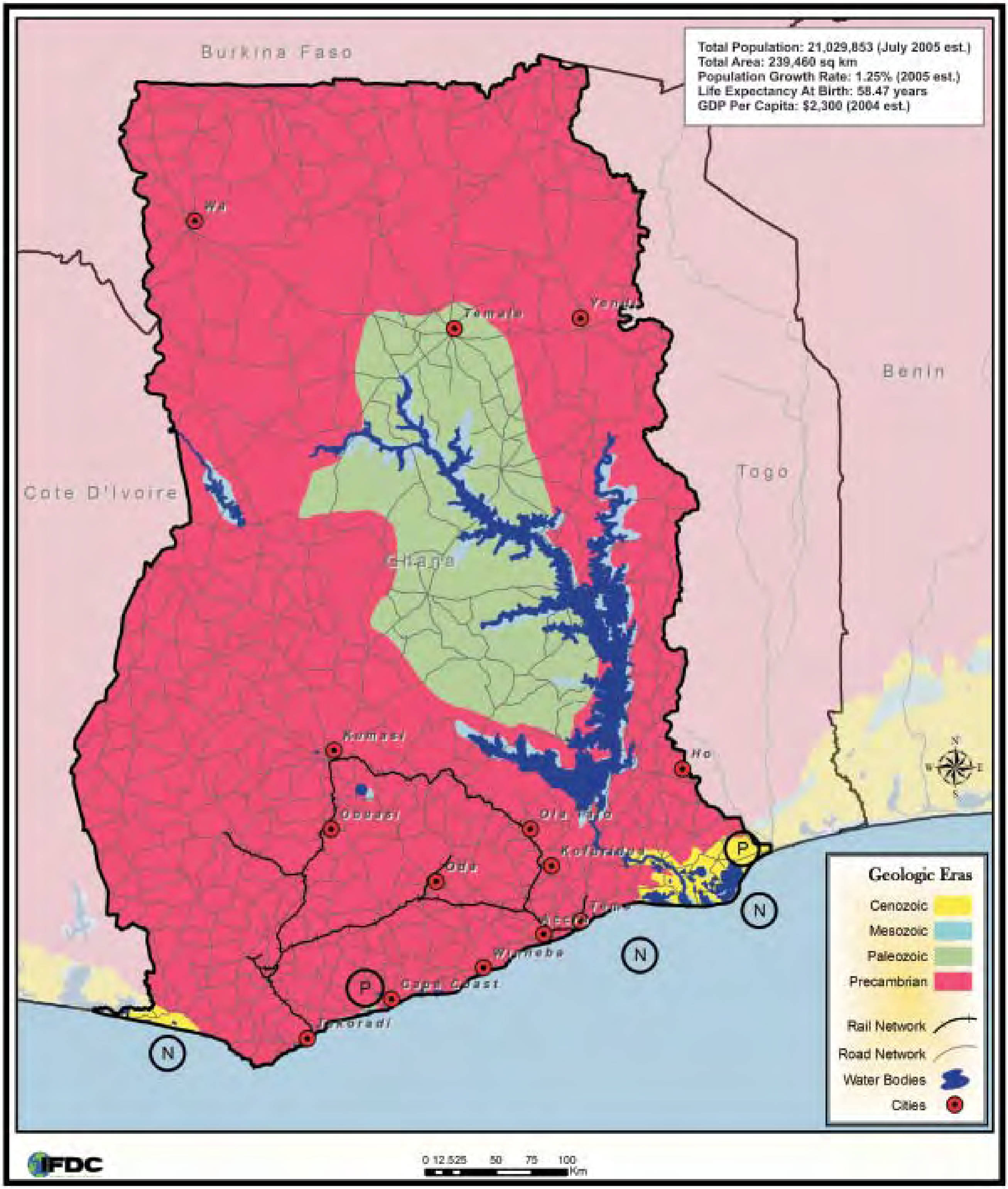


Figure Ghana 1. Geology, Major Cities, and Transportation Network

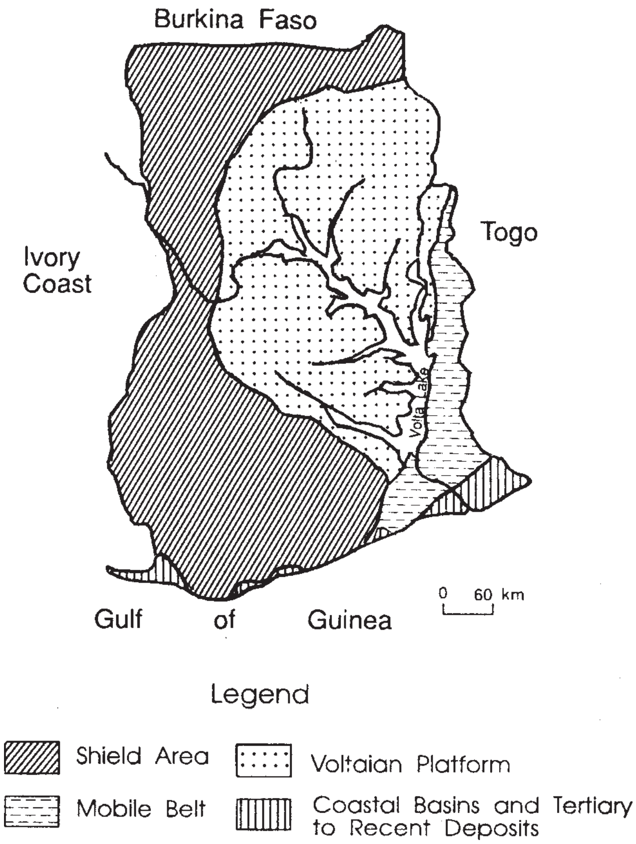


Figure Ghana 2. General Geologic Map of Ghana Showing the Shield Area, the Mobile Belt, the Voltaian Platform, the Coastal Basins, and Tertiary to Recent Deposits (After G. O. Kesse, 1985)

Nitrogen Resources

Petroleum—The search for oil has been concentrated in Ghana in four areas (Kesse, 1985): the Tano Basin, the Keta Basin, the Volta Basin, and on the continental shelf. Drilling began onshore in the Tano Basin as early as 1896 and continued in the 1960s. There are many oil seeps in this area. Many traces of oil and gas were found, but commercial reserves were not proven. Several wells have been drilled onshore in the Keta Basin. The rocks of the basin are both marine and nonmarine and are rich in organic matter. However, only traces of oil and gas were found.

Shell Exploration and Production Company (Ghana) Limited prospected in the Volta Basin. A seismic survey was performed in the basin, and a structural nose was located near Premuase village. A well was drilled to a depth of 1,167.5 m and bottomed in Precambrian sandstone. No traces of hydrocarbons were encountered. The results of this study indicated that geological conditions in the basin were clearly adverse for the preservation of liquid hydrocarbons.

In 1968 the Government of Ghana invited private foreign oil companies to explore the continental shelf. The offshore area was divided into 22 blocks, and all the blocks were taken by the end of the year. The only significant finds were in Block 10 off the Saltpond area in Devonian and Cretaceous age strata by Signal Oil Company. The initial reserve estimate was about 7.5 million barrels.

In 1971 Signal Exploration joined with Amoco Ghana and Occidental Oil to further explore the Saltpond discovery. Two wells were drilled in Block 10, and calculations indicated about 2.4 million barrels in about a 175-ha area. An additional well was needed to prove 6,337,000 barrels of recoverable oil in a 422-ha area.

In 1977, Agri-Petco International Inc. was granted a prospecting license covering Blocks 10 and 13. Additional drilling proved encouraging, and production began in late 1978. Production was to be carefully controlled because the structure of the field was very complex and the bottom hole pressure was close to the bubble point. The Saltpond Field was to initially produce 5,000-6,000 barrels per day (bpd).

Table Ghana 1 shows the projected production and actual production of the Saltpond Field. Many

Table Ghana 1. Oil Production From the Saltpond Field

	Production	
	Projected	Actual
	(barrels)	
1978	519,500	295,988
1979	1,717,300	655,781
1980	1,258,100	664,254
1981	921,600	599,797
1982	672,200	434,750
1983	494,600	498,634
1984	313,700	–
Total	5,897,000	3,149,204

Source: Kesse (1985).

difficulties were associated with producing from the field, and reservoir pressure fell below the bubble point. The *Oil and Gas Journal* indicated there were three producing wells at 2,000 barrels of oil per day in 1985. In the first 6 months of 1986, the three producing wells were listed at 300 bpd. Cumulative production was 3,938,000 barrels in 1986.

In 1977 the Côte d'Ivoire government announced it had struck oil. This discovery spurred on exploration in Ghana in the offshore Tano Basin. Phillips Petroleum drilled six wells near the offshore border with Côte d'Ivoire. In the South Tano 15-1X Well, Phillips encountered a 27-m-thick pay zone between 1,844 and 1,871 m that flowed 5.5 million ft^3 of gas per day from the upper part of the zone and 1,475 bpd of oil in the lower part of the zone plus 8.2 million ft^3 of gas per day with no water. A drill stem test in the Lower Cretaceous sands below 1,828.8 m tested 1,475 bpd of oil and flowed 8.2 million ft^3 of gas per day. It was estimated the structure held 25-50 million barrels of recoverable oil.

Phillips Petroleum's South Tano 15-3X Well tested four gas zones. Although results were encouraging, Phillips did not consider the well as commercial.

Phillips Petroleum's North Tano IN-1X Well was drilled to a total depth of 4,267.2 m in the last quarter of 1980. Gas flowed at 8.4 million ft^3 per day with 100 bpd of oil between 2,213 and 2,234 m. Oil flowed at 400-500 bpd between 2,252 and 2,288 m and at up to 1,400 bpd between 2,585 and 2,629 m.

In 1984 Petro-Canada Incorporated acquired the concessions formerly held by Phillips Petroleum and drilled two wells. In drill stem tests of three zones of the South Tano 5 Well, pressure fell rapidly in each of the intervals tested. Phillips drilled one more well, North Tano 1N-2X, in the area in 1981 with negative results.

Agip (Africa) Ltd. drilled the Ghana Branch-Axim 4-3X Well in 1981. Oil flow was minor from several zones. Gas flow from Zone 3 (1,828-1,840 m) exceeded 24 million ft^3 per day. An extended 24-h flow test was conducted, and well response was considered exceptional.

In 1983 the government established Ghana National Petroleum Corporation (GNPC) to promote exploration and production. U.S.-based Amoco prospected in 10 offshore blocks between Ada and the Togo border. Petro-Canada prospected in the Tano River Basin, and Diamond Shamrock prospected in the Keta Basin. In 1989 three companies—two American and one Dutch—spent US $30 million drilling wells in the Tano Basin. On June 21, 1992, an offshore Tano basin well produced about 6,900 barrels of oil daily (Country Studies, 2005). The refinery at Tema underwent the first phase of a major rehabilitation in 1989. The second phase began in 1990 at an estimated cost of US $36 million.

In the early 1990s, GNPC reviewed all oil and gas exploration work. GNPC wanted to set up a floating system for production to feed a floating electrical generation plant. Offshore exploration and development was stimulated in the Keto Basin, West Tano Block, and Saltpond Field. Several American, Canadian, British, and other companies formed partnerships and signed agreements with GNPC.

In 2003 GNPC produced an estimated 8,200 bpd of crude oil from the Saltpond and Tano fields. North Tano was to be developed to supply 736 million m^3 of gas to Effasu where a gas processing plant was to be built adjacent to the 134-MW power generation barge (Coakley, 2003). The South Tano Field, located in deeper water further offshore, would come onstream at a later date.

Oil for the refinery at Tema is sourced from Nigeria. Oil consumption is approximately 38,000 bpd (World Factbook, 2005). Gas for increased power generation in the future is to come from a pipeline from Nigeria laid offshore along the coasts of Benin, Togo, and Ghana. The pipeline would connect to onshore power generation installations at Cotonou (Benin); Lomé (Togo); and Tema, Takorad, and Effasu (Ghana). ChevronTexaco (2005) formally announced as of September 7, 2005, that the West Africa Gas Pipeline Company (WAPCO) had commenced installation of the 569-km-long main offshore segment of the line. ChevronTexaco, through an affiliate, is a 38% shareholder in WAPCO.

Proven oil and gas reserves of Ghana were indicated as 8.255 million barrels and 11.89 billion m^3 as of January 2002 (World Factbook, 2005). Coakley (2003) indicates petroleum reserves of 16.2 million barrels and gas reserves at 23.8 billion m^3 at year-end 2002.

Bitumen occurs in the coastal sediments and is associated with oil seeps. Bitumen (or "tar sands") has been reported at several localities in the Cretaceous-Eocene (Apollonian) sedimentary rocks of southwestern Ghana and also in the Volta Basin (Tamale, Buipe, and Bonga Da areas).

Phosphate Resources

The existence of the Eocene phosphate deposits in Togo and discoveries of Upper Proterozoic phosphate deposits in Voltaian, Buem, and Atakora formations in Niger, Burkina Faso, Benin, and Togo indicated that extensions of these deposits, or similar types of deposits, could be found in Ghana. The results of a limited exploration program conducted by the Ghana Geological Survey in the Keta Basin to locate Eocene phosphate beds (Anan-Yorke, 1974) were disappointing. In 1975 geologists from Bureau de Recherches Géologiques et Minières (BRGM) conducted a 4-week geologic reconnaissance program in northern Ghana focusing on the Upper Proterozoic rocks of the Volta Basin; the results were also disappointing.

In 1986 R. P. Sheldon (also in Kesse and Iddirisu, 1988) determined five target areas for phosphate exploration in Ghana and analyzed and classified each target on the basis of probability of occurrence, minability, and location (Table Ghana 2). Based on prior work and existing literature, each deposit was assigned a probability of containing substantial amounts of phosphate rock of usable quality. Minability depends on several factors, including the geologic structure and physical setting of the deposit. The evaluation of the location of a deposit was based on proximity to transportation routes or to local farming areas with a potential demand for phosphate fertilizer. On the basis of this analysis, the Keta Basin was selected as the best potential target area for the development of phosphate resources within Ghana.

Keta Basin Phosphates—The term Apatuemian (Khan, 1970) is used to describe the sequence of sediments in the Keta Basin. This basin continues to the east where it joins the Dahomey Basin in Togo and Benin and the Niger Delta Basin in Nigeria and Cameroon. Tertiary phosphogenesis has been correlated in the Nigeria, Benin, and Togo coastal basin (Johnson, 1987). The phosphates that occur in the Keta Basin are an extension of the Hahotoe-Kpogame Deposit of Togo (Middle Eocene age). Figure Ghana 3 shows the structure and lithostratigraphy of the Keta Basin.

Data obtained from 114 rock samples from six water supply wells drilled by the Ghana Geological Survey during 1966/67 in the Keta Basin indicated that P_2O_5 contents generally increased with depth (Anan-Yorke, 1974). The most significant samples were found at Aflao (Borehole K 41 BHS 219), where the computed mean through the richest zone at 120-131 m was 14.53% P_2O_5. As a result of these analyses, an exploration program was conducted in the Ho-Denu area. The Ho-Denu road was used as a baseline, and a grid system bearing N40ºW on 3.2-km (2-mile) centers was used. Continuous core samples were taken from the "A" limestone horizon and overlying clays and marls. Sledge samples of the overlying sand and gravel deposits were also ana-

Table Ghana 2. Priority of Investigation of Phosphate Targets According to Probability of Occurrence, Minability, and Location

Priority Target		Probability of Occurrence	Minability	Location
I	Keta Basin	High	High	High
II	Sekondi System	Medium	Medium	High
III	Voltaian System	Medium	High (Voltaian) Low (Buem)	Medium to high
IV	Appollonian Fm.	Low	High	High
V	Nepheline Syenite (Dahomeyan System)	Medium	Low (primary rock) Medium (Alluvium)	Medium to high

Source: Kesse (1988).

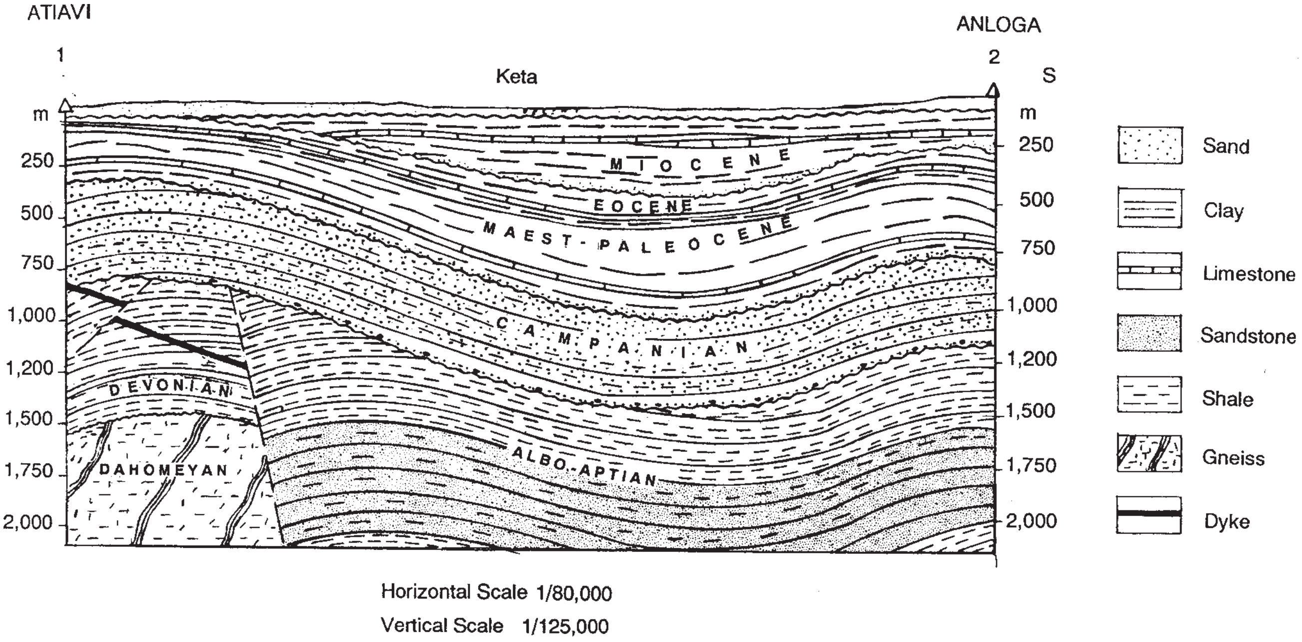


Figure Ghana 3. Geologic Cross Section of Keta Basin (Adapted from Khan, 1970)

lyzed. In the Ho-Denu area the reported phosphate values of the clays, marls, and the "A" limestone horizon were generally below 2.3% P_2O_5, with a few samples analyzing between 10.5% and 25.2% P_2O_5. The investigating party considered the economic cutoff for phosphate rock to be 30% P_2O_5. The Ghana Geological Survey concluded that the P_2O_5 contents of beds in the Aflao-Denu area were too low to warrant further consideration.

Several unperceived factors may have contributed to the lack of success in the Ho-Denu area. The surface extent of the main ore deposit in Togo ranges from 1 to over 2.5 km wide in the subsurface. The ore zone in Togo is known to become narrower to the west in the general direction of the Ghana border. Using the 3.2-km grid spacing, a significant phosphate ore zone could have been missed. Also, the ore of the Togo deposit is very soft. Extreme care is required during the drilling of such soft sediments to ensure good core recovery. Thin, soft ore zones can very easily be missed if drillers and geologists are not accustomed to working under such conditions. The results of this exploration program in the Ho-Denu area are impossible to evaluate. The original maps, cores, and data sheets cannot be located at the Ghana Geological Survey.

Based on the limited information available, Sheldon (1986) pointed out that the total phosphate contents of the 6-m ore zone at the Hahotoe-Kpogame deposit in Togo and the 10-m sequence drilled at depth near Aflao are essentially the same. The Hahotoe beds near the surface may be a weathered equivalent of the Aflao beds, with calcite, some of the clay constituents, and a portion of the CO_3 of the apatite removed by leaching.

If weathered phosphate ores similar to the Togo deposit can be located in the Keta Basin, they might be upgraded by the same processes used in Togo. The main impurities in the weathered Togo deposit are clays. These clays are removed by washing and cycloning. Beneficiation of unweathered ores containing carbonate (possibly diluted by quartz sands) may require more involved processes. Unweathered Togo phosphate ores (13%-16% P_2O_5) containing carbonate gangue have been beneficiated to over 30% P_2O_5 by flotation (IFDC, 1981).

Phosphate ores containing carbonate might also be used for direct application. The carbonate-apatite (francolite) found at depth in the Togo deposit that is associated with carbonates is more highly carbonate substituted (5%-6% CO_2) than the francolite occurring in the weathered economic ore beds (2%-3% CO_2) (Van Kauwenbergh and McClellan, 1990).

Sekondi System Phosphates—The sediments of the Sekondi System outcrop along the coast near Sekondi and Takoradi and occur in the subsurface of southeastern Ghana. The Sekondi System has been correlated with the Devonian Accraian System (Kesse, 1985). Crow (1952) reported tillite at the base of the Sekondi System, which may correlate with the Obossum Group at the top of the Voltaian System of the Volta Basin (Crow, 1952; Jones, 1978).

Phosphate particle occurrences are sporadic in the sediments of the middle and upper beds of the Sekondi System black shales and cherts. The types of phosphate particles include teeth, bones, and scales of fish and linguloid brachiopods. Phosphatic shells are usually associated with Upper Paleozoic phosphorites. Austin and Smit (1965) reported phosphate nodules containing 14.75% P_2O_5 in the Sekondi area in the beds of a cliff below Fort Orange.

Voltaian System and Buem Formation Phosphates—The association of tillite, dolomite, chert, and phosphate in African pericratonic sediments of Upper Proterozoic age is well known in the northern part of the Volta Basin (Burkina Faso, Niger, Benin, and Togo) in the Oti-Pendjari Supergroup (Pascal, 1972; Trompette, 1972). The main part of the Volta Basin occurs in Ghanaian territory; however, no evidence of potentially economic occurrences of phosphate has been found although the tillite and dolomites are present. At Buipe, phosphates are absent above the tillite in a Shell Oil Company well. Dolomite and barite are present above the tillite in this area (Junner and Hirst, 1946; Donnot, 1975). At Yendi, also in a Shell Oil Company well, phosphate is not found above the tillite (Anan-Yorke, 1980). The Ghana Geological Survey suggested that a more pragmatic program be initiated to study the Voltaian sediments in detail after a 4-week reconnaissance by BRGM geologists (Donnot, 1975). The BRGM geologists identified the tillite at a number of localities but, other than noting a slightly phosphatic dolomite (3% P_2O_5), did not find any phosphate rock.

Cretaceous Age Phosphates—Located in the southwestern part of Ghana, the Cretaceous sediments of the Tano Basin were studied during the course of petroleum prospecting. However, Khan (1970) reported that the data produced by prospecting have been lost. The use of plate tectonics reconstruction suggests there is a possibility of finding phosphates in these Upper Cretaceous sediments because the phosphates found in continental shelf sediments in eastern Brazil and Gabon were formed during this time period.

Nepheline Syenites of the Dahomeyan System—Undersaturated igneous intrusions and the Kpong conglomerate (possibly a cataclastic breccia or a volcanic breccia accompanying alkaline intrusion) are found in the external units of the Dahomeyides. Similar rock types are associated with carbonatites in eastern South America and East and South Africa where they are the source of significant phosphate rock production.

Potassium Resources

There are no known deposits of potassium salts in Ghana. The granitic complexes of Ghana contain potassium-bearing micas and feldspars. There is no known deficiency of potassium in the soils of Ghana at the present time (Kesse and Iddirisu, 1988).

Sulfur Resources

Barite occurs at several localities in Ghana. Barite occurs at Du, northwest of Wale-Wale, and has been investigated in an area north of Daboya on the White Volta River west of Tamale. Daboya resources are estimated at 200,000 tons. The barite at Daboya is associated with dolomitic limestone. The barite content ranges from 4% to 15% in a bed ranging in thickness from 0.6 to 1.5 m. Barite occurrences have been noted at Babatu in the Brong Ahafo Region and between Abodom and Agona Swedru in the Winneba area.

Gypsum occurrences have been noted in the lagoons of the Ada and Accra areas. Intercalated lenses have also been found in the Accraian Series. Gypsum crystals have been found at the Kagan and Alenguzuri localities in the Western Region. Sporadic occurrences of gypsiferrous clays have been noted in the Cretaceous and Tertiary sediments of the Keta area. None of these occurrences are considered economic.

No significant deposits of pyrite have been discovered in Ghana. Pyrite and arsenopyrite have been reported several times in association with the Birimian gold deposits.

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GUINEA-BISSAU

Guinea-Bissau is bordered by the Atlantic Ocean to the west, Senegal to the north, and Guinea to the south and east. Total area is about 36,120 km^2; approximately 10.7% of the land is arable. The total population was estimated as 1.4 million inhabitants in mid-2005 (World Factbook, 2006). Annual population growth is about 2.0%. Agricultural products include rice, corn, beans, cassava, cashew nuts, peanuts, palm kernels, cotton, timber, and fish. Approximately 84% of the population is occupied in agriculture. The transportation network (Figure Guinea-Bissau 1) consists of 453 km of paved roads and 3,947 km of unpaved roads. There is no railroad. There are 3 airports with paved runways and 25 airports with unpaved runways.

Guinea-Bissau lies on the southern flank of the Senegal-Guinea-Mauritania sedimentary basin (Figure Guinea-Bissau 1). From east to west, the rocks range from Precambrian to Quaternary in age. The sedimentary rocks of Paleozoic age are mainly clastics with some carbonates occurring in the Silurian. The Cenozoic sediments are largely of marine origin. The Cenozoic sediments in Guinea-Bissau lie on the southern margin of the Gulf of Casamance, a feature in the Cenozoic age wherein marine waters flowed to the east and north into the Senegal-Guinea-Mauritania sedimentary basin. Throughout this area, the Eocene, Paleocene, and Maastrichtian age rocks are unconformably overlain by an Oligocene-Miocene-Pliocene, and Quaternary sandy-argillaceous sedimentary sequence.

Nitrogen Resources

There has been active oil exploration onshore and offshore Guinea-Bissau since the late 1960s. Companies involved in oil exploration include Esso, Elf, Pecten, Sasmo, Sipetrol (Chile), West Oil, Sterling Energy, Benton Oil and Gas, Petrobank Energy and Resources, Premiere Oil, Amerada Hess, Agip, and Fusion Oil (MBendi, 2006). The industry is regulated by the Ministry of Natural Resources and Industry and Petrominas, the national oil company of Guinea-Bissau.

There are two main areas of interest offshore of Guinea-Bissau—in the north at the border with Senegal in the area of the Casamance trough and directly to the east of the Guinea-Bissau archipelago. Under an agreement signed in 1995, the area of border dispute that contains the Dome Flore and Dome Gea heavy-oil discoveries is now jointly managed through the Agence de Gestion et de Cooperation entre la Guinee-Bissau et la Senegal (AGC). Off the Guinea-Bissau archipelago, numerous salt diapirs occur in the subsurface.

There has been a flurry of activity in recent years involving Premier Oil, Occidental Oil, Amerada Hess, and Fusion Oil. As of early 2006 there were advertisements on the internet looking for drilling personnel for work in offshore Guinea-Bissau. While there has been a flurry of drilling activities and oil discoveries have been indicated, no reserve estimates could be located (Petroquin, 2006; Bermúdez-Lugo, 2004; and World Factbook, 2006). Brownfield and Charpentier (2003) consider the area underexplored and indicate that the area has considerable oil and gas potential.

Phosphate Resources

Phosphate in the Farim area of northern Guinea-Bissau was discovered during oil drilling in the early 1950s (van Straaten, 2002). Drilling carried out by the Guinea-Bissau Directorate of Geology and Mines in 1975 identified a bed nearly 5 m thick with

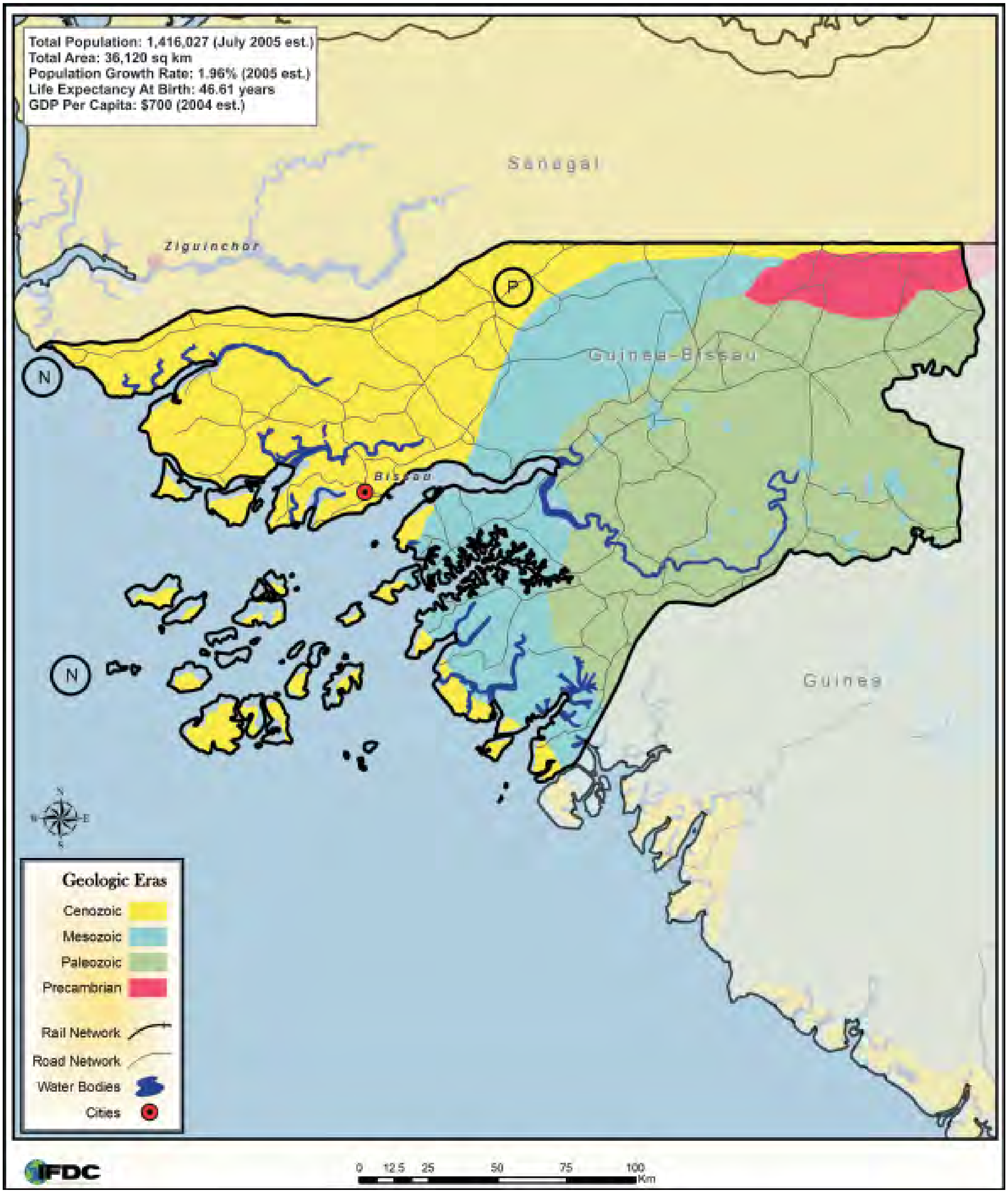

Figure Guinea-Bissau 1. Geology, Major Cities, and Transportation Network approximately 27% P_2O_5. Subsequent exploration in collaboration with the Bureau de Recherches Géologiques et Minières (BRGM) delineated deposits near the village of Saliquinhe, 4 km west of the town of Farim (Sustrac, 1986). The drilling program identified a reserve of 112 million tons at 29.85% P_2O_5, 7.8% SiO_2, and 7.1% R_2O_3 ($Al_2O_3 + Fe_2O_3$). The average thickness of the phosphate bed is about 3 m. Beneficiation tests in France produced a concentrate assaying 37.8% P_2O_5 and 1.02% iron (1.46 Fe_2O_3).

The Farim-Saliquinhe Deposit is Eocene in age, similar to the phosphate deposits to the north in Senegal. The phosphate was deposited on the north flank of a feature called the Jumbembem Ridge on the south side of the Gulf of Casamance, which existed in Eocene times.

Champion Industrial Minerals Inc. (CIM), a subsidiary of Champion Resources Inc., Canada, acquired a 100% interest in the Farim-Saliquinhe Deposit. A study conducted by CIM indicated 166 million tons of ore at 29.1% P_2O_5 (*Fertilizer International*, 2003). The project envisaged a 15-year mine plan, indicating that ample resources existed to increase the mine life beyond 25 years. An annual production rate of 2.1 million tons of concentrate at 32.3% P_2O_5 was planned.

The mine would be an open pit. Ore would be slurried to an onsite beneficiation plant. The ore would be wet screened, and fractions would be subjected to magnetic separation. The coarse fraction would be filtered on a belt filter. The fine fraction would be centrifuged. Both fractions would be fed through a dryer. The overall P_2O_5 recovery rate would be expected to be between 80% and 84% by this method. Higher grade concentrates could be obtained utilizing flotation. One plan considered loading the product on barges at the Cacheu River and transporting it downstream to a transshipment point at the mouth of the river. However, the Cacheu River is rather shallow and there is a barrier sandbar at the mouth. A 90-km slurry pipeline from the beneficiation facility to the deep-water port at Port Chugue on the Rio Geba was considered a better solution, although it would be a capital-intensive solution.

Rescan Environmental Services of Canada performed an environmental study, which concluded that the environmental impact of the project could be minimized by responsible mine planning and waste handling. The mine plan would include progressive reclamation of the pit, landscaping of replaced overburden and waste tips, replacement of soils, and replanting programs.

In 2003 Champion Resources merged with Red Back Mining NL of Australia to form Red Back Mining Inc. Subsequently Red Back Mining entered into a purchase agreement with Geyser Ltd., a Dubai-based company wherein Geyser would acquire CIM for US $10.5 million. Geyser was unable to meet purchase obligations (Bermúdez-Lugo, 2004).

There are several potential problems in the mining and utilization of the Farim-Saliquinhe Deposit. The overburden is relatively thick; it ranges from 26 m near Farim to 50 m in the northern part of the deposit. The stripping ratio is over 6:1. A portion of the deposit lies under a river valley; there may be problems with water handling. The Fe_2O_3 of the ore is high due to the presence of 1%-8% pyrite. No data were available to evaluate the Fe_2O_3 content of the concentrates produced by wet screening and magnetic separation. There is some discrepancy in the reported cadmium contents of the Farim-Saliquinhe phosphate rock. *Fertilizer International* (2003) reports a low cadmium content (not specified). Prian (1989) indicates cadmium values of 80 ppm for a composite sample collected from four boreholes. High cadmium contents would be a definite negative factor in developing the deposit.

Sulfur Resources

Sulfur may be an eventual byproduct of oil production. Oil produced from carbonate sequences and fields based around salt diapirs often has a significant sulfur content, which must be removed. Native sulfur may be present in the cap rock over salt diapirs.

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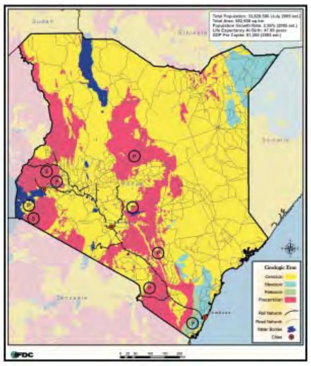
KENYA



The Republic of Kenya (Figure Kenya 1) is bordered by Tanzania to the south, Uganda to the west, Sudan and Ethiopia to the north, and Somalia and the Indian Ocean to the east. Total area of the country is 582,650 km^2 and arable cropland is 8.1% of the land area. The population was estimated at 33.8 million inhabitants in mid-2005 (World Factbook, 2006). Annual population growth was estimated at 2.6%. Seventy-five percent of the population is occupied by agriculture. Kenya is the regional hub for trade and finance in East Africa. The transportation network (Figure Kenya 1) consists of 7,737 km of paved roadways and 56,205 km of unpaved roadways. Kenya has 2,778 km of narrow-gauge (1 m) railway. There are 15 airports with paved runways and 209 airports with unpaved runways. Mombasa is the main port.

Geologically Kenya is composed of Archean granitic complexes and greenstone terrain in the west along the Uganda border; the Neoproterozoic Panafrican Mozambique Belt, which lies north to south in the middle of the country; and Paleozoic to Cenozoic sediments, which are found in the coastal basins. The Eastern Rift Valley crosses Kenya from north to south. Volcanics and lacustrine sediments infilling the Rift Valley cover and mask much of the Mozambique belt. Several basins and troughs are found within the interior and along the coast (Figure Kenya 2).

Nitrogen Resources

Oil and gas exploration in Kenya has been overseen by the National Oil Company of Kenya, Limited (NOCK) since 1984. NOCK officially launched its website (www.nockenya.co.ke) on December 12, 2005. NOCK provides information and services, undertakes exploration activities, and monitors petroleum exploration contracts for the Government of Kenya.

British Petroleum drilled the first exploration well in Kenya in the 1950s. Shell began exploring in Kenya in 1954 and drilled 10 wells. Many other companies conducted geophysical studies and drilled wells into the 1970s. Seismic data indicated there were salt diapirs in the thick sedimentary sequence off the Kenyan coast, and several wells were drilled offshore in the early 1980s. This work continued into the late-1980s.

While none of these wells resulted in commercial reserves, there were several oil and gas shows associated with the wells. NOCK has continued a limited exploration effort and continues to provide information to international oil companies.

In 2003, Woodside Energy, Australia, acquired a 40% interest in several offshore blocks from Dana Petroleum Ltd. (Yager, 2003). Woodside carried out 7,881 km of seismic surveys that year. NOCK holds the data from this survey. The Woodside Energy internet site (woodside.com.au) does not offer any current information on the status of exploration in the area.

The oil refinery in Mombasa was built in 1959 and typically processes an average of about 95,000 barrels per day (bpd). Refinery products include gasoline, jet fuel, light diesel oil, and fuel oil.

Naturally occurring sodium nitrate has been described from the Lake Turkana area in northern Kenya (Owen and Renault, 1989). The nitrates are found in the Galana Boi Formation, which represents a series of stranded raised Holocene sediments that

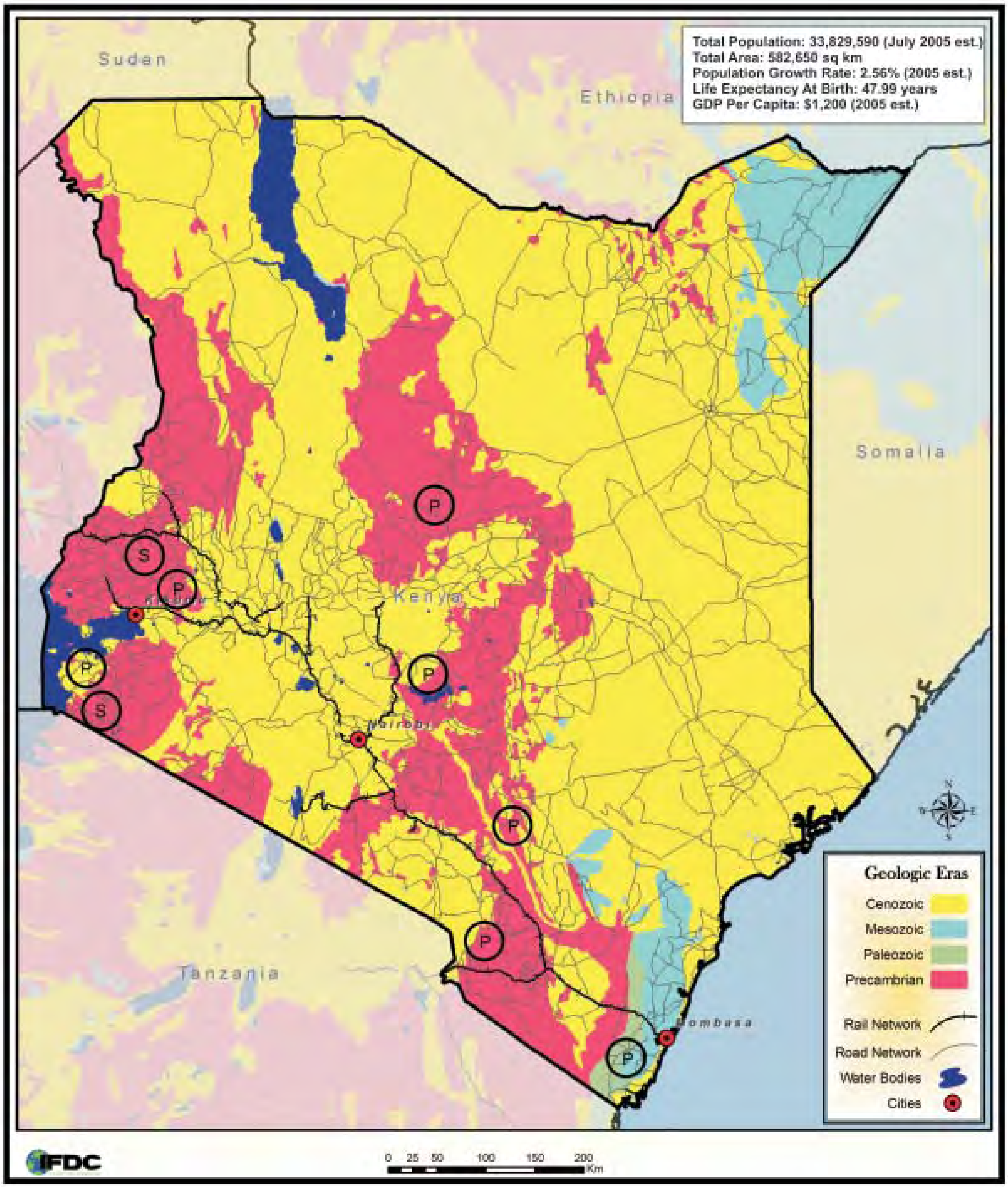


Figure Kenya 1. Geology, Major Cities, and Transportation Network

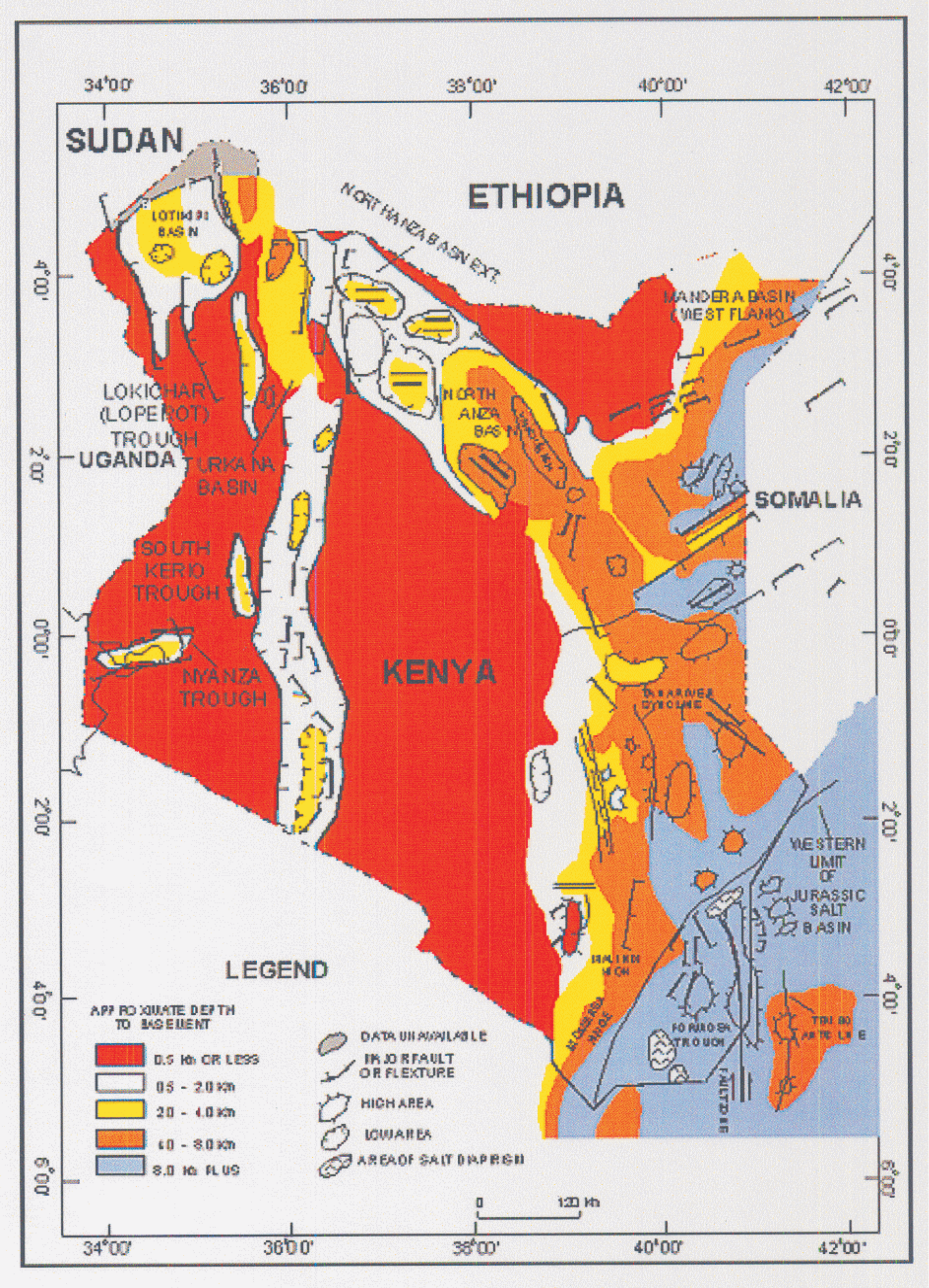


Figure Kenya 2. Sedimentary Basins Structural Framework
(adapted from www.nockenya.co.ke)

surround present-day Lake Turkana. The sodium nitrate content ranges from 1.1% to 7.5% by weight. The nitrate-bearing beds are widely distributed within the area. There is no resource estimate. Owen and Renault (1989) indicated that the material probably would never be utilized as a low-grade fertilizer due to the remoteness of the region, lack of agriculture in the region, and the fact that the deposit lies within the Sibiloi National Nature Reserve.

Phosphate Resources

Mrima Hill Carbonatite—The Mrima Hill Carbonatite Complex is located in southwest Kenya about 65 km from Mombasa near the Tanzanian border. The elliptical hill is about 1.6 km in width and rises approximately 225 m above the coastal plain. Residual ferruginous soils from 30 to 180 m thick blanket the carbonatites.

The hill has been extensively explored for niobium minerals including pyrochlore. Resources in the soils amount to 7.7 x 10^6 tons at 1.24% Nb_2O_5 (Harris and Jackson, 1966). No satisfactory method for beneficiating the ore has been found.

Typical phosphate values for the deposit run from 2.5% to 3.3% P_2O_5. The phosphate has been altered to the crandallite group minerals, gorceixite and goyazite. Although free apatite has not been observed, X-ray diffraction (XRD) patterns indicate that some apatite is present (Harris and Jackson, 1966).

Rangwa Area Intrusions—Twelve carbonatites and alkali intrusions have been investigated for phosphate potential in the Rangwa area of western Kenya on the eastern shores of Lake Victoria (Idman, 1985). These intrusions can be correlated with the younger group of intrusions in eastern Uganda (King et al., 1972).

The intrusions and their associated mean P_2O_5 contents are as follows:

	Mean P_2O_5	Number of Samples
Rangwa Carbonatite	3.92	142
South Ruri Carbonatite	2.84	108
Ndiru Hill Carbonatite	2.83	99
North Ruri Carbonatite	1.90	63
Rapogi Ijolitic Complex	1.22	22
Okuge Carbonatite	4.95	16
Usaki Ijolitic Complex	1.29	12
Soklo Point Carbonatite	2.45	27
Sagurume Ijolitic Complex	1.40	18
Wasaki Carbonatite	1.64	29
South Rangwa Uncompahgrite-Turjaite Complex	2.43	23
Ndiru-Mbili Complex	1.45	14

The Rangwa Carbonatite has been the most extensively investigated of the intrusions. Both soil and bedrock surveys have been undertaken.

The Rangwa bedrock survey indicated that apatite containing 2% to 30% P_2O_5 is concentrated in a zone located in the central southeastern region of the complex. Idman (1985) noted that the apatite associated with the bedrock occurs in fine, vein-like disseminations. Discontinuous veins or layers of apatite rock may reach 4-5 m thick at maximum. The cryptocrystalline nature of the apatite suggests a late-stage (epigenetic) origin.

A sample of Rangwa Carbonatite ore containing 4.8% P_2O_5 was analyzed at IFDC (Table Kenya 1) (Van Kauwenbergh, 1985). This sample was composed of calcite, apatite, and goethite (Table Kenya 2). The apatite occurs primarily as a cryptocrystalline vein and void fillings with minor primary igneous apatite crystals. The crystallographic properties of a cryptocrystalline sample from which the

Table Kenya 1. Chemical Analyses of Kenya Phosphate Samples

	Rangwa Carbonatite Ore	Rangwa Soil No. 5142.2	Rangwa Soil No. 4378.3	KSRC Sample
	(wt %)			
P_2O_5	4.8	8.0	3.7	25.3
CaO	50.3	10.8	3.8	48.6
F^{1-}	0.6	0.7	0.3	2.8
SiO_2	1.5	26.5	36.0	1.0
Fe_2O_3	5.8	30.6	24.5	3.6
Al_2O_3	0.3	9.7	12.9	0.3
MgO	0.42	0.9	1.68	0.3
MnO	0.63	1.5	1.6	0.56
K_2O	0.04	2.6	3.9	0.06
Na_2O	0.26	0.36	0.2	1.3
TiO_2	0.10	1.8	3.3	0.08
SrO	0.43	0.29	0.16	0.97
BaO	0.31	0.71	1.2	0.30
CeO	0.19	0.40	0.53	0.20
La_2O_3	0.07	0.14	0.15	0.08
Nb_2O_5	0.27	0.61	0.27	0.18
CO_2	34.9	1.6	0.5	13.3
Cl^{1-} (ppm)	196	25	36	89
C (organic)		0.5	0.10	0.3
Free H_2O^a	0.4	9.6	15.2	0.33
LOI[b]	35.5	14.5	20.2	14.6
NAC-Soluble P_2O_5[c]	0.4	0.4	0.4	3.6

a. Free H_2O = weight loss, 105ºC, 1 h.
b. Loss on ignition = weight loss, 1000ºC, 1 h.
c. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).

Table Kenya 2. Mineralogical Analyses of Kenya Phosphate Samples (Normalized)

	Rangwa Carbonatite Ore	Rangwa Soil No. 5142.2	Rangwa Soil No. 4378.3	KSRC Sample
	(wt %)			
Apatite	13	17	6	3
Al-phosphate		4	5	–
Calcite	81	1	–	20
Feldspar		9	15	–
Iron oxides	6	32	27	4
Micas		37	47	–

calcite was dissolved indicate that the apatite was a secondary carbonate-fluorapatite variety (francolite). The fine, disseminated nature of the apatite, low grade of the sample, and type of gangue (calcite) indicate that upgrading will be difficult and expensive.

Soils from the Nyakirangacha Valley (near the Rangwa Carbonatite center) contain from 2% to 10% P_2O_5 (Idman, 1985). Phosphate-rich soils overlie areas of phosphate-rich bedrock. An area of about 220,000 m^2 with greater than 3% P_2O_5 has been delineated. Within this area a site of 80,000 m^2 with 4% to 5% P_2O_5 exists. Depth to bedrock appears to average about 5 m. Studies at the Kenya Mines and Geological Department indicated that little, if any, upgrading of the P_2O_5 in the soils was possible by magnetic separation and sizing.

Two Rangwa soil samples with 3.7% and 8.0% P_2O_5 have been chemically analyzed at IFDC (Van Kauwenbergh, 1985) (Table Kenya 1). The phosphate in these soils occurs as francolite, igneous apatite crystals, and crandallite group minerals (Table Kenya 2). Gangue minerals present include micas, clays, iron oxides, and feldspars. Laboratory-scale beneficiation tests involving attrition scrubbing, desliming, sizing, and magnetic separation have been suggested.

A third phosphate sample from the Rangwa area has been analyzed (IFDC, 1986) for the Kenya Superphosphate Research Company (KSRC), Nakuru, Kenya (Table Kenya 1). The sample is composed of apatite, calcite, and goethite (Table Kenya 2). Petrographically and crystallographically, the apatite of this sample is very similar to the secondary francolite observed in the Rangwa carbonatite sample. The neutral ammonium citrate solubility of this sample is 3.6% P_2O_5. This rock may be of value as a direct-application material if a deposit of suitable tonnages can be confirmed.

Guano Deposits—In 1966 deposits of bat guano were discovered in caves in the Chyulu Range, Machakos District, southeast of Nairobi. The deposits are as much as 13 ft thick (Notholt, 1978). Kenya Guano Limited, Nairobi, worked a cave deposit, containing about 11.2% P_2O_5 near Ithundu, 11 miles south of Kiboko railway station on the Nairobi-Mombasa line.

Guano occurrences have been observed in the extinct Suswa Volcano in the Great Rift Valley (Savage, 1987). Small deposits of guano occur near Mombasa and in western Kenya near Kisumu, Nyanza Province.

Ruri Complexes—The Ruri complexes are situated to the east of the Rangwa Complex. Idman (1991) indicated that a sample from Ruri South had a P_2O_5 content of 2.19% while a Ruri West sample had a P_2O_5 content of 12.09%.

Buru Hill—This carbonatite complex occurs east of Kisumu. Van Straaten (2002) noted that the results of Japanese exploration for rare earths and follow-up work by Finnish and Kenyan geologists indicated sporadic and low concentrations of apatite in the complex.

Other Phosphate Occurrences—Subordinate amounts of apatite occur in kyanite-graphite schists near Longalonga in the Taveta area. Larger and richer deposits may be revealed by more detailed prospecting (Du Bois, 1966). Alluvial gravels containing apatite have been discovered at Songhor in the Kericho area. The deposit is too small to be of economic interest. Apatite crystals occur in lenses associated with an altered basic igneous intrusion 16 km west of Lodosoit in the Nanyuki-Maralal area. A pegmatite near the Thura River in the district southeast of Embu contains apatite crystals.

A magnetite deposit near Ikutha had been reported to contain up to 25% apatite (Notholt, 1978). The Ikutha Deposit is an intrusive-type vein deposit. Geophysical and geologic investigations (Kuivasaari, 1991) indicated a potential resource of 31,000 tons of apatite concentrate at 35%. In 2002, van Straaten indicated that the deposit was not economic.

Sulfur Resources

Potentially economic deposits of iron sulfides occur in the Nyanza Goldfields, North Nyanza Province (Pulfrey, 1947). Most significant are the pyrite gossans and pyrrhotite deposits that occur at Bukura and Mbesa near Kakamega (Gaciri, 1991). Pyrite lodes are associated with copper ore bodies at the Macalder Mine, South Nyanza Province (Pulfrey, 1947).

Gypsum deposits occur along the coast in Jurassic sediments and as Tertiary and Pleistocene lake and marsh deposits in the interior.

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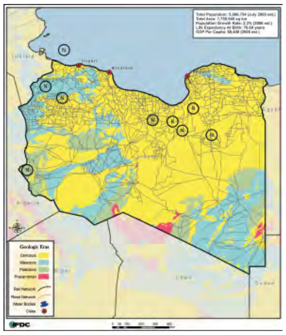
LIBYA



The Great Socialist People's Libyan Arab Jamahiriya is bordered to the east by Egypt and Sudan, the south by Chad and Niger, the west by Algeria and Tunisia, and the north by the Mediterranean Sea (Figure Libya 1). The total area is 1,759,540 km^2 and approximately 1.0% of the land is arable. The population was estimated in mid-2005 as 5.9 million inhabitants (World Factbook, 2006). Agriculture occupies approximately 7.6% of the labor force.

The transportation network consists of 47,590 km of paved roads and 35,610 km of unpaved roads. There are no railroads in Libya. There are 59 airports with paved runways and 80 airports with unpaved runways. There are two heliports. Pipelines within the country include 3,611 km for gas, 225 km for natural gas condensate, and 7,252 km for oil. Major ports and terminals include As Sidrah, Az Zuwaytinah, Marsa al Burayqah, Ras Lanuf, Tripoli, and Zawiyah.

Precambrian age rocks occur along the south central border with Chad and near the junction of the boundaries with Egypt and Sudan. The Lower Precambrian age rocks are composed of granites and strongly metamorphosed gneisses, schists, and amphibolites. The Upper Precambrian is mainly composed of moderately to weakly metamorphosed sedimentary rocks.

Paleozoic age rocks include marine and continental sediments with minor carbonates in the Upper Carboniferous. Paleozoic age rocks are particularly well developed in the southeast and southwest of the country.

The Nubian Series, composed mainly of clastics, was deposited from the Permian to the Lower Cretaceous ages. The Triassic and Jurassic age rocks are mainly clastics with some carbonates. Upper Cretaceous age rocks are mainly marls and carbonates with some evaporites. Mesozoic age rocks outcrop extensively in the western third of the country and the extreme southwest and are found at depth in the Sirte Basin in north-central Libya.

Pliocene and Quaternary age sediments of both continental and marine origin are found near the coast. Inland sediments of these ages become progressively lacustrine and fluvial; eventually dune deposits and desert pavement become prevalent. Tertiary to Quaternary volcanics cover extensive areas to the south of Tripoli and southeast into the Sirte Basin and beyond to near the Chad border.

Nitrogen Resources

Oil was discovered in Libya in 1959 at Amal and Zelten (MBendi, 2006). Oil production began in Libya in 1961. Libya has been a member of the Organization of Petroleum Exporting Countries (OPEC) since 1962. Natural gas production began in 1970 (World Energy Council, 2001). In 2003 the UN Security Council lifted sanctions against Libya, which were instituted as the result of the 1988 bombing of Pan Am Flight 103 over Lockerbie, Scotland. In 2004 the United States eased economic sanctions against Libya, and on July 28, 2004, the United States and Libya formally resumed diplomatic relations. On the same day, the state-owned National Oil Corporation (NOC) announced the first oil shipment to the United States in over 20 years. With UN and U.S. imposed sanctions, production of

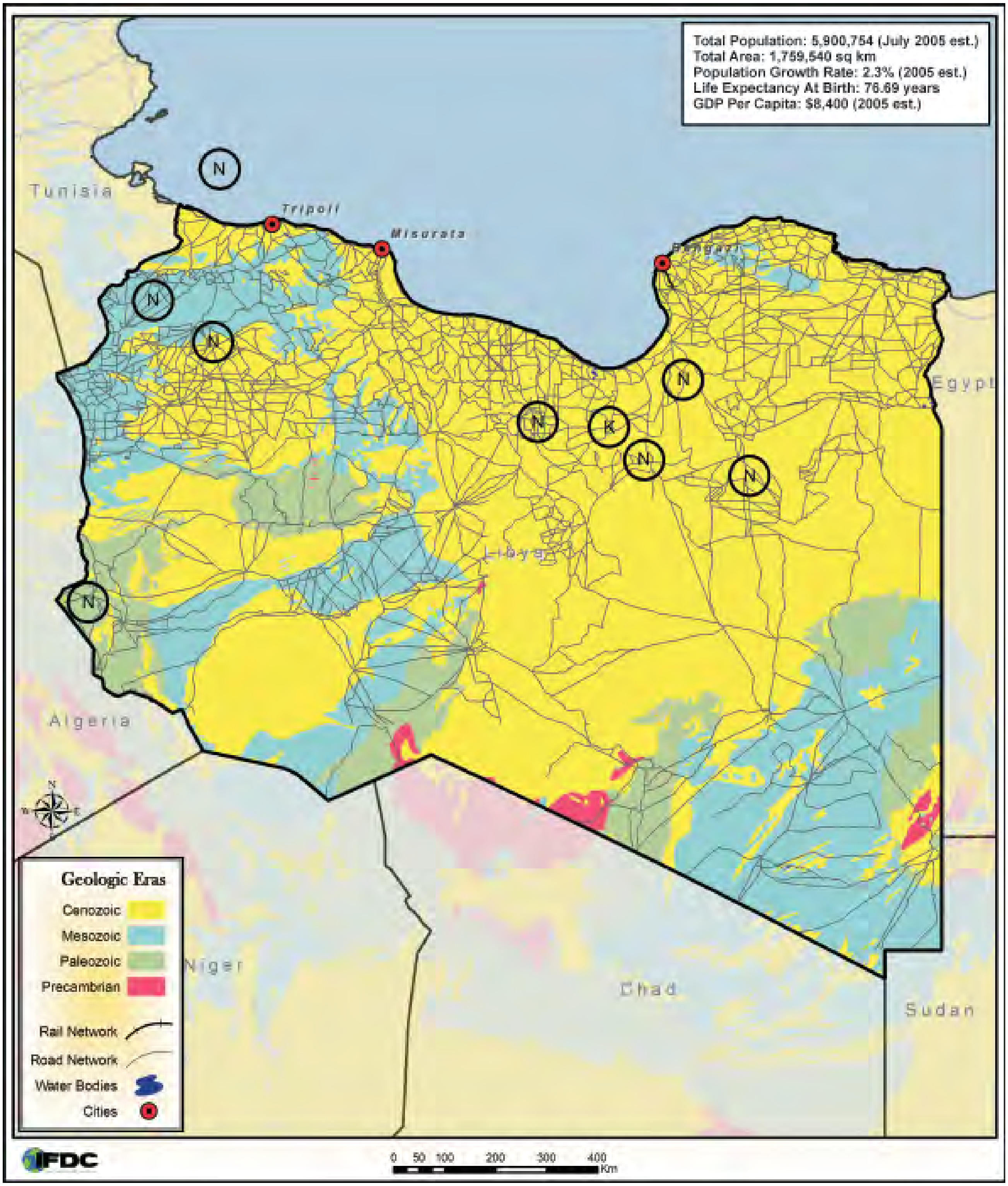

Total Population: 5,900,754 (July 2005 est.)
Total Area: 1,759,540 sq km
Population Growth Rate: 2.3% (2005 est.)
Life Expectancy At Birth: 76.69 years
GDP Per Capita: $8,400 (2005 est.)

Figure Libya 1. Geology, Major Cities, and Transportation Network oil and gas had languished and production in 2004 was less than one-half of the production in 1970 (Mobbs, 2004). With the lifting of sanctions, activity has increased in Libya with companies such as British Petroleum, Royal Dutch/Shell, ChevronTexaco, ConocoPhillips, ExxonMobil, Marathon Oil, and North Korean and Chinese state-owned energy companies submitting bids for concessions (Nichols, 2004).

The Energy Information Administration (EIA) reported that oil production in Libya in January 2006 was 1,650,000 barrels per day (bpd), up from the 2003 yearly average of 1,421,000 bpd (EIA, 2006). Most of the oil production is from the onshore Homra and Sirte Basins. Offshore development is increasing. The crudes produced are generally light (over 35º API) and very low in sulfur (World Energy Council, 2001). The only oil refinery is located at Ras Lanuf. The capacity is 220,000 tons of combined products per year (Mobbs, 2004).

Natural gas production was 7 billion m^3 in 2003 (World Factbook, 2006), slightly higher than natural gas consumption (6.25 billion m^3). Natural gas exports were 770 million m^3 in 2001. Libya became a natural gas exporter in 1970/71 when a liquefied natural gas (LNG) plant began production at Marsa el-Brega. This was reportedly the world's second LNG facility (Bahgat, 2004). In 1980 the government nationalized the Esso facilities and imposed price increases. Many customers cancelled contracts or scaled down purchases. Gas is currently being exported via a pipeline to Italy through Sicily in partnership with Agip. This is said to be the largest investment in Libya since UN sanctions were suspended (Bahgat, 2004).

Proven oil reserves are 40 billion barrels (2005 estimate), and natural gas proven reserves are indicated as 1.321 trillion m^3 (2005 estimate) (World Factbook, 2006). Gas fields occur offshore north of Tripoli and onshore in the Sirte Basin.

Nitrogen Fertilizer Production—The Sirte Oil Company operates the Marsa el-Brega I and II ammonia plants at Marsa el-Brega. Combined ammonia production capacity is 730,000 tpy of ammonia (IFDC, 2006a). Associated with the ammonia plants are the Marsa el-Brega I and II urea plants. Combined urea production capacity is 908,000 tpy (IFDC, 2006b). All of the plants were listed as operating in 2006.

Potassium Resources

Potash-bearing brines occur in a depression about 125 km south of Al Aquylah (or El Agheila) near Maradah. The depression covers an area of approximately 150 km^2 (British Sulphur Corporation, 1985). Beneath the salt flats, clays and sandstones are interbedded with halite. Gypsum and halite are deposited in the western part of the flat, and potassium and magnesium chlorides are found in the deeper areas.

The salt-bearing brine has a variable composition. At the center of the halite crust, the brine may have a composition of 20.45% sodium (Na), 13.05% potassium (K), and 2.28% magnesium (Mg). Near the edge of the halite crust, the brine may contain 4.4% Na, 1.88% K, and 5.15% Mg (British Sulphur Corporation, 1985).

The brine was experimentally produced by Italian interests in 1939. The brine was collected from shallow pits (0.5 m), and fractional crystallization yielded a product with 40%-50% K_2O. Reserves in a 15-km^2 area were estimated at 1.6 million tons of potash salts at 40% K_2O. Cabien Exploration Corporation, California (United States), conducted a drilling program in the area in 1961. The deposit was not further developed at that time.

In 1985 it was reported (British Sulphur Corporation) that the Government of Libya had instituted a project to develop the brines of the area for potash and other chemical applications. There are no apparent records of potash production from Libya in the last 15 years.

Sulfur Resources

Mobbs (2004) indicates that 15,000 tons of sulfur was produced in Libya in 2004 as a byproduct of petroleum and natural gas production. Mobbs (2004) also indicates that 175,000 tons of gypsum was produced in Libya in 2004.

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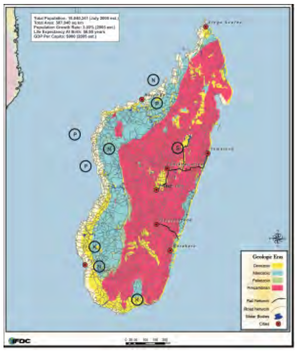
MADAGASCAR



The Republic of Madagascar (Figure Madagascar 1) is the world's fourth largest island. The total area is 587,040 km^2 and approximately 5.1% of the land is arable. The population was estimated in mid-2005 as 18.0 million inhabitants. Annual population growth is about 3.0% (World Factbook, 2006). Agriculture occupies 80% of the labor force and is the mainstay of the economy. The transportation network (Figure Madagascar 1) comprises 5,780 km of paved roadways, 44,047 km of unpaved roads, 600 km of waterways, and 116 airports of which 29 have paved runways. There are four main seaports (Antsiranana, Mahajanga, Toamasina, and Toliara).

Precambrian age rocks form the backbone of the country and predominate on the eastern side of the country. Archean Precambrian rocks include medium- to high-grade metamorphic rocks such as mica schists, gneisses, migmatites, and amphibolites. Protozoic metasediments are also found within the Precambrian terrain. Paleozoic to Tertiary age sediments offlap the Precambrian basement to the west and south. A narrow band of Mesozoic to Tertiary age sediments is found along the east coast.

Nitrogen Resources

Petroleum—The Government of Madagascar and the Office de Mines Nationales et Industries Strategique (OMNIS) are promoting petroleum exploration and are inviting companies to apply for licenses in the Mozambique channel and onshore. The country's petroleum code was issued in 1996.

More than 90 exploration wells have been drilled in Madagascar (2005 estimate, Conne, 2005), only 10 of which were drilled offshore. Companies that have explored in Madagascar include Conoco, Amoco, Agip, Chevron, Petro-Canada, Mobil, Copetma, Shell, Hunt Oil, Vanco, Norsk Hydro, Vuna Energy, and China's Sino Union Petroleum and Chemical. ExxonMobil opened an office in the capital, Antananarivo, in 2005 and hoped to drill its first deep-water well in late 2006 or 2007.

Although oil and gas finds have been made in the past, none have been developed and no hydrocarbon production has been established. With estimated resources of 20 billion barrels of oil, the underdeveloped Bemolanga tar sands and Tsimiroro heavy-oil deposits (8 billion barrels of reserves) are the best known hydrocarbon accumulations in the country. The Bemolanga tar sands cover an area of >400 km^2 and have been appraised by 250 shallow boreholes (Jeans and van Meerbeke, 2006). About 1 billion barrels may be recoverable by open-pit mining. The Tsimiroro heavy-oil field has been appraised by over 45 shallow wells. Madagascar Oil SA holds production-sharing contracts for many of the blocks encompassing the Bemolanga tar sand and Tsimiroro heavy-oil deposits.

The entire Mozambique Channel is an area of intense interest. Structures mapped by seismic surveys indicate the area could potentially be another North Sea or Middle East giant oil field area (Explorer, 2003).

Coal—Coal deposits are found in southwestern Madagascar. In 2003 Vuna Energy Ltd., United Kingdom, signed an agreement with the government to explore the Sakao Coal Deposit east of Tulear (Yager, 2003).

Phosphate Resources

Phosphate nodules (containing approximately 20% P_2O_5 or less) occur in the Majunga Basin in

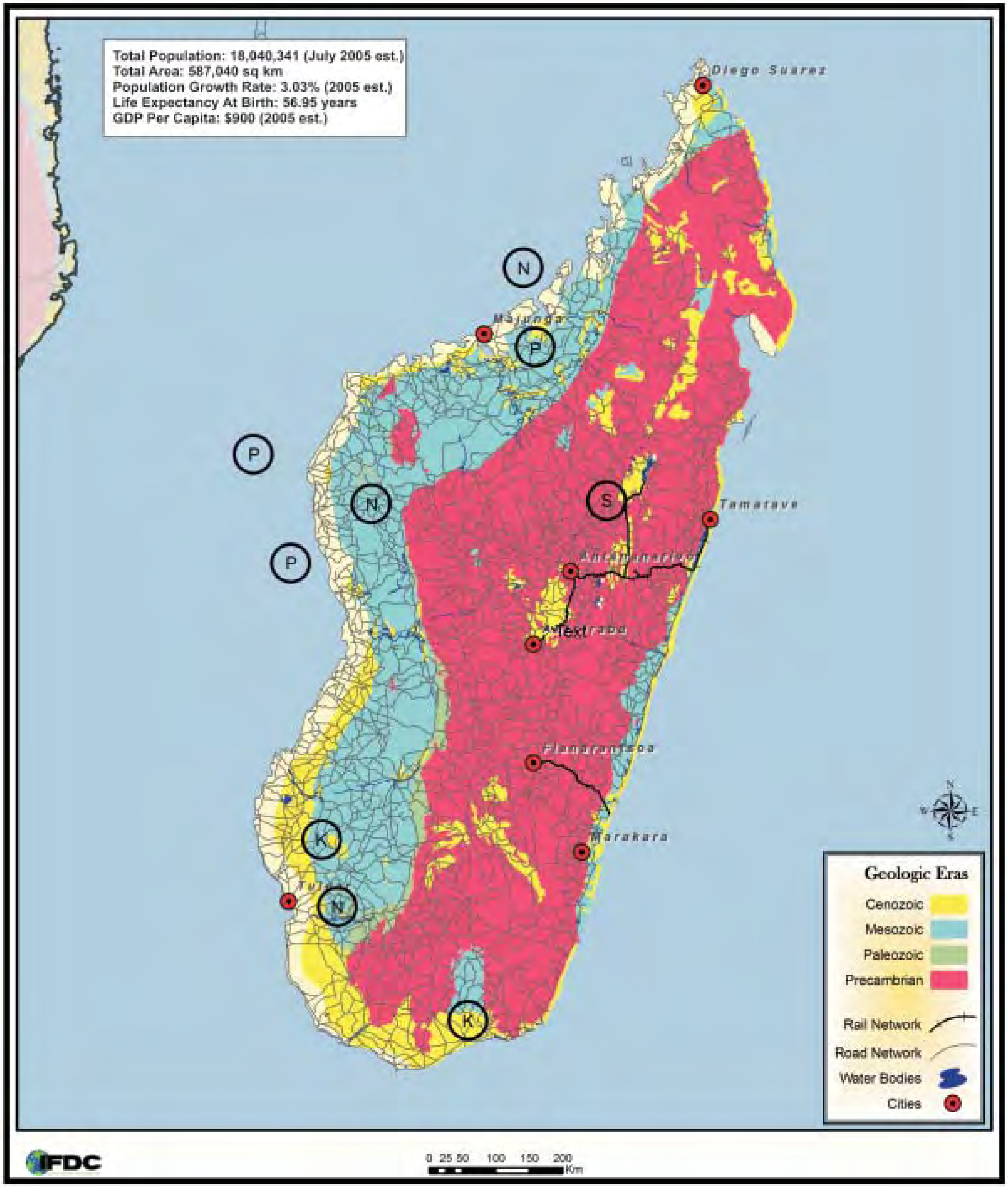


Figure Madagascar 1. Geology, Major Cities, and Transportation Network marls of lower Cretaceous Age near Ambato-Boeni, in upper Cretaceous age sediments near Marovoay, and in beds of comparable age south of Soalara and near Sitampiky (Notholt, 1994). Phosphate beds also occur on the Antonibe Peninsula at the base of the Paleocene. Phosphatic grits are found in the lacustrine sediments of Lake Alaotra, and phosphate values are associated with Pliocene marls at Antanifotsy.

Igneous apatite was reported from phlogopite-bearing pyroxenites near Betroka and Bekily (Murdock, 1963). Mining began in 1913. Murdock (1963) reported that, in some of the pegmatoid veins, apatite was the predominant mineral.

Guano-related deposits were mined for many years on the French-administered Island of Juan de Nova off the west coast of Madagascar. The deposit is about 5.4 km x 1.5 km. Murdock (1963) indicated that analyses of the phosphatized bedrock were 29.1% P_2O_5, 44.0% CaO, and 8.5% H_2O. Production started in 1922 and lasted until 1940. Total production was 122,316 tons. Production was reinitiated in 1956 and lasted to 1960, and average annual production was about 6,000 tons.

The Barren Islands, 10-20 km off the Madagascar coast, contain estimated reserves of 613,000 tons of phosphatized rock. Approximately one-half of the reserves (312,000 tons) occur on Andrano Island (Support and Supervision Team, 1997). These guano-related rocks typically have a high reactivity in commonly used reactivity media. Because these deposits are located on carbonate bedrock islands in proximity to coral reefs and the environment supports a wide variety of marine life, mining may require special efforts to mitigate the effect on marine life and preserve the ecology of the area. In the late-1990s, the Government of Madagascar gave permission to a private company (GEMEX) to mine the deposit.

Potassium Resources

Glauconite occurs within the Analavelona Hills north of Toliara (Tulear) in lower Cretaceous sandstones (Murdock, 1963). Glauconite also occurs in the Menarandroy Valley, west of Betioky, in extreme southern Madagascar (Besaire, 1966).

Sulfur Resources

Gypsum lenses, up to 3 m thick and 10-85 m long, occur on the banks of the Ankay River, 20 km north of Mahazoma (Murdock, 1963).

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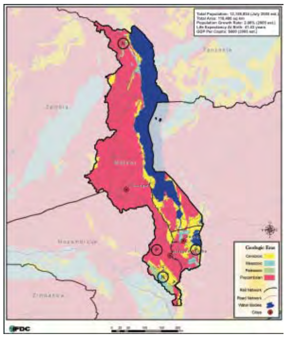

MALAWI

The Republic of Malawi is bordered to the west by Zambia; to the north by Tanzania; and to the south, east, and west by Mozambique (Figure Malawi 1). The total area is 118,480 km^2 and approximately 23.4% of the land is arable. The population was estimated in mid-2005 as approximately 12.1 million inhabitants. Annual population growth was estimated at 2.1% (World Factbook, 2006). Agriculture occupies 90% of the labor force.

The transportation network is composed of 5,254 km of paved roads, 23,146 km of unpaved roads, and 797 km of 1.067-m-gauge railway. There are 6 airports with paved runways and 36 airports with unpaved runways. Malawi is totally landlocked. However, it has 700 km of waterways on Lake Malawi and the Shire River. The main ports are Chipoka, Monkey Bay, Nkhata Bay, Nkhotakota, and Chilumba.

Lake Malawi, also known as Lake Nyasa, is the most southerly large lake in the Great African Rift Valley system. The lake lies in a graben bounded by faults on either side. The Precambrian age basement complex of Malawi is mainly composed of gneiss, granulites, and schists, with associated mafic, ultramafic, syenitic, and granitic rocks. Two dominantly psammitic groups outcrop along the western border, rest with marked unconformities on gneisses, and may be of Proterozoic age.

The occurrence of Paleozoic age rocks in Malawi is very limited. The Nachipere Series, which may be Devonian in age, contains poorly preserved plant remains. Rocks of the Permo-Triassic Karroo (or Karoo) Series outcrop at the southern border with Mozambique and in the extreme north of the country. Tertiary and Quaternary sediments infill areas along Lake Malawi and the Rift Valley depressions. Upper Karroo dolerite dike swarms and basaltic lavas are found in southern Malawi. In late Jurassic to Cretaceous time, plutons, volcanic vents, and minor intrusions of the Chilwa Alkaline Province formed.

Nitrogen Resources

The Ministry of Natural Resources and Environmental Affairs Geological Surveys Department (2006) of the Government of Malawi indicates there are 13 coalfields in Malawi with “speculated” reserves of 800 million tons. The reserves and possible resources of seven of these coalfields are given in Table Malawi 1.

The Mchenga Coal Mine is located in the Livingstonia Coalfield. The Mchenga Mine produces subbituminous coal for domestic consumption and export to Tanzania. Production in 2002 was almost 42,000 tons (Yager, 2003). In 2003 floods damaged

Table Malawi 1. Malawi Coal Fields, Reserves, and Resources

Coal Field	Reserves		Possible Resources
	Proven	Probable	
	(million tons)		
Ngana	15.0	50.0	–
Livingstonia	0.6	5.0	20.0
Lufira	0.6	50.0	–
Mwabri	5.0	10.0	–
Lengwe	–	10.0	–
North Rukuru	0.5	5.0	165.0
Nthalire	–	–	15.0

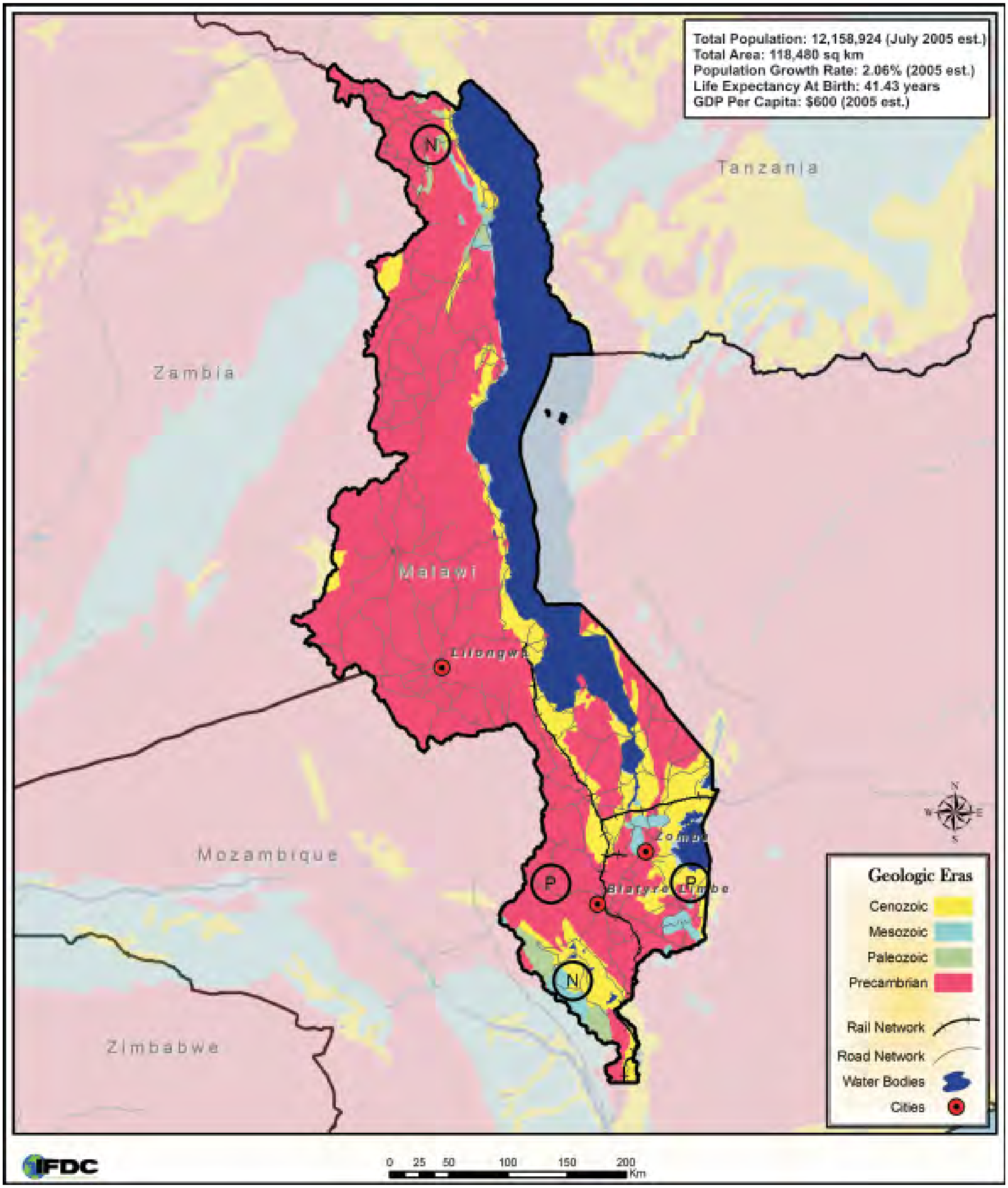

Figure Malawi 1. Geology, Major Cities, and Transportation Network equipment and reduced production by two-thirds. Mchenga produced at a rate of about 60,000 tpy in late 2004 (Yager, 2004). About 12,000 tons was exported to Mbeya Cement in Tanzania. The company was exploring for additional reserves in the Livingstonia coalfield in 2004. The company planned to open the Chombe Mine in Livingstonia and to increase output to 96,000 tpy in 2005.

Phosphate Resources

Tundulu Carbonatite—The Tundulu Carbonatite Complex lies at the southern end of Lake Chilwa (Figure Malawi 1). Apatite-rich rock and apatite sovite are found in an arcuate zone on the southeast and east side of Nathace Hill (Garson 1962, 1965) (Figures Malawi 2 and Malawi 3). Garson (1965) indicated that the apatite crystals of Tundulu occur as pink ovate grains with turbid (cloudy) cores and clear rims. Refractive indices range from N_o = 1.632 to 1.634 and from N_E = 1.627 to 1.629, indicating a fairly pure fluorapatite composition. Some of the very cloudy apatite crystals have cores with N_o = 1.636, probably indicating apatite cores with hydroxyl substitution. Garson (1965) indicated that chalk-like weathered patches in some of the apatite-rich rocks consist of staffelite (francolite) similar to the apatitic rock found at Busumbu in Uganda.

Analyzed P_2O_5 contents for apatite-rich rocks from Tundulu (Garson, 1965) were from 20.80% P_2O_5 to 38.94% P_2O_5. The results of analyses by IFDC and Appleton (1994) indicate the apatite-rich rocks contain significant amounts of silica (Table Malawi 2). The results of neutral ammonium citrate (NAC) extractions indicate that the presence of carbonates suppressed the results of the first NAC extraction. The results of a second NAC extraction by Appleton on two Tundulu samples indicate NAC solubility of 1.6% P_2O_5. This solubility is typical of igneous apatites and is considered very low.

Garson (1965) indicated that to a depth of about 30 m there was 800,000 tons of phosphate rock with a P_2O_5 content of over 20%. There was an additional 100,000 tons of apatite-sovite and apatite-rich bastnaesite-carbonatite with over 10% P_2O_5 plus nearly 500,000 tons of feldspathic apatite-sovite with a P_2O_5 content of about 5%. Malunga (1999) notes that Met-Chem Canada did a preliminary review of the Tundulu Carbonatite for Malawi Development Corporation. The results suggest that the potential recovery of niobium (1.7 kg/ton) and medium-weight rare earths (1.9 kg/ton) might make the recovery of phosphate more attractive.

Malunga (1999) lists 2 million tons of reserves of phosphate rock at 17% P_2O_5 in Malawi. It is not clear if this is an estimate for Tundulu or a country-wide estimate.

Mlindi Pyroxenite—The Mlindi Deposit is located in Mwanza District 13 km from Neno. Residual soils are developed over a metapyroxenite core. Two areas within the core showed P_2O_5 contents of 7% and 14% (Chisale and Kaphwiyo, 1987). To a depth of 2.5 m, probable reserves are estimated at about 2.4 million tons.

Chingale Deposit—The Chingale Deposit is located 22 km west-southwest of Zomba. This ring structure has an inner core of metapyroxenite. The average P_2O_5 content of the soil over a 135-ha area is 3.7%. The calculated probable reserves are 0.32 million tons (Chisale and Kaphwiyo, 1987).

Other Deposits—Garson (1965) pointed out that apatite is present at practically all the carbonatite complexes in Malawi. At Chilwa Island, apatite is associated with pyrochlore-rich rocks and is enriched in soils derived from them. The average P_2O_5 content in soils from Chilwa Island is over 5%, and values in the summit soils are higher (Garson, 1965). Patches of apatite-sovite on the inner slopes of the Northern Spur contain more than 50% apatite, but these occurrences are of limited extent.

The central part of the manganese-rich Kangankunde Carbonatite Complex contains fine-grained streaks and lenses of apatite similar to that of Tundulu. Garson (1965) estimated the apatite ranges from 3% to 50% with average grades of 5% to 10% P_2O_5. Although there are considerable tonnages of apatite in the manganiferous area, Garson (1965) indicated that, because of the difficulty of separation, the deposits are of doubtful economic importance.

Numerous other apatite and rare earth prospects have been investigated in Malawi, including Bilira, Choani, Nkholonje, Mongolowe Hill, Namangali Hill, Chinduzi Hill, Songwe, Junguni, Zomba Plateau, Ntonya, and the Nsili Dome (Chisale and

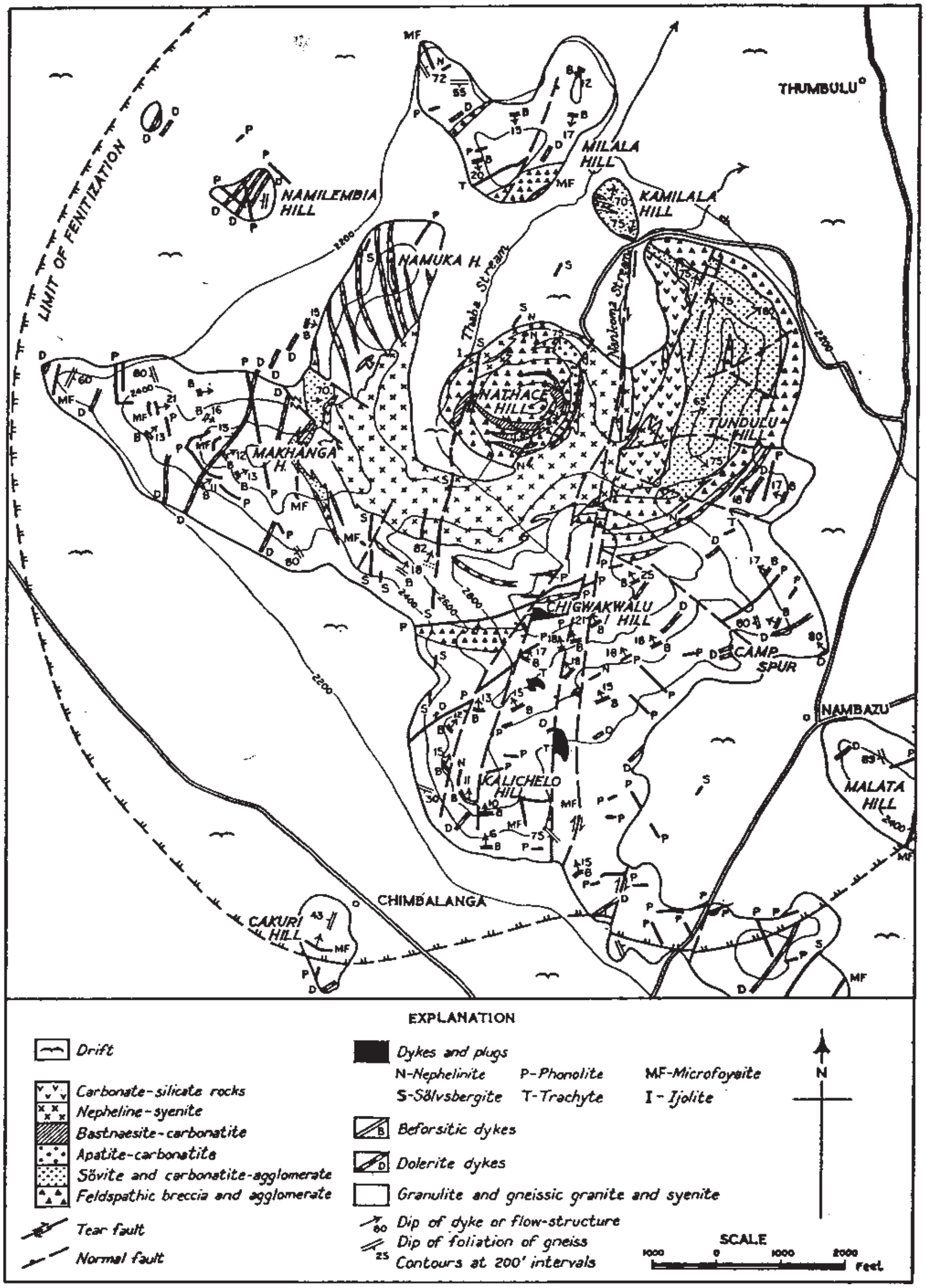

Figure Malawi 2. Geology of the Tundulu Carbonatite Complex (Garson, 1965)

Figure Malawi 3. Nathace Hill, Tundulu Carbonatite Complex

Table Malawi 2. Chemical Analyses, Tundulu Phosphate Rock

	IFDC	Appleton, 1994[a]
	(wt %)[b]	
P_2O_5	23.2	27.7
CaO	39.2	36.28
F	2.3	2.77
SiO_2	16.6	17.66
Fe_2O_3	4.9	4.21
Al_2O_3	1.3	0.91
Na_2O	0.31	0.39
MgO	0.37	0.19
K_2O	0.13	0.54
SrO	0.71	0.92
BaO	0.56	0.62
CO_2	6.5	–
Organic C	0.1	–
Free H_2O[c]	0.08	–
LOI[d]	7.8	–
NAC P_2O_5[e]	0.4	1.6[f]

a. Average of 29 samples, except NAC P_2O_5, 2 samples.
b. Except as noted.
c. Free H_2O = weight loss, 105ºC, 1 h.
d. Loss on ignition = weight loss, 1000ºC, 1 h.
e. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).
f. Second extraction.

Kaphwiyo, 1987). Most of these prospects are associated with ring structures.

Sulfur Resources

Small gypsum occurrences are known from several seasonally flooded shallow valleys in the northern part of Malawi (van Straaten, 2002).

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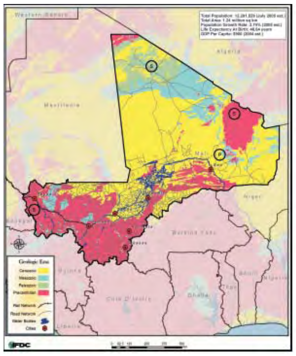
MALI



The Republic of Mali is bordered to the north by Mauritania and Algeria; the east by Niger; the south by Niger, Burkina Faso, Côte d'Ivoire, and Guinea; and the west by Senegal (Figure Mali 1). The total area of the Republic of Mali is 1.24 million km^2 and about 3.8% of the land is arable cropland. In mid-2005 the population was about 12.3 million inhabitants. The annual population growth rate is estimated to be 2.7% (World Factbook, 2006).

Mali is a totally landlocked country. The transportation network (Figure Mali 1) consists of 15,100 km of roads, of which 1,827 km is paved; 1,815 km of waterways (Niger and Senegal Rivers); and 729 km of railways. The ports of Dakar, Senegal, and Abidjan, Ivory Coast (Côte d'Ivoire) are the primary access routes from Bamako to the sea at 1,080 and 1,272 km, respectively. There are nine airports with paved runways. Except on the paved roads, transportation is difficult and even impossible during the rainy season.

Geologic maps (Figures Mali 1 and Mali 2) indicate five major divisions. Lower Precambrian formations are found in eastern Mali in the Adrar of Iforas and were subjected to the Eburnean and Panafrican orogenic cycles. Birimian formations are well developed in western and southern Mali and also exist in the Adrar of Iforas, in eastern Gourma, and in northern Mali where they constitute the border of the Taoudeni Basin. Upper Proterozoic formations in the Adrar of Iforas and Gourma region have been folded and metamorphosed. To the west these epicontinental sediments form the basement of the Taoudeni Basin and are overlain by Paleozoic sediments. The sediments of the Taoudeni Basin are of marine and continental origins. At the end of the Cretaceous period, a marine transgression began in a tectonic trough that created a strait between the Tethys Sea and Gulf of Guinea. Paleocene and Eocene sedimentation in this trough is characterized by alternating marine and continental influences and is ended by distinctly continental sedimentation. The "Continental Terminal" is the final sedimentary sequence deposited during the Tertiary.

Nitrogen Resources

Petroleum—Petroleum prospecting in Mali was funded by the World Bank. Several boreholes were drilled by Elf Aquitaine and ESSO, but with the exception of light gas, no petroleum was found.

Coal and Peat—Deposits of peat, lignite, and bituminous shales have been identified in Mali. Peat is found in the sediments of the internal delta of the Niger River between Segou and Tombouctou in a 36,000-km^2 area. A peat exploration program was funded by the European Development Fund (EDF) and led by the Bureau de Recherches Géologiques et Minières (BRGM) (Spencer and Bathily, 1987). The southern part of the internal delta is characterized by fluviatile sedimentation. Dunes are superimposed on the central and northern areas of the delta. Between the dunes, peat deposits are associated with paleosoils. The peat formation is a black organic mud with gray, brown, or reddish silty clays and coarse sandy intercalations; it rarely reaches 1 m in thickness. In Faguibine Lake, organic mud (5 m maximum) is associated with diatomites. The calorific value of the peat (studied by BRGM) is low (l,335 cal/g maximum). BRGM evaluated the agricultural potential of the peat and concluded it was suitable for a soil amendment.

Lignite occurrences have been recognized in Mesozoic-Tertiary sediments on the western and

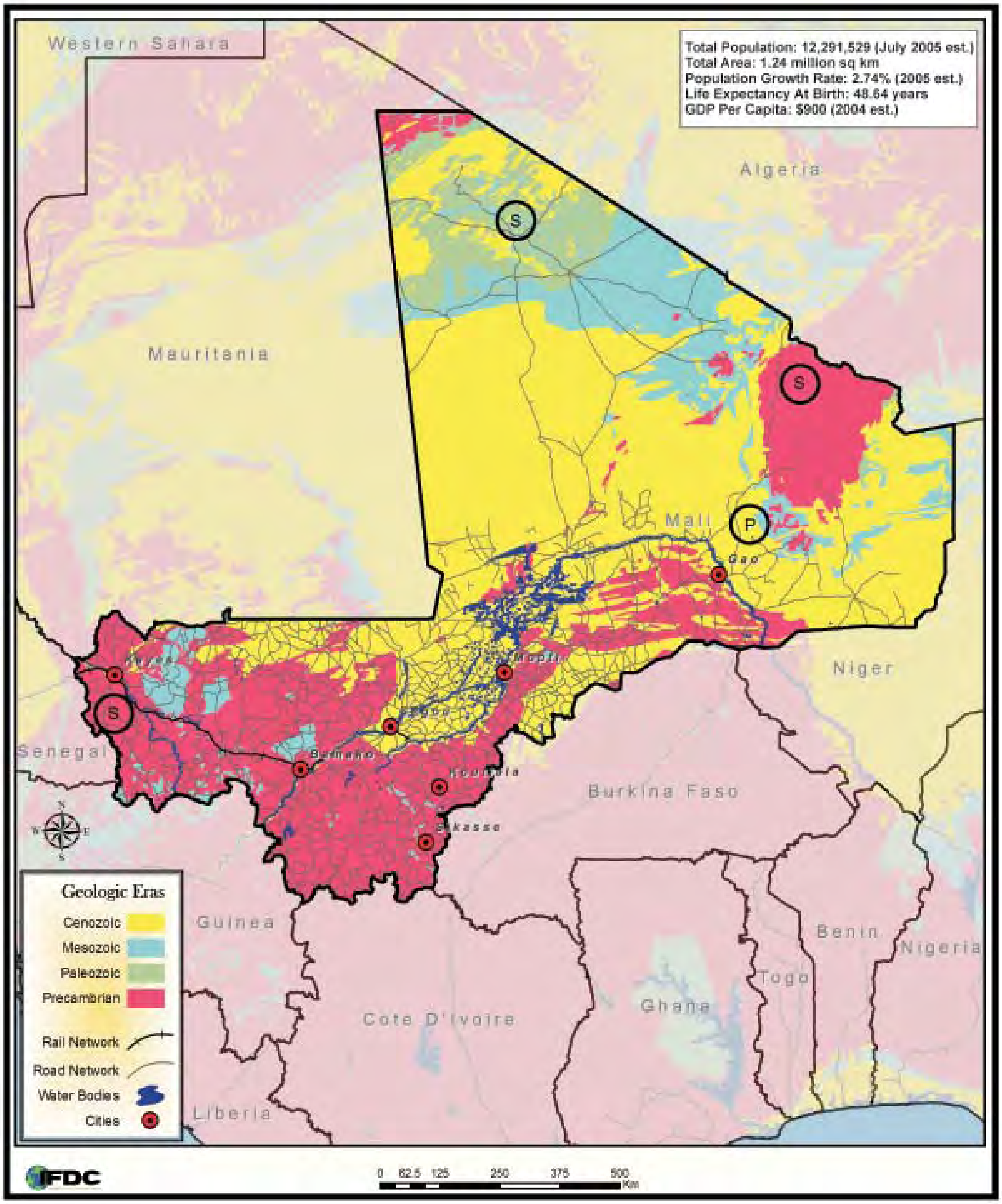


Figure Mali 1. Geology, Major Cities, and Transportation Network

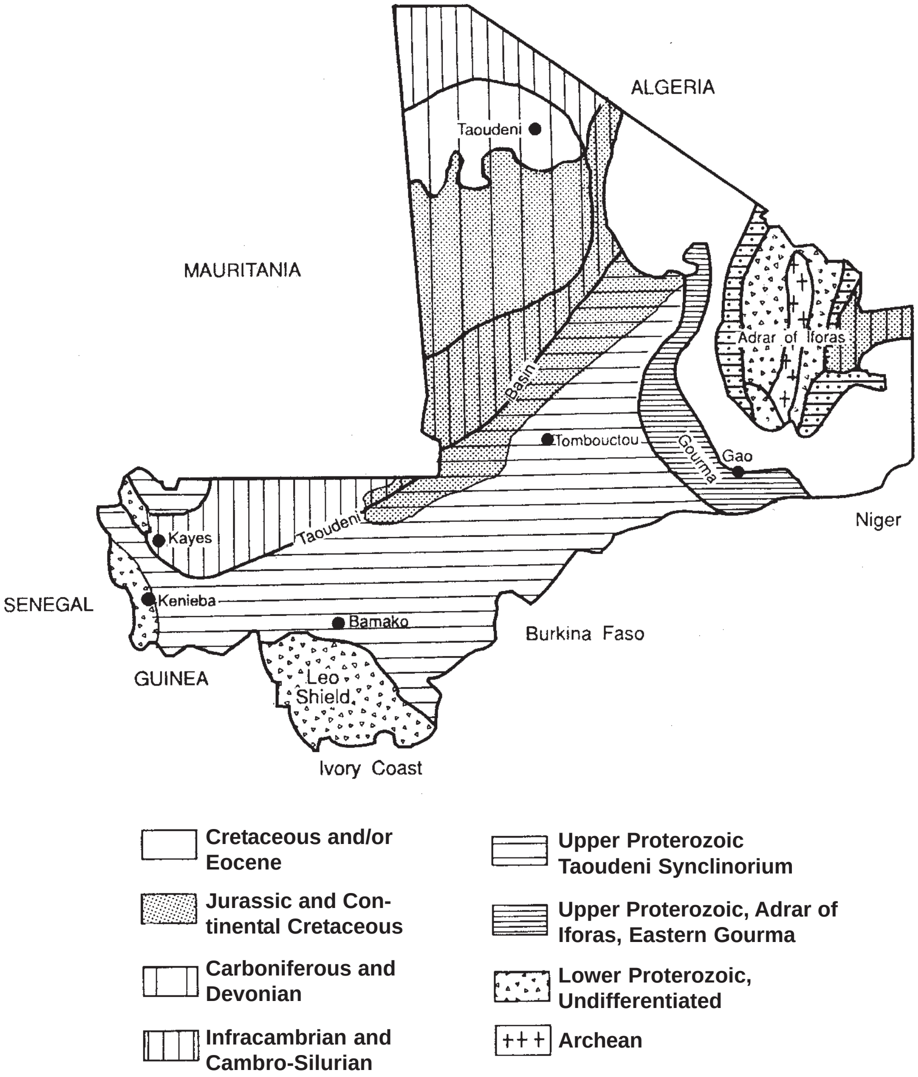


Figure Mali 2. Detailed Geology of Mali

southern boundaries of the Adrar of Iforas at Menaka, Hanouzigren, Koreï, and Bourem. Prospecting (using German aid) was terminated after initial results proved insignificant.

Bituminous shales were investigated by The SNC Group in 1983 in the Agamor area north of Bourem. This Oligocene deposit contains several beds with thicknesses varying between 0.9 and 2.9 m with 54 to 80 m of overburden. Resources are estimated to be 870 million tons, equivalent to 91 million barrels of petroleum (Van Kauwenbergh et al., 1991).

Phosphate Resources

Precambrian or Infracambrian sedimentary phosphates may be present in western Mali (Kayes region). The known phosphate deposits of Mali are concentrated in the eastern part of Mali, west and south of Adrar of Iforas and particularly in the Tilemsi Valley (Figure Mali 3).

The Tilemsi erosional valley exposes a half graben filled by Cretaceous and Tertiary marine and continental sediments. Four main deposits are known in the phosphate-bearing area of the Tilemsi Valley: Tamaguelelt, Chanamaguel, Tin Hina, and

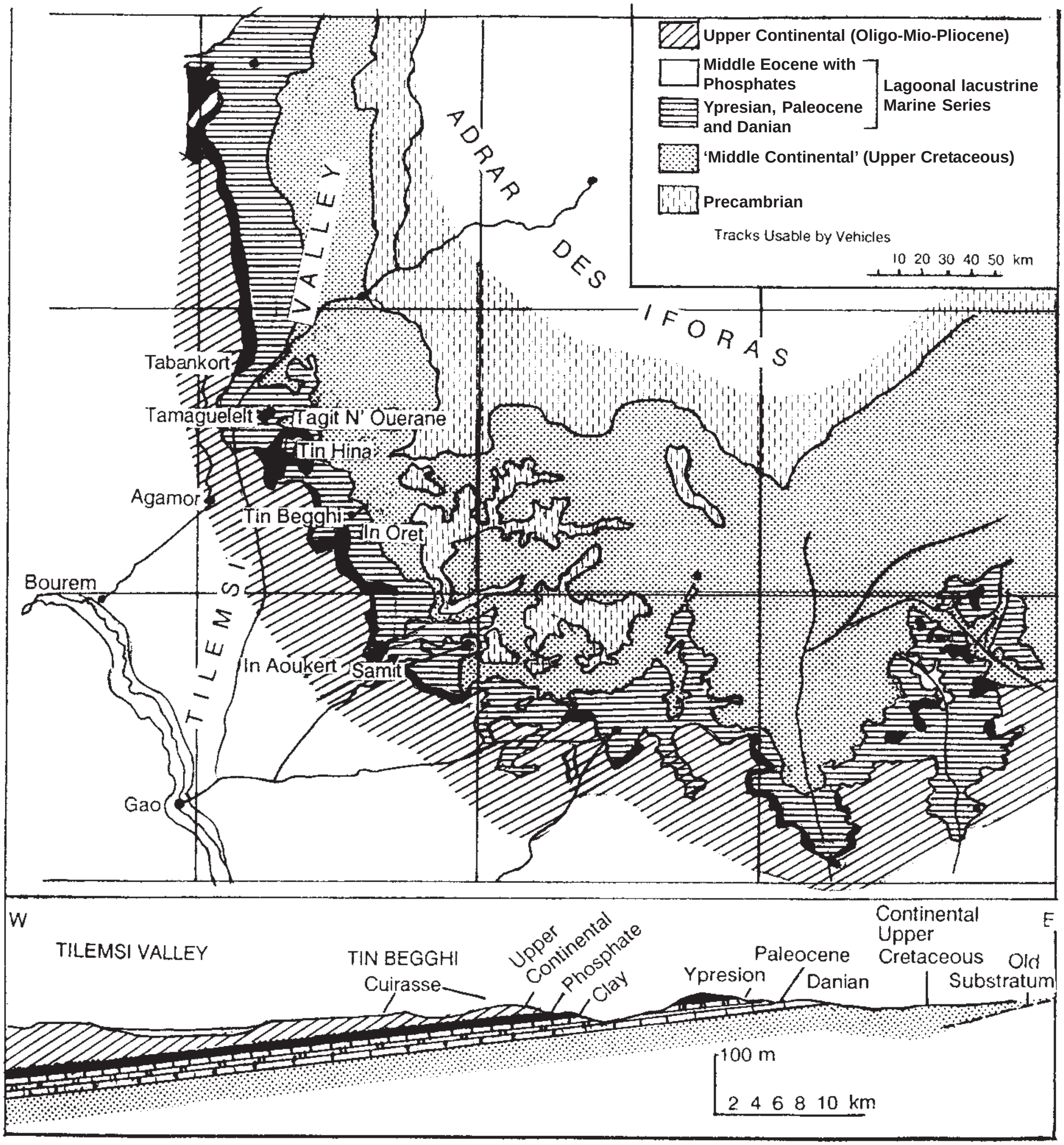


Figure Mali 3. Geology of the Tilemsi Valley Area

Anderakoyene (or Andarakoyene or Andrakoyene). These occurrences have been known since 1927-35. Through the work of Perebaskine (1932), the Tamaguelelt Deposit was discovered in 1935 by Chidaine and Urvoy, who estimated resources at 15 million tons of calcium phosphate with 17.0%-31.5% P_2O_5 (Alabouvette and Pascal, 1980a).

Detailed exploration work was carried out in the Tilemsi Valley in 1958 and 1959 by the Bureau Minier de la France d'Outre-Mer (BUMIFOM) (Allon, 1959a,b). As a result of reconnaissance exploration throughout the entire Tilemsi Valley (Table Mali 1), work was concentrated at the Tamaguelelt Plateau where 131 pits were dug.

From 1979 to 1980 BRGM performed a geological reconnaissance of the area. The BRGM study confirmed and expanded knowledge of the area, and a synthesis of the regional geology was developed (Alabouvette and Pascal, 1980a,b). The Japanese Power Nuclear Corporation (PNC) drilled the area in search of uranium associated with the phosphate deposits (Alabouvette and Pascal, 1980a; Hirono et al., 1987). Technoeconomic studies have been performed on Tilemsi phosphates by various organizations: Klöckner Industrie (1969); Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) (1977); IFDC (1976, 1989); and Autorité de Développement Intégré de la Region du Liptako Gourma (ALG) (1988).

Tamaguelelt Deposit—The Tamaguelelt Deposit is located approximately 105 km northeast of Bourem, which is about 70 km northwest of Gao. The phosphate formation outcrops on the flanks of a tabular plateau within Middle Eocene laminated clays. At Tamaguelelt the thickness of the phosphate bed varies from 0.5 to 2.2 m. To the west and under the "Continental Terminal," Eocene phosphate strata have been found at Tabankhort (15 km from Tamaguelelt) under 6 m of overburden and at Agamor (25 km to the southeast) under 114 m of overburden.

The surface area of the Tamaguelelt Plateau is 70 km^2. Below this surface it is estimated there is 11.4 million tons of phosphate rock in the following categories (Klöckner Industrie, 1969):

1. 1.84 million tons at the surface or <1 m of overburden.
2. 0.04 million tons with <2 m of overburden.
3. 9.52 million tons with >2 m of overburden.

Various facies can be distinguished in the phosphate beds. There is a fine-grained to clayey phosphate composed primarily of peloids. Coarse-grained beds contain peloids, nodules, coprolites, phosphatized shells, teeth, and bones up to 10 cm in diameter. The exogangue is generally quartz grains (20-50 μm), palygorskite, montmorillonite, and kaolinite clays and is typically stained by goethite/limonite.

According to the Klöckner report (1969), individual phosphate particles can assay 35%-37% P_2O_5. The phosphate content of the beds generally

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Table Mali 1. Summary of Exploration in the Tilemsi Valley by BUMIFOM During 1958/59

Category	Tamaguelelt	Chanamaguel	Tina Hina	Andrakoyene (Samit)
Pitting				
Number of pits	131	19	18	
Total depth (m)	262	28	30	
Trenches				
Number of trenches				10
Total length				122
Number of chemical analyses for P_2O_5	202	7	10	8
Number of complete chemical analyses	6	2	2	2

Source: Allon (1959b).

varies between 25% and 30% P_2O_5, with an average of 27% P_2O_5. In the northern area of the deposit, the P_2O_5 content is higher because coarse particles are more numerous. Klöckner (1969) analyses indicate 27.3% P_2O_5 for the top of the bed, 34.1% P_2O_5 for the middle, and 26.9% P_2O_5 for the base of the bed in the northern area. In the southern area the formation contains fewer coarse particles, and the P_2O_5 content is lower. Klöckner (1969) analyses indicate 25.7% P_2O_5 at the top of the beds, 23.9% P_2O_5 in the middle, and 21.5% P_2O_5 at the base of the beds in the southern area. The BRGM data (Table Mali 2) (Alabouvette and Pascal, 1980b) show the same trends as the Klöckner data. Across the entire deposit the upper beds are generally coarser, with a higher P_2O_5 content.

Several samples from Tamaguelelt were collected and chemically analyzed as a result of the joint fact-finding mission to the area by IFDC and Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in 1989 (Table Mali 3). Four samples from the Tilemsi Valley had been previously analyzed at IFDC and the Tennessee Valley Authority (TVA) National Fertilizer Development Center at Muscle Shoals, Alabama (Table Mali 4). The samples analyzed by IFDC prior to 1989 were used for agronomic trials and processing tests.

Sample WAMA1 (Table Mali 3) is a composite of two channel samples of the 1-m ore bed currently mined at Tamaguelelt. Only the upper ore bed, the coarser and higher grade material, is currently used. Comparison of the previous IFDC data (Table Mali 4) with the BRGM data and WAMA1 data indicates that the samples previously analyzed by IFDC probably came from the upper ore bed. The main impurities in the IFDC-analyzed ore zone samples (WAMA1, R231.15, R231.31, and R231.32) and the TVA-analyzed samples (MR585) are SiO_2 (3.5 wt %–11.5 wt %), Fe_2O_3 (5.3 wt %–6.3 wt %), and Al_2O_3 (1.3 wt %–2.5 wt %). Analysis of phosphatic nodules in the red shale above the main phosphate beds (36.1 wt %) (Table Mali 3) indicates the general upper limit to which these coarse particles can be beneficiated.

The apatite of the Tilemsi Valley Deposits is a carbonate-fluorapatite variety (francolite). Crystallographic analyses of the Tilemsi Valley francolites (Table Mali 5) indicate that the measured unit-cell a-values range from 9.350 Å (±0.001 Å) to 9.358 Å (±0.001 Å). At an average of 9.354 Å, based on established statistical models (McClellan, 1980), the composition of the francolite would be:

$$Ca_{9.85}Na_{0.11}Mg_{0.04}(PO_4)_{5.55}(CO_3)_{0.45}F_{2.18}$$

Table Mali 2. Chemical Analyses of Phosphate Beds of Tamaguelelt Deposit

Locality/Beds	Thickness	P_2O_5	CaO	SiO_2	Fe_2O_3	Al_2O_3	MnO_2
	(m)	(wt %)					
West Tamaguelelt							
Coarse coprolite bed	0.6	31.73	45.68	3.29	5.10	3.50	1.58
Fine yellow coprolite bed	0.45	29.35	42.94	3.95	7.50	2.98	1.00
Clays with coprolites	0.4	17.82	28.08	21.51	8.80	6.08	0.79
Coarse indurated bed	0.05	14.04	20.38	18.32	29.90	10.00	3.36
South Tamaguelelt							
Coarse coprolite bed	0.4	29.98	43.30	7.12	6.90	4.62	2.98
Fine coprolite bed	0.45	28.28	41.08	10.65	7.90	4.94	1.19
Fine coprolite bed	0.45	24.28	34.54	1.33	6.30	3.58	0.89
Phosphatic clays	0.90	20.43	29.28	25.77	6.80	4.70	0.89
East Tamaguelt							
Upper bed	0.6	30.22	46.04	6.35	5.50	2.66	1.38
Lower bed	0.85	28.70	42.76	10.65	7.10	2.76	0.89

Source: Alabouvette and Pascal (1980b).

Table Mali 3. Chemical Analyses of Tamaguelelt Phosphate Rock Samples[a]

	WAMA1 Ore Zone as Mined	WAMA1-1[b] (+1 mm)	WAMA1-2[b] (-1 mm + 74 µm)	WAMA1-3[b] (-74 µm)	WAMA2 Nodules in Red Shale
	(wt %)				
P_2O_5	29.8	35.4	34.3	2.9	36.1
CaO	40.0	48.4	46.3	3.8	48.9
F	2.7	–	–	–	3.3
SiO_2	7.3	0.7	3.3	36.3	0.7
Fe_2O_3	5.6	3.4	3.5	16.1	2.5
Al_2O_3	1.4	not determined	not determined	12.0	0.3
K_2O	0.6	–	–	–	0.2
Na_2O	0.2	–	–	–	0.2
MgO	0.6	–	–	–	0.2
Cl^- (ppm)	55	–	–	–	65
S	0.2	–	–	–	0.2
CO_2	2.3	–	–	–	2.6
Free H_2O[c]	2.3	–	–	–	1.2
LOI[d]	8.4	–	–	–	6.0
NAC P_2O_5[e]	4.4	4.6	4.4	1.0	4.1

a. Collected by joint IFDC-BGR Mission, 1989.

b. Size fractions of Sample WAMA1, hand washed and screened with tap water. Head sample wt = 199 g. WAMA1-1 wt = 122 g WAMA1-2 sample wt = 41 g. WAMA1-3 sample wt = 36 g.

c. Free H_2O = weight loss, 105ºC, 1 h.

d. Loss on ignition = weight loss, 1000ºC, 1 h.

e. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).

Table Mali 4. Chemical Analyses of Tilemsi Valley Phosphate Rock Samples

	R231.15[a]	R231.31[a]	R231.32[a]	MR585[b]
	(wt %)			
P_2O_5	26.2	28.6	28.8	31.3
CaO	39.5	41.40	41.4	45.0
F	3.1	3.1	3.0	2.9
SiO_2	11.5	9.4	9.9	3.5
Fe_2O_3	6.3	6.1	5.7	5.3
Al_2O_3	2.5	2.1	1.9	1.3
K_2O	0.16	0.10	0.10	0.11
Na_2O	0.29	0.37	0.28	0.1
MgO	0.55	0.52	0.57	0.31
Cl^- (ppm)	–	73	87	55
S	0.28	0.33	0.34	0.36
CO_2	2.3	2.4	2.6	2.3
Organic C	0.15	0.23	0.22	–
Free H_2O	0.56	2.5	2.5	–
LOI	4.5	7.9	7.9	–
NAC P_2O_5	4.2	4.2	4.2	3.7

a. IFDC analyses.

b. TVA analysis. Collected near Tabrichat.

A pure francolite concentrate would contain about 2.0 wt % CO_2, and the maximum P_2O_5 content would be 39.63 wt %.

The properties of the francolites of the Tilemsi Valley Deposits do not conform to the established chemical and crystallographic statistical models of francolites. Carbonate contents of impure samples are above that predicted by X-ray diffraction (XRD) for pure francolite; no free carbonates were detected in the samples by XRD or optically. The neutral ammonium citrate (NAC) solubilities of TVA- and IFDC-analyzed samples of 3.7%-4.6% P_2O_5 are far above the predicted solubilities of 2.7%-3.5% P_2O_5 (Table Mali 5).

Gremillion and Lehr (1976) noted that the francolite in a sample (MR585) from near Tabrichat (north of Tamaguelelt) was slightly fluorine deficient (Table Mali 4). This fluorine deficiency was attributed to the presence of organically derived apatite

Table Mali 5. Chemical and Crystallographic Analyses of Tilemsi Valley Phosphate Rock

Sample No.	Deposit	Total P_2O_5	R_2O_3[a]	Unit Cell a	Unit Cell c	Predicted[b] NAC P_2O_5	Measured NAC P_2O_5
		(%)		(±0.001 Å)		(%)	
R231.32	Tamaguelelt	28.8	7.6	9.355	6.883	3.0	4.2
R231.15	Tamaguelelt	26.2	8.8	9.357	6.886	2.8	4.2
R231.31	Tamaguelelt	28.6	8.2	9.356	6.885	2.9	4.2
WAMA1	Tamaguelelt	29.8	7.0	9.353	6.884	3.2	4.4
WAMA1 -1 (+1 mm)	Tamaguelelt	35.4	3.4	9.352	6.882	3.3	4.6
WAMA1 -2 (-1 mm +74 µm)	Tamaguelelt	34.3	3.5	9.358	6.885	2.7	4.4
MR585	Near Tamaguelelt	31.3	6.6	9.350	6.884	3.5	3.7

a. Fe_2O_3+Al_2O_3.

b. Based on statistical models of sedimentary francolites (McClellan, 1980).

particles (bones and teeth) which typically contain OH- substitutions. Hydroxyl-containing carbonate-apatites do not conform to crystal-chemical models of sedimentary francolites, which typically contain excess fluorine. Hydroxyl substitution in the carbonate-apatites of the Tilemsi Valley deposits is the only identified factor influencing deviations from predicted chemical and crystallographic properties.

Beneficiation tests that have been reported on Tamaguelelt phosphate ore are limited to simple screening tests. The results of a Klöckner (1969) test on a combined sample (Table Mali 6) indicate about a 40% increase in P_2O_5 content with 87% P_2O_5 recovery. McClellan and Saavedra (1981) reported about a 38% increase in P_2O_5 content with attrition scrubbing and screening (Table Mali 6). Washing and screening of a sample from the upper ore bed (WAMA1) for this study (Table Mali 5) resulted in P_2O_5 content increases of 19% and 15% for the plus 1-mm and the minus 1-mm plus 74-µm fractions, respectively. The total P_2O_5 recovery of the combined plus 1-mm and minus 1-mm plus 74-µm fractions was 98.6%.

Several studies have indicated that, because of the high aluminum and iron oxide contents (Fe_2O_3+Al_2O_3=R_2O_3), Tamaguelelt ores and concentrates are not the best quality for the manufacture of conventional fertilizers such as single superphosphate (SSP), phosphoric acid, diammonium phosphate (DAP), and triple superphosphate (TSP) (Alabouvette and Pascal, 1980a; Gremillion and Lehr, 1976; McClellan and Saavedra, 1981; Klöckner, 1969). A further complication is the high MnO_2 content of some of the ores that may behave similarly to Fe_2O_3 and Al_2O_3 in chemical fertilizer processing (Gremillion and Lehr, 1976).

Table Mali 6. Chemical Analyses of Concentrates Produced From Tamaguelet Phosphate Ores

	Klöckner, 1969[a]	McClellan and Saavedra, 1981[b]
	(wt %)	
Head grade, P_2O_5	22.31	27.6
Concentrate		
P_2O_5	31.4	38.0
CaO	42.5	53.7
R_2O_3 (Fe_2O_3+Al_2O_3)	4.17	3.9
SiO_2	9.05	2.4
R_2O_3/P_2O_5	0.13	0.10
Recovery (%)	87.0	-[c]

a. Size fraction 0.2-5 mm.

b. Attrition scrubbed and wet screened, no size fraction given.

c. Not reported.

The R_2O_3/P_2O_5 ratio of Tamaguelelt concentrates (R_2O_3/P_2O_4=0.10 to 0.13) is considered marginally acceptable for SSP manufacture, one of the simplest forms of fertilizer processing; experiments have not been carried out to determine the suitability of Tilemsi Valley concentrates for SSP production. Partially acidulated phosphate rock (PAPR) has been successfully produced from run-of-mine Tilemsi rock (IFDC, 1989). Both run-of-pile (ROP) and granular PAPR products have been manufactured at 15% and 30% acidulation levels.

Chanamaguel Deposit—In this area the phosphate beds outcrop on the flanks of a network of plateaus and hills separated by narrow valleys. The phosphate beds contain partings and thickness variations (1 m maximum) that are more complex than at Tamaguelelt. Tagit N'Ouarane Hill, situated southeast of Tamaguelelt and separated from it by a sandy fluvial depression, appears to be the most interesting area in the Chanamaguel Deposit. At Tagit N'Ouarane, the phosphate beds are thinner and the P_2O_5 content is generally lower than at Tamaguelelt (Table Mali 7). Allon (1959b) estimated resources minable by open pit in the area between 500,000 and 800,000 m^3 with an average of 28% P_2O_5.

Tin Hina Deposit—This deposit is situated on the northern flank of several plateaus oriented east-west. To the south, the phosphate beds are obscured by lateritic cover. The thickness of phosphate beds in the area varies between 0.2 and 1.6 m, with an average of 21.6% P_2O_5 (Table Mali 8). The BRGM estimated that 3-5 million tons of ore is available in the area (Alabouvette and Pascal, 1980a).

Table Mali 7. Chemical Analyses of Phosphate Beds of Chanamaguel Deposit

Locality/Beds	Thickness	P_2O_5	CaO	SiO_2	Fe_2O_3	Al_2O_3	MnO_2
	(m)	(wt %)					
Tagit N'Ouarane							
Sandy phosphate	(?)	10.65	27.86	15.96	5.20	3.42	0.44
Coprolite bed	0.1	20.99	31.98	25.24	6.60	6.54	1.28
Sandy coprolitic bed	0.8	18.76	29.30	11.98	16.20	6.10	12.22
Coprolite bed	0.1	17.45	36.90	23.29	2.20	2.30	0.63

Source: Alabouvette and Pascal (1980b).

Table Mali 8. Chemical Analyses of Phosphate Beds of Tin Hina Deposit

Locality/Beds	Thickness	P_2O_5	CaO	SiO_2	Fe_2O_3	Al_2O_3	MnO_2
	(m)	(wt %)					
Tin Rioua							
Coarse coprolite bed	0.3	29.59	43.82	5.3	4.10	3.14	1.49
Fine coprolite bed	0.2	31.12	44.20	4.89	5.00	2.74	1.39
Clayey sandy phosphate	0.5	18.50	27.40	21.74	7.60	8.02	0.65
Clays with lenticular phosphate	0.6	27.11	39.50	11.39	7.50	5.26	0.89
Tin Rioua							
Sample of entire phosphate level	1.6	21.64	30.80	15.14	9.00	7.46	1.28
In Oref-East							
Fine coprolite bed	0.4	29.52	44.20	1.51	7.60	1.18	10.38
In Oref-South							
Coprolite cuirassé	0.6	21.19	31.36	20.71	9.00	7.76	3.07
In Oref-Center							
Brown coprolite bed	<0.5	17.61	27.22	22.32	9.10	7.62	7.92
In Oref-North							
Dark coprolite bed	<0.5	15.42	24.20	22.64	13.40	6.78	9.89
Akoubayen							
Brown coprolite bed	0.2	25.92	37.34	9.46	7.20	1.76	7.52

Source: Alabouvette and Pascal (1980b).

Anderakoyene (Samit) Deposit—This area is 76 km to the southwest of Tin Hina. There are four or five phosphate beds separated by clays and sands. The thickness of the entire Eocene formation varies between 2 and 11 m. The P_2O_5 content of individual beds ranges from below 10% to over 25% P_2O_5 (Table Mali 9). The SiO_2 and Fe_2O_3 contents of 8%-46% and 10%-17%, respectively, are much higher than in other deposits in the Tilemsi Valley. The MnO_2 content is typically near 2% and may be close to 12% in the surficial weathered zone.

Total Phosphate Resources of the Tilemsi Valley—The phosphate resource estimates of the Tilemsi Valley (based on Klöckner, 1969, and Alabouvette and Pascal, 1980a) are summarized as follows:

	Million Tons
Tamaguelelt	11.4
Chanamaguel	1.0-1.6
Tin Hina	3-5
All others	2-4

The total phosphate resources of the Tilemsi Valley are therefore estimated to be 17.4-22.0 million tons. The only firm estimates are from the Tamaguelelt Plateau where the phosphate is exposed around the entire periphery of the hill and extensive exploratory pitting and analyses have been performed.

Deposits South of the Adrar of Iforas—During the 1980 field season, BRGM (Alabouvette and Pascal, 1980b) concentrated reconnaissance work in the areas where Eocene age rocks are exposed south of the Adrar of Iforas. The phosphate beds discovered in this area (Table Mali 10) were thinner (up to 0.3 m thick), lower in grade, and contained substantially higher impurity contents (Fe_2O_3, Al_2O_3, MnO_2) than the deposits in the Tilemsi Valley. On the basis of the results of this expedition, the BRGM geologists concluded that economically interesting surficial phosphate deposits did not exist in the area.

Development and Agronomic Studies of Tilemsi Valley Phosphates—The high cost of imported fertilizers, significant amount of resources, analyzed solubility, and results of agronomic testing of the Tilemsi Valley phosphates encouraged the Malian government to emphasize its development for local use. GTZ provided managerial and technical assistance for this project. From 1976 to 1980 the Tamaguelelt phosphate rock was exploited by hand methods, transferred by trucks to Bourem, and transported by the Niger River to Mopti and Markala where it was ground. The production was 950 tons from 1976 to 1978 and 1,400 tons from 1978 to 1980.

Beginning in 1980, the Tamaguelelt Deposit was mined by mechanized methods and managed by the Société Nationale de Recherche et d'Exploitation

Table Mali 9. Chemical Analyses of Phosphate Beds of Anderakoyene (Samit) Deposit

Locality/Beds	Thickness	P_2O_5	CaO	SiO_2	Fe_2O_3	Al_2O_3	MnO_2
	(m)	(wt %)					
In Abalen							
Phosphate cuirassé	1	15.04	22.78	18.74	16.60	3.74	11.71
Agueulgueul-S.E.							
Coarse coprolite bed	0.4	10.94	15.72	35.91	15.00	3.58	2.98
Fine coprolite bed	0.6	14.46	20.34	24.40	11.80	4.15	1.58
Clayey sandy phosphate	0.9	8.63	12.24	46.11	10.40	2.08	2.18
Agueulgueul-N.W.							
Ferruginous coprolite bed	0.25	19.95	27.50	7.67	17.00	4.60	2.98
Clayey coprolite bed	0.25	13.58	19.62	26.21	15.60	7.98	2.58
Clayey phosphate	0.40	13.33	18.42	38.05	10.10	4.66	1.28
Coarse coprolite bed	0.45	25.94	36.60	15.90	9.90	3.54	2.18

Source: Alabouvette and Pascal (1980b).

Table Mali 10. Chemical Analyses of Phosphate Beds From South of Adrar of Iforas

Locality/Beds	Thickness	P_2O_5	CaO	SiO_2	Fe_2O_3	Al_2O_3	MnO_2
	(m)	(wt %)					
Aborak							
Dispersed coprolites	–	32.45	41.47	8.19	8.40	1.08	0.35
Arejerech-N							
Sandy ferruginous bed with coprolites	–	5.64	10.66	54.96	12.40	3.54	2.41
Arejerech-S							
Phosphate bed	0.2	24.78	35.25	1.88	20.00	1.88	3.86
Arejerech-W							
Phosphate bed	0.2	7.50	11.84	29.46	18.40	4.91	5.79
Arejerech-W							
Coprolites	–	32.30	49.35	4.65	2.80	0.31	1.93
In Amassas							
Phosphate bed	0.20	7.41	13.54	29.65	19.6	8.33	1.45
In Amassas-Center	0.20-0.25	13.00	16.07	18.7	28.80	6.53	2.90
Aouchi-N							
Coprolites and bones	–	29.79	43.70	8.20	5.20	1.09	0.29
Ticket							
Phosphate bed	0.2-0.3	13.26	22.56	36.95	12.00	3.02	0.32
In Aguerguer-N							
Phosphate bed	0.15	20.97	31.58	18.40	10.00	3.42	0.42
Tegassat-N							
Ferruginous bed with coprolites	0.3	18.00	24.25	5.63	34.00	2.92	2.41

Source: Alabouvette and Pascal (1980b).

Minière (SONAREM). A modern grinding and bagging unit with a capacity of 7.5 tph at 100% minus 90 µm was installed at Bourem. Figures Mali 4, 5, 6, 7, 8, and 9 illustrate the mine and production facilities. Mining is carried out on an intermittent basis because the Tamaguelelt-Bourem road is not passable during the rainy season (July-September). Approximately 80% of the production was transported to Mopti, Segou, and Koulikoro by the Niger River, which is navigable from July to November. About 20% of the product was transported by road. During 1985/86, production was 7,000 tons; production for 1987/88 was 8,000 tons; and production for 1989/90 was expected to reach 10,000 tons. The Compagnie Malienne pour le Développement des Textiles (CMDT), a private company, marketed and sold the product. The last recorded production was more than 18,650 tons in 1990 (Ballo, 1995). Social unrest occurred in the area in the early 1990s.

A prefeasibility study conducted by Luxconsult S.A. (1985) and funded by the EDF proposed building a granulation unit at Koulikoro based on Tamaguelelt phosphate rock ground at Bourem. Compound fertilizers (NP and NPK) would be produced using 10,000-13,500 tons of Tamaguelelt rock per year.

A technoeconomic study (ALG, 1989) investigated the use of Tamaguelelt rock for the production of compound fertilizer using a nitrogen gas attack process. Under the production and financial assumptions of the ALG study, an internal rate of return of 24.6% (without taxes) was calculated at a production level of 27,000 tpy. On the basis of total P_2O_5 content, the product would analyze 4% N and 14.8% P_2O_5.

Several studies in Mali (Pieri, 1973; Poulain, 1976; Thibout et al., 1980) indicated that Tilemsi Valley phosphate rocks could be used directly on crops. The most exhaustive agroeconomic analysis of the use of Tilemsi Valley rock for direct application and as a PAPR product (15% and 30% acidulation)

Figure Mali 4. Mine at the Tamaguelelt Plateau

Figure Mali 5. Phosphate Ore Bed, Tamaguelelt Deposit

Figure Mali 6. Feed Station for the Grinding Mill at Bourem

Figure Mali 7. Grinding Mill, Bourem

Figure Mali 8. Bagging Station Associated With the Grinding Mill, Bourem

Figure Mali 9. Warehouse for Tilemsi Valley Phosphate Rock, Bourem

was completed in 1989 by IFDC based on data obtained during the 1982-86 cropping seasons (IFDC, 1989). Ten Malian agricultural experiment stations were selected to cover the entire range of agroclimatic conditions in Mali. The agronomic results of this program are summarized below:

1. When applied along with the other needed nutrients, i.e., nitrogen, potassium, and sulfur, Tilemsi phosphate rock (TPR) was, on average, about 78% as effective as TSP, and Tilemsi PAPR had, in some cases, the same efficiency as TSP.
2. With crops in humid and subhumid areas and in soils with a pH of 5.0 or higher, the practice of broadcasting and incorporating TPR before planting gave crop yield increases 20%-25% higher than those obtained with banding.
3. On very acid soils (pH less than 5.0), banding of phosphate sources prior to planting resulted in higher yields for millet, sorghum, and groundnuts.
4. A 20% differential increase in yield was observed with rice when TPR was broadcast and incorporated rather than banded.
5. During the first year only, basal applications of TPR supplemented with later annual applications of TPR resulted in lower crop yields than those obtained with annual applications of TSP. For subsequent years the crop response value for TPR was similar to that for TSP in humid and subhumid areas.
6. PAPR results showed that granule size influenced the efficiency of PAPR products. It was found that the granular PAPR products gave crop yields approximately 15% lower than those obtained with ROP products. The relative agronomic effect of the PAPRs increased with increases in the degree of acidulation.
7. Results of the on-farm trials conducted in a humid area confirmed that TPR, applied in addition to urea and potassium sulfate, performed as well as the complex fertilizer now used by Malian farmers.

The economic analyses of results of this long-term study support the following conclusions:

1. Use of TPR can result in net returns and value to cost ratios similar to those for the use of TSP.
2. In the more arid climates, annual applications of TPR are less useful for maximizing net returns than are annual applications of water-soluble TSP. Maximum net returns are:
   Humid zone TPR = TSP
   Subhumid zone TPR ≤ TSP
   Semiarid zone TPR < TSP
   This effect should disappear with long-term (greater than 4 years) continuous TPR use; see Items 3 and 7, below.
3. In the semiarid and more humid zones, one-time basally applied TPR every 4 years, supplemented with either TPR or TSP applied annually, results in net returns that equal or exceed maximum net returns from annual applications of TSP.
4. Greater (80%-100% more) P_2O_5 is required from TPR than from TSP to obtain similar yields and net returns to P fertilization when the two products are applied in the same manner.
5. No consistent economic advantage was indicated for PAPR when compared with TPR or TSP. Only an identified need for sulfur fertilization could positively change the economics to justify further processing of TPR.
6. All of the P fertilization practices tested were marginal at Koporo Keniepe (sandy soils in the arid zone).
7. Net returns from TPR are less than those from water-soluble sources during the year of application for irrigated rice at Kogoni. In succeeding years, net returns from the three sources are similar when annually or basally applied. Supplementing TPR with about 30 kg P_2O_5 as TSP during the year of initial application of TPR should overcome that deficiency.

Infracambrian Phosphate of Western Mali—In Senegal on the border of the Taoudeni Basin, siliceous phosphorites similar to those discovered in the Volta Basin are found above tillites. In western Mali in the Kayes region, there are similar rock associations. The basal tillite is present, overlain by limestones with barite and cherts. The presence of phosphate rock has not been reported in this area.

Sulfur Resources

Potential resources of sulfur in Mali occur as pyrite, barite, and gypsum. There are no known indications of native sulfur. The presence of pyrite is reported in boreholes drilled in the sedimentary Senonian-Maastrichtian formations of the “Gao Trough” (400 km long, 50-100 km wide, and 1,500 m deep). Pyrite crystals (up to 3 cm) have also been reported in the metamorphic shales of the Doro area. Barite occurs in western Mali in the Kayes region at Dinguira. Barite occurrences are also known in the Koulombo, Nahali, Serinati, Melgue, Bouyagui, and Aïte regions in dolomitic limestone formations. In eastern Mali, barite occurrences are reported near Tessalit.

Only the Dinguira Barite Deposit, however, is suitable for exploitation, due to its location. The original reserve estimate indicated that 52,000 tons of barite could be extracted from 500,000 m^3 of rock. A Direction Nationale de la Géologie et des Mines (DNGM) project increased reserves from 52,000 to 150,000 tons. The purpose of the project was to determine if ore from the deposit could be used to produce sulfuric acid for the Communauté Economique des Etats de l’Afrique de l’Ouest (CEDEAO) countries.

Gypsum deposits are mostly located in the northern part of Mali. One deposit, located 80 km north of Tessalit, was exploited by a Belgian non-profit organization together with the Centre d’Etude pour la Promotion Industrielle (CEPI) for plaster production (l,200 tpy).

The Quaternary salt deposits of the Taoudeni area in the central depression zones of the Taoudeni Basin have been exploited since 1585 by Touaregs. The cumulative production of salt by manpower was about 6 million tons in 1965 (Lang, 1965). Today production is about 20,000 tpy. The surface area of the deposit is about 160 km^2. This evaporite deposit displays an alternating sequence of clays, salt, and gypsum.

The main minerals present in the deposit are gypsum, halite (NaCl), mirabilite [$Na_2SO_4 \cdot 10H_2O$], and glauberite [$Na_2Ca(SO_4)_2$]. Accessory minerals include sylvite (KCl), sylvinite [(K,Na)Cl], and thenardite (Na_2SO_4). The resources of the area are estimated as:

	Tons
Halite	53.1
Gypsum	34.9
Mirabilite	198.7
Glauberite	336.7

Two gypsum occurrences have been reported by SONAREM in northern Mali in the Bamafle and Koulikoro areas.

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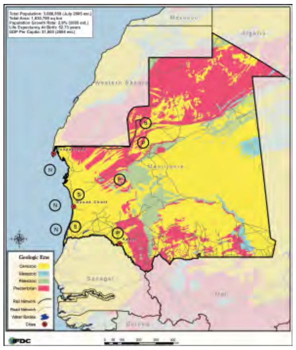
MAURITANIA



Mauritania is bounded to the north by Western Sahara and Algeria, to the east by Mali, to the south by Senegal, and to the west by the Atlantic Ocean. In mid-2005 the population of the Islamic Republic of Mauritania was estimated as 3.1 million inhabitants and with a total area of 1,030,700 km^2. The annual population growth rate is estimated to be 2.9% (World Factbook, 2006). Of the total land area, 0.48% is arable cropland, and most of this cropland is located along the Senegal River Valley.

The transportation network comprises 866 km of paved roads and 6,794 km of unpaved roads (Figure Mauritania 1). Many of the secondary roads are impassable during bad weather. There are vast areas within the Sahara Desert where there are no roads. The only rail line in the country is used to transport iron ore from a mine near Zouérat to the port of Nouadhibou.

Four major geologic subdivisions (Figure Mauritania 1) can be distinguished in Mauritania:

1. A Precambrian basement composed of the Reguibat Shield and its southwestern extensions.
2. The Taoudeni Basin filled by Infracambrian to Quaternary sediments.
3. The Panafrican Mauritanides Chain (approximately 600 million years old).
4. The Atlantic Coastal Basin with Mesozoic to Quaternary sediments.

Nitrogen Resources

Petroleum—Several oil and gas exploration studies have been conducted in the Coastal Sedimentary Basin (near Nouadhibou and Nouakchott) and in the Taoudeni Basin. Traces of oil and gas were found in the Taoudeni Basin.

In 1985, seismic surveys conducted by Occidental Oil Company, Chinese Petroleum Corporation of Taiwan, and Yuhong Limited of South Korea indicated a high probability of petroleum- and gas-bearing structures in Mauritanian waters. Amoco began work offshore in 1987 (Bermúdez-Lugo, 2003). Since that time several companies have conducted exploration off Mauritania including Woodside Petroleum (Australia), Hardman Resources (Australia), Agip, Fusion Oil (Australia), Dana Petroleum, Premier Oil, and Roc Oil (Mauritania).

The Chinguetti Project will be the first oil-producing field offshore Mauritania. The Chinguetti Field was discovered in 2001. The project is based on a floating production/storage/offloading vessel, six production wells, one injection well, and four water-injection wells. The field is located 90 km southwest of Nouakchott in 800 m of water. Woodside Petroleum (47.384% equity) is the operator. Phase I is scheduled to produce oil in 2006 at an initial production rate of 75,000 barrels per day (bpd). Gas flaring will be avoided. The gas will be reinjected in the Banda Gas Field 25 km shoreward of the Chinguetti Field. Proven and probable resources are 123 million barrels (Hardman Resources Ltd., 2006).

Several other fields/prospects are being investigated or developed. The Tiof-6 Well flow tested at 9,150 bpd (Hardman Resources, Ltd., 2006). The Tiof Field is located about 25 km north of Chinguetti. The Tevet Field is being evaluated and is within tie-back distance to Chinguetti. The Faucon prospect, with predrilled estimated resources of 100-250 million barrels of oil, lies 200 km to the south of Nouakchott near the Senegal border.

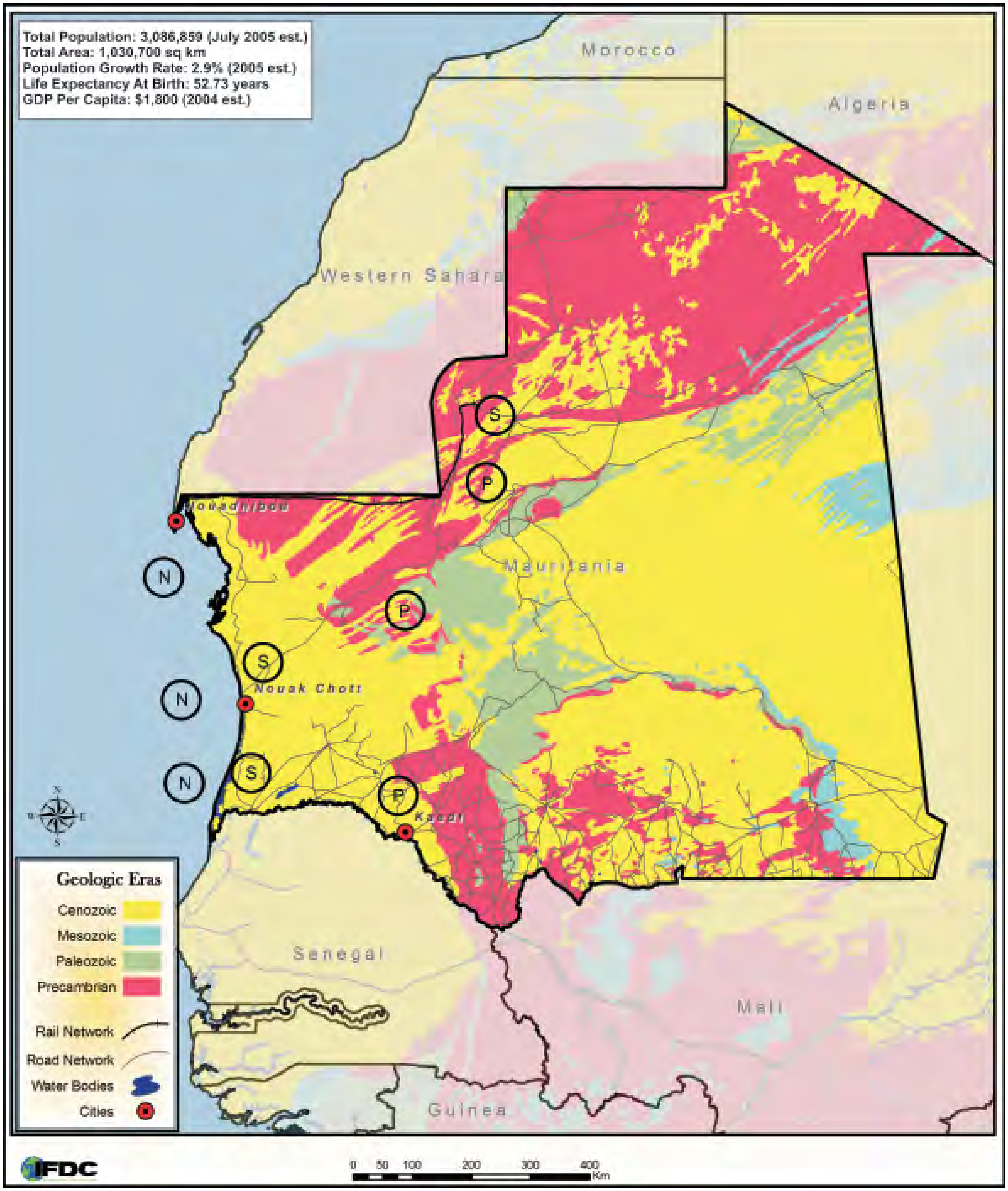


Figure Mauritania 1. Geology, Major Cities, and Transportation Network

The Banda discovery well drilled in 2002 encountered a 110-m-thick gross gas column and a 25-m-thick oil column. The Banda Field is estimated to contain 2.4 trillion ft^3 of gas (Hardman Resources, Ltd., 2006). The Pelican discovery well intersected a gross gas column of approximately 370 m in upper Cretaceous sands. The Pelican discovery is located about 150 km north of the oil discoveries off Nouakchott. The gas resources at the Pelican prospect have not been fully assessed, but may be 1 trillion ft^3 (Hardman Resources Ltd., 2006). Estimated reserves of gas for a liquefied natural gas (LNG) export scheme were considered to be on the order of 4 trillion ft^3.

Peat—Peat exploration was first conducted in southwest Mauritania between December 1984 and April 1985 after the discovery of peat in Senegal at Niayes and along the Senegal River (N'Diaye, 1985). During this campaign the Office Mauritanien de la Recherche Géologique (OMRG) discovered the peat deposits of Tigent, Keur-Macene, and the Tekane area in a network of depressions and ancient channels in a 5,000-km^2 area situated between aeolian dunes.

The thickness of the peat deposits varies from 0.25 to 3.3 m, with an average of 0.8 m. Overburden thicknesses are between 0 and 1.7 m. The peat may be wet and/or contain salt; it is also clayey and sometimes sandy. Chemical analysis of a peat sample from near Bosna, Mauritania, indicates the high-impurity contents:

Chemical Analyses of Peat From Bosna, Mauritania

	Wt %
Organic C	8.9
SiO_2	46.0
Al_2O_3	3.1
SO_4	3.1
Cl^-	5.0
Na_2O	1.0
CO_2	3.7

The Mauritanian government, with a preliminary estimate of 500 million m^3 of peat resources, planned to put emphasis on exploration of the peat for three different applications:

1. An energy resource (direct combustion, gasification).
2. Domestic construction (peat brickmaking).
3. Agricultural uses (soil amendment, mixtures with P_2O_5 sources, etc.).

Phosphate Resources

The earliest studies of phosphate deposits in Mauritania date from 1911 (Chudeau, 1911). Deposits have been reported on the western border of the Taoudeni Basin in the Adrar area. Silurian iron-phosphates in the area were probably derived from apatitic phosphates by continental alteration (Trompette, 1973). The P_2O_5 content in apatitic phosphate pebbles of the Oued Chig Formation varies between 16.90% and 21.80%. In the Idjibitene region, Precambrian phosphate-bearing formations (limestone, chert, and tillite) outcrop, but the structural complexity of the geology in the region makes exploration and interpretation difficult.

Outcrops of phosphatic Eocene strata in the Senegal River Valley led to the discovery of the deposit at Bofal-Loubboïra. The phosphate deposit at Civé can be correlated with the Matam deposits on the south side of the river in Senegal.

Bofal-Loubboïra Deposit—The Bofal-Loubboïra Deposit is located in the Aleg-Boghué-Kaedi sector about 300 km southeast of Nouakchott on both sides of Oued Guellouar Valley. This deposit was studied by a phosphate research consortium between 1974 and 1983. The consortium was formed by the Mauritanian government represented by Société Industrielle et Minière (SNIM), Bureau de Recherches Géologiques et Minières (BRGM), Société Sénégalaise des Phosphates de Thiès (SSPT), and GEOMIN (Romania).

After an area-wide exploration program, fieldwork was concentrated near Bofal and Loubboïra during 1980-82. The phosphatic formation is underlain (Figure Mauritania 2) by the Gorgol

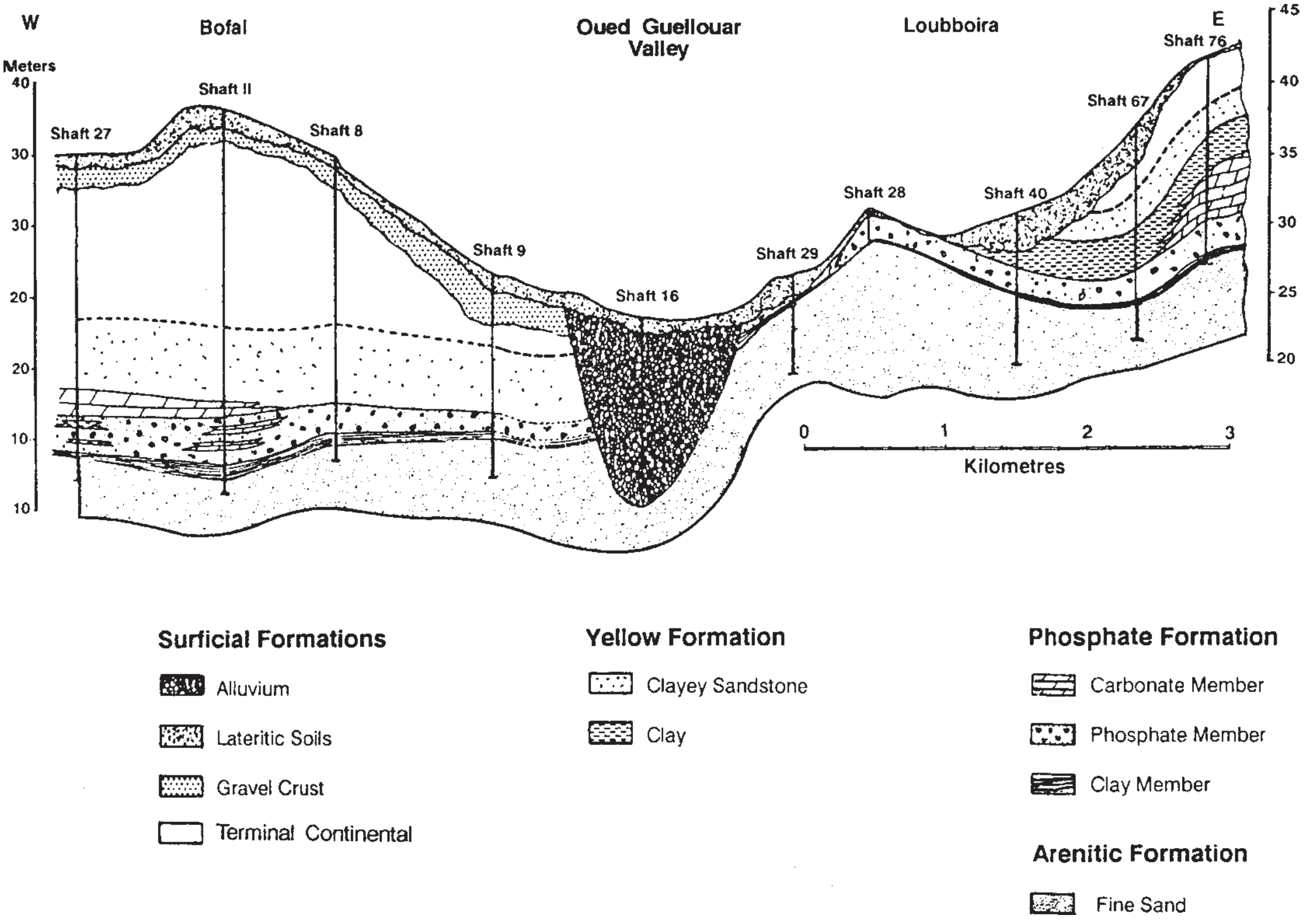


Figure Mauritania 2. Cross Section of the Bofal and Loubboïra Deposits (Adapted From Boujo and Ould Jiddou, 1983)

Sandstone of Middle Eocene age. The phosphatic formation has been interpreted as a condensed neritic facies in the western part of the deposit with a succession of phosphates, carbonates, and magnesium clay members. In the eastern part of the deposit, the phosphatic formation has been interpreted as a littoral facies with ferruginous sands or sandstones. In the central part of the phosphate-bearing area, the sequence is represented by a clayey phosphate succession. The phosphate member of the deposit varies in thickness from 0.40 m in the east to 5.10 m in the west.

The phosphate ore ranges from a phosphorudite (phosphate grains >1 mm) to a phospharenite (grains <1 mm to 0.062 mm). The coarse phosphate particles are mainly coprolites, lithoclasts, and fish teeth and bone fragments. The fine phosphate grains are mainly peloids. The endogangue ranges from clays and silica to carbonates in unweathered portions of the deposit.

The phosphatic formation is overlain by detrital sediments. The Yellow Formation is composed of a lower member, with fissile-laminated clays, that is very slightly phosphatic (4 m thick maximum) and an upper member with alternating yellow clays and yellow fine sandstones. The maximum thickness of the Yellow Formation is 5 m. In the southern area of the deposit, the Yellow Formation laterally progresses into “Terminal Continental” sediments.

Chemical analyses of typical Bofal and Loubboïra ores by the BRGM (Table Mauritania 1) indicate that the main impurities are silicates. Three samples from Bofal, collected during an IFDC-

Table Mauritania 1. Chemical Analyses of Bofal and Loubboïra Phosphate Rock Samples

Elements	Bofal (Pit 3)	Loubboïra (Pits 67 and 78)
	(wt %)	
P_2O_5	20.15	19.40
SiO_2	40.23	36.30
Na_2O	0.18	0.14
K_2O	0.11	0.13
MgO	0.81	0.51
CaO	28.90	28.10
Fe_2O_3	1.70	2.66
MnO	0.13	
Al_2O_3	2.36	5.20
TiO_2	0.10	0.25
CO_2	1.56	1.70
SO_3	0.27	0.08
H_2O^-	1.49	1.38
H_2O^+	0.49	2.85
Cl^-	0.06	0.01
C organic	0.27	0.014
F	1.60	2.14
Weight loss at 1000°C	5.49	5.65
–O=F	0.674	0.90
Total	99.754	99.954

Source: SNIM/BRGM (1985).

Bundersanstalt für Geowissenschaften und Rohstoffe (BGR) mission, were chemically and crystallographically analyzed by IFDC (Table Mauritania 2). Two of the samples have a high P_2O_5 content (Pit 28 = 34.4 wt % and Pit 69 = 26.2 wt % P_2O_5) with silicate impurities. The third sample that was analyzed by IFDC (Pit 30) had a very low P_2O_5 content (0.3 wt %); it appears to be from a bed containing dolomite and calcite.

The unit cell a-values of the carbonate-fluorapatite (francolite) obtained on samples from Pit 28 and Pit 69 are 9.352 ± 0.001 Å and 9.347 ± 0.001 Å, respectively. Based on previously established statistical models (McClellan, 1980), the francolite from Pit 28 has a theoretical CO_2 content of 2.24 wt %; the sample from Pit 69 has a theoretical CO_2 of 2.84 wt %.

Table Mauritania 2. Chemical Analyses of Bofal Phosphate Rock Samples[a]

	Pit 28[b]	Pit 69[c]	Pit 30
	(wt %)		
P_2O_5	34.4	26.2	0.3
CaO	47.6	38.4	43.0
F	3.6	2.9	0.1
SiO_2	4.6	21.6	5.7
Fe_2O_3	3.3	2.6	0.7
Al_2O_3	3.4	2.6	1.1
K_2O	0.1	0.1	0.1
Na_2O	0.1	0.2	0.1
MgO	0.1	0.7	6.6
Cl^- (ppm)	100	70	130
S	0.1	0.2	0.1
CO_2	2.1	2.0	40.8
Free H_2O[d]	0.4	1.8	0.8
LOI[e]	3.9	6.1	42.1
NAC P_2O_5[f]	2.3	3.4	ND

a. Collected during the joint IFDC-BGR fact-finding mission of 1989.
b. Unit cell a-value of apatite = 9.352 ± 0.001 Å.
c. Unit cell a-value of apatite = 9.347 ± 0.001 Å.
d. Free H_2O = weight loss, 105°C.
e. Loss on ignition = weight loss, 1000°C.
f. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).

These unit cell a-values and CO_2 contents for the francolites of the Bofal samples are very similar to values obtained by Van Kauwenbergh and McClellan (1990) for Togo phosphate rock concentrates (average of 12 samples = 9.345 ± 0.001 Å). The low level of carbonate substitution in Togo francolites leads to low neutral ammonium citrate (NAC) solubility. An average NAC solubility of 10 Togo concentrates is 2.9% P_2O_5. The NAC solubility of the Bofal phosphate rocks from Pit 28 and Pit 69 is 2.3% P_2O_5 and 3.4% P_2O_5, respectively (Table Mauritania 2). Some type of processing is needed to increase the amount of available P_2O_5 (water soluble + NAC soluble).

Crystallographic analyses of Bofal-Loubboïra apatites by Lô (1987) produced unit-cell a-values similar to the IFDC analyses (Table Mauritania 3). Interestingly, the samples from Bofal-Southwest

Table Mauritania 3. Unit Cell a-Values of Carbonate Apatites From Bofal-Loubboïra Deposit

Area	Sample Number	Unit Cell a-Value (Å ± 0.005)
Loubboïra	243-3	9.350
	243-4	9.346
	243-5	9.346
Bofal	202-8	9.354
	202-9	9.346
	202-11	9.350
Bofal-Southwest	187-3	9.345
	187-6	9.346
	187-8	9.340

Source: Lô (1987).

have lower unit cell a-values than samples from Loubboïra or Bofal. This may indicate higher levels of NAC solubility and greater potential for use as a direct-application P_2O_5 source. The composition of francolites can vary in individual deposits as the result of depositional factors and/or weathering effects (Van Kauwenbergh and McClellan, 1990). Below the main ore zone in Togo and in association with carbonates, francolites can have unit cell a-values as low as 9.324 to 9.333 Å. Such francolites (similar to North Carolina and Tunisia francolites) have a high potential for use in direct application. There may be zones in the Bofal-Loubboïra Deposit that contain highly substituted francolites that may be suitable for direct application.

The resources of the Bofal-Loubboïra Deposit were calculated on a square grid of 500 m to 1 km using exploration pits. The initial estimate (Boujo and Ould Jiddou, 1983) indicates a minimum of about 70 million tons of probable reserves at Bofal and 24 million tons at Loubboïra calculated on a dry bulk density of 1.58. The average thickness and grade for the Bofal Deposit are 1.73 m and 20.05% P_2O_5. Average thickness and grade for the Loubboïra Deposit are 2.03 m and 19.05% P_2O_5.

Additional pits were dug in 1984 and 1985 (SNIM/BRGM, 1985). Near the village of Boubou Aoudi, 5 million tons of ore was delineated on limited evidence. To the south of the main area on a line with Debai Doubel, 2-5 million tons of ore was estimated to exist. Southwest of the permit area on a line through Bagoudine-Ferralla, an additional 25 million tons was estimated at 20% P_2O_5.

As a result of the activity in 1984 and 1985, the reserves of the Bofal Deposit were increased to 106 million tons at an average overburden thickness of 8 m. The reserves of Loubboïra were revised to 29 million tons at an average overburden of 4.9 m. The total geologic reserves of the area are considered to be 135 million tons at near 21% P_2O_5 with an average overburden of 7.2 m.

Phosphate resources also are present in a 60-km^2 area near Aleg, Tamourt, and Beira, about 30 km northwest of Bofal (Boujo and Ould Jiddou, 1983). Boreholes show that the phosphate bed ranges from 1.5 to 2 m thick at a depth of 45-50 m. In the Senegal Valley, phosphate beds have been reported in pits. If the bed thicknesses and P_2O_5 grades are similar to those of Bofal and Loubboïra, these resources might become important. At the present time it is impossible to evaluate these occurrences because of a lack of data. Boujo and Ould Jiddou (1983) indicated that the present identified reserves could be doubled or tripled in the area, provided the phosphate bed remains uniform across the entire area. Although the Lutetian phosphatic formations are practically horizontal near the Senegal River Valley, they plunge to considerable depths in central and northern Mauritania, thereby reducing chances to increase the phosphate resources.

A two-stage process has been used to beneficiate the Bofal-Loubboïra ore (Boujo and Ould Jiddou, 1990). In the first stage, a pebble-concentrate (0.4 mm to 5 mm) is produced by attrition scrubbing and screening. The pebble-concentrate assays between 34.0% and 35.5% P_2O_5. The middlings (0.05-0.4 mm) are treated by froth flotation to obtain concentrates with over 36% P_2O_5 and satisfactory weight recovery (Table Mauritania 4). The concentrates are of very high grade and quality. The $(Fe_2O_3+A1_2O_3)/P_2O_5$ ratios of the concentrates (average = 0.025) are far below the ratio of 0.10

Table Mauritania 4. Chemical Analyses of Bofal-Loubboïra Concentrates

Elements	Bofal	Loubboïra
	(%)	
P_2O_5	37.1	36.6
SiO_2	1.5	4.7
Na_2O	0.2	0.16
K_2O	0.03	0.02
MgO	0.2	0.05
CaO	53.0	51.6
Fe_2O_3	0.6	0.88
MnO	0.04	0.03
Al_2O_3	0.21	0.37
TiO_2	–	0.4
CO_2	2.70	2.25
SO_3	0.64	0.13
C organic	0.28	0.16
F	3.85	3.90
Weight loss at 1000°C	4.60	3.18
H_2O^+	–	0.64
H_2O^-	–	0.38

Source: SNIM/BRGM (1985).

Table Mauritania 5. Quality Characteristics of Bofal-Loubboïra Deposits

	Bofal	Loubboïra
$Fe_2O_3+Al_2O_3/P_2O_5$	0.0218	0.0341
F/P_2O_5	0.1038	0.1065
CaO/P_2O_5	1.4286	1.4098
$CO_2 + F/P_2O_5$	1.4286	1.4098
CO_2/P_2O_5	0.0728	0.0615
Trace Elements		
Cd: 12 ppm at Bofal and		5 ppm at Loubboïra
As:		10 ppm at Loubboïra
Pb:		60 ppm at Loubboïra
V:		110 ppm at Loubboïra
Cr:		45 ppm at Loubboïra
Possible Byproducts		
Uranium and yttrium contents are about 80–100 ppm		

Source: SNIM/BRGM (1985).

considered suitable for commercial ore (Table Mauritania 5). The cadmium content of the concentrates is low at 5 to 12 ppm.

The prefeasibility study by the consortium in 1983/84 investigated the economic viability of producing 2 million tons of concentrate per year for export with a 20-year mine life (de Coussemaker and Ould Jiddou, 1983). Several transportation scenarios were considered, including river transport, railways (to St. Louis, Senegal, or via Dara to an offshore loading facility), and a slurry pipeline. The capital investment required, including transportation-handling facilities, ranged from US $147 million to US $203 million (Table Mauritania 6). Operating costs ranged from US $23.4/ton to US $25.52/ton, depending on the option chosen. The internal rate of return ranged from 12.9% to 9.4%, based on the costs for improvements-modifications to existing systems being assumed, at least in part, by existing organizations in Mauritania responsible for specific transportation systems. When all transportation improvement-modification investments are considered to be the responsibility of the project, the internal rate of return drops to between 10.1% and 6.6%, depending on the option chosen. The internal rate of return from the pipeline option remains the same (9.4) because the capital investment required for this option is considered the sole responsibility of the project.

In 1985 the funding required for a detailed feasibility study was estimated at US $2 million. Due to the perceived impact of transportation costs (by road, Senegal River, railway, or pipeline) and the general situation of the international phosphate market, funding could not be obtained for this study. A unit cost of US $40/ton for concentrate was used in the calculations of the prefeasibility study. Undoubtedly the capital costs of developing the mine and handling and transportation systems have increased since the study was performed. The feasibility study also was to consider phosphoric acid production (1.2 million tons at 54% P_2O_5) for export to increase earnings, and triple superphosphate (TSP) production for local use.

Table Mauritania 6. Results of the Preliminary Economic Study of Bofal-Loubboïra Deposit at 2 Million Tons of Concentrate Per Year, 1984 (20-Year Mine Life)

	Capital Investment (Mine and Transport)	Operating Costs	Internal Rate of Return[a]	
	(million US $)	($ per ton)	(%)	
River transport	147	25.40	12.3	(10.1)
Railway				
St. Louis (Plan B)	147	25.52	12.3	(6.6)
Via Dara (Plan D)	165	23.44	12.9	(8.5)
Pipeline	203	24.50	9.4	(9.4)

a. Based on $40/ton. Percentage based on investments for improvements-modifications of existing systems being assumed by separate organizations responsible for transport. Percentage in parentheses based on all investments-modifications to existing systems being assumed by the project.

Civé Deposits—Phosphatic outcrops are found at the Civé Cliffs near Kaédi on the north bank of Senegal River (BRGM, 1975). The entire phosphate-bearing bed is about 4 m thick with clay intercalations. Individual phosphate beds are lenticular and are 0.3-1 m thick. The average cumulative thickness of the phosphate beds across the deposit is about 1 m. The P_2O_5 content of individual beds ranges from 26% to 28% P_2O_5 (Table Mauritania 7).

The chemical analyses of the Civé phosphate samples generally indicate CaO/P_2O_5 ratios of 1.06-1.28, which is less than that of pure apatite (1.32). These ratios indicate that some of the phosphate is present as iron and/or aluminum phosphate minerals. These iron-aluminum phosphates are generally the product of near-surface weathering of apatite. Iron-aluminum phosphates and the apatites formed under such conditions have low NAC solubilities.

Resources are estimated at about 150,000 tons and might be used for local purposes. It was rumored that local residents were digging some phosphate and using it for direct application in their fields.

Table Mauritania 7. Chemical Analyses of Civé Phosphate Rock

	Quarries 9 and 10[a]	Quarry 7[a]	Quarry 4[b]	Quarry 13[a]
	(wt %)			
P_2O_5	27.7	26.2	27.5	28.1
CaO	29.3	32.1	35.3	34.5
SiO_2	17.7	18.1	19.5	18.1
Al_2O_3	10.0	9.5	7.2	7.2
Fe_2O_3	7.5	7.6	4.0	5.8
CaO/P_2O_5	1.06	1.22	1.28	1.22

a. Weighted average of mineralized zones.
b. Principal bed.

Source: BRGM (1975).

Nouedgui-Bou Naga Area Phosphorites, Idjibitene Region—Precambrian phosphorites occur in the northwestern sector of the Mauritanides southwest of the town of Iriji (Lecorché, 1980). The phosphatic sandstones occur near an angular disconformity, thought to be caused by glaciation in the uppermost Proterozoic (Trompette, 1973). These late Precambrian phosphorites belong to Supergroup 2 of Itar, which transgressively overlies the basement. A typical sequence includes a basal conglomerate followed by sandstone and limestone-phosphorite.

Chemical analyses (McClellan and Saavedra, 1986) (Table Mauritania 8) of selected samples indicate the phosphorites are relatively low in grade (7.5%-10.0% P_2O_5). Mineralogical analysis (Table Mauritania 9) indicates the samples are composed primarily of quartz and apatite with detrital micas,

Table Mauritania 8. Chemical Analyses of Phosphate Rock From Nouedgui-Bou Naga Area, Mauritania

	Sample Number		
	505	506	522
	(wt %)		
P_2O_5	8.8	7.5	10.0
CaO	12.7	10.6	13.9
F	0.7	0.7	0.9
SiO_2	68.3	66.7	69.0
Fe_2O_3	4.3	4.2	3.3
Al_2O_3	4.4	6.8	3.1
K_2O	0.7	1.5	0.61
Na_2O	0.07	0.15	0.07
MgO	0.5	0.22	0.19
S	0.02	0.02	0.02
CO_2	0.30	0.29	0.69
LOI[a]	2.4	1.7	1.2

a. LOI = weight loss, 1000ºC, 1 h.

Source: McClellan and Saavedra (1986).

sericite, and goethite. Traces of fluorite are found in the samples and are indicative of the metamorphism these rocks have undergone. Crystallographic measurements (Table Mauritania 9) indicate the apatite is a fluorapatite with essentially no carbonate substitution. Such apatites have the lowest potential as P_2O_5 sources of direct application.

These deposits are not well known, and their reserve/resource potential has not been assessed. The low grade of the samples, low potential for direct application, remote location of the deposits, and occurrence of other sedimentary phosphate deposits in Mauritania near the principal farming areas in the Senegal River Valley suggest a low priority will be given to further exploration of these deposits.

Sulfur Resources

Gypsum—One of the largest gypsum deposits in the world is located in the Quaternary Sebkha N'Drahamcha area (Figure Mauritania 3). Two main types of gypsum deposits are found in the area.

Bedded gypsum, at the surface or under thin overburden (0-2 m), has been well studied in the southern and eastern area of the Sebkha (Gouzes et al., 1965); it is laterally extensive and vertically regular. The average thickness is 2 m, and the thickness increases toward the center of the Sebkha. There is a regular decrease in thickness to the west and to the north. The average gypsum content is about 84% because of clay intercalations, and the NaCl content is about 1%.

There is a network of active and indurated gypsum dunes, oriented north-northeast, that have not been entirely studied (Figure Mauritania 4). The gypsum content can be 94%-95%, with about 1.40% SiO_2. The height of the gypsum dunes may reach 2.7 m. Gypsum is also associated with clays and salt in depressions between dunes.

The total gypsum resources of the area are estimated to be 4 x 10^9 tons, of which 140 million tons is considered proven reserves. The deposits are managed by Société Arabe des Industries Métallurgiques (SAMIA) and are located in a 65,000-km^2 area at a distance of 45-100 km from Nouakchott near the Nouakchott-Akjoujt road.

Table Mauritania 9. Mineralogic and Crystallographic Analyses of Phosphate Rock Samples From Nouedgui-Bou Naga Area, Mauritania

Sample No.	Apatite	Quartz	Goethite	Micas	Fluorite	Unit Cell		Refractive Index
						a	c	
	(wt %)					(±0.001Å)		
505	22	57	6	11	TR	9.382	6.882	1.630
506	20	55	6	16	1	9.370	6.880	1.630
522	26	59	4	8	1	9.370	6.880	1.630

From 1973 to 1981 the gypsum was mined at an annual rate of 10,000-12,000 tons. The Mauritanian government and the French Ministry of Cooperation funded the installation (1984) of a 100,000-tpy plaster plant, which is managed by SAMIA. Some of the plaster was used in-country and some was exported to West Africa (Communauté Économique des États de l'Afrique de l'Ouest [CEDEAO] countries), Spain, and France.

Native Sulfur—A native sulfur deposit is located on the eastern border of the Sebkha N'Drahamcha. The first study of the sulfur deposits (association of gypsum, bituminous marls, and native sulfur) was done by Chavarel (1947). Native sulfur nodules are concentrated in a mineralized zone. The thickness of the bed that contains sulfur nodules varies from a few centimeters to 1.5 m. Sulfur nodules occur at the interface of gypsum beds and clays overlying bituminous marls. Fine-grained sulfur is also disseminated in the bituminous marls. This type of sulfur mineralization is not widespread in the gypsum-bearing series of the Sabkha. Resources have not been assessed.

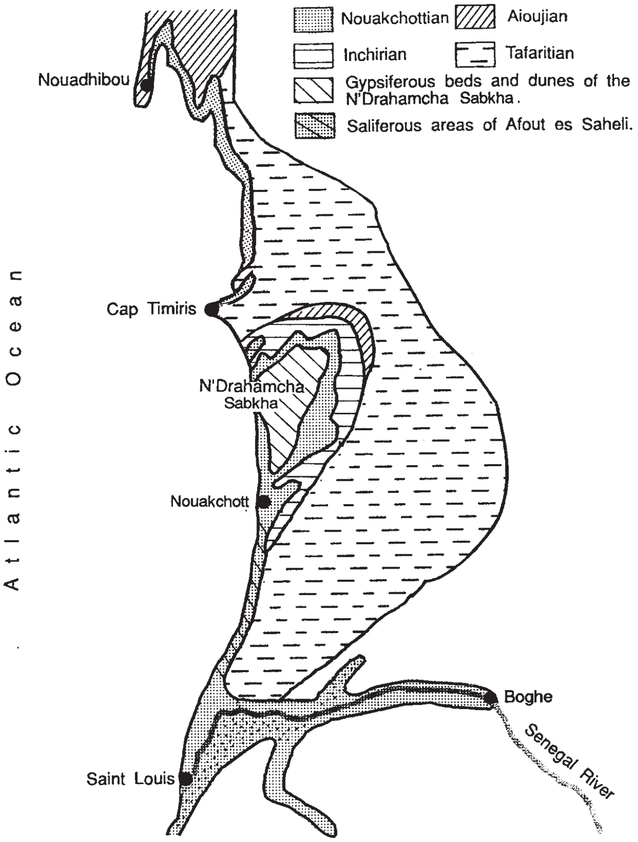


Figure Mauritania 3. Quaternary Salt and Gypsum Deposits of Mauritania

Figure Mauritania 4. Gypsum Dunes, Sebkha N'Drahamcha Area

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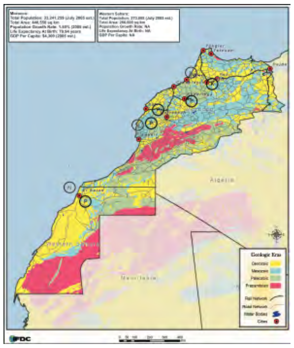


The Kingdom of Morocco (Figure Morocco 1) is bordered on the east and south by Algeria, to the south by Mauritania, to the north by the Mediterranean Sea, and to the north and west by the Atlantic Ocean. Total area is 446,550 km^2 and 19% of the land is arable. The population was estimated in mid-2005 as 33.2 million inhabitants (World Factbook, 2006). Agriculture occupies 40% of the labor force.

The transportation system is composed of 32,551 km of paved roadways, 25,143 km of unpaved roadways, and 1,907 km of 1.435-m-gauge railway. There are 25 airports with paved runways and 35 airports with unpaved runways. Pipelines include 695 km for gas and 285 km for oil. The main ports and terminals are Agadir, Casablanca, Jorf Lasfar, Mohammedia, Nador, Safi, and Tangier.

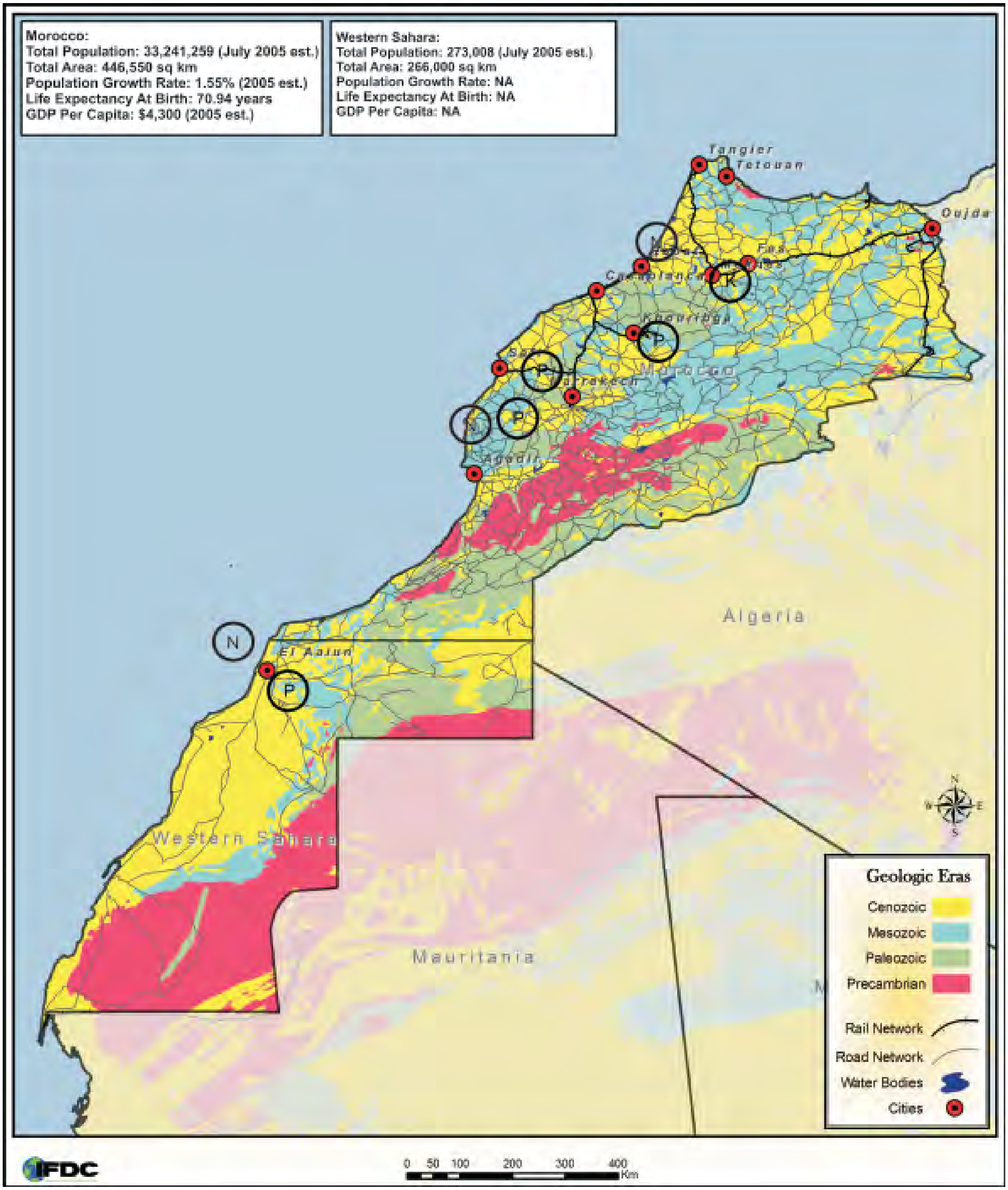
While the status of sovereignty of Western Sahara is a matter of international debate, for purposes of this volume, the fertilizer raw material resources of the area are considered with Morocco. The area is referred to as Moroccan Sahara in Moroccan literature.

The geology of the area encompassing Morocco and Western Sahara is very complex due to the tectonic history of northwest Africa. The Precambrian Reguibat Shield found in southern and eastern Western Sahara is an uplifted area of the West African Craton. These Precambrian rocks were affected by several events related to the formation of the supercontinents of Gondwana and Pannotia during the Neoproterozoic (Late Precambrian). To the west of the Reguibat Shield, the Mauritanides Fold Belt was formed in the Variscan Orogeny (Carboniferous through the Permian, also known as the Hercynian Orogeny). The Anti-Atlas Mountains in Morocco were a center of deformation in this event. Granites were emplaced in Morocco during the Variscan Orogeny.

The opening of the Atlantic Ocean was accompanied by Triassic to Early Jurassic rifting, which was followed by regional subsidence during the Jurassic and Early Cretaceous along the Atlantic margin. Several basins within present-day Morocco were opened and filled with sediments from the Jurassic to the Eocene. During the Late Eocene to Oligocene, the High and Middle Atlas Mountains were formed as a result of continental convergence between Africa and Eurasia. Collision again with Europe in the Neogene resulted in the formation of the mountains of the Rif area of northern Morocco.

The Reguibat Shield area of Western Sahara consists of Archean and Early Proterozoic rocks including migmatites, gneisses, mica schists, and quartzites. Precambrian rocks also form the core of the Anti-Atlas Mountains. Paleozoic age rocks unconformably overlie crystalline Precambrian basement rocks and thicken to the north towards the Tindouf Basin, which is most extensively developed in Algeria. In Morocco a series of sandstones, mudstones, and volcanic sediments unconformably overlie the Precambrian basement, followed by up to 2,000 m of limestones and dolomites known as the Lower Limestone Formation. These carbonates are overlain by continental deposits up to 600 m thick. These sediments are thought to be Infracambrian in age.

The Upper Limestone Formation of Morocco contains trilobite remains and is Cambrian in age. It is about 400 m in thickness in the Anti-Atlas Mountains. Cambrian age clastics are found in the High



Morocco:
Total Population: 33,241,259 (July 2005 est.)
Total Area: 446,550 sq km
Population Growth Rate: 1.55% (2005 est.)
Life Expectancy At Birth: 70.94 years
GDP Per Capita: $4,300 (2005 est.)

Western Sahara:
Total Population: 273,008 (July 2005 est.)
Total Area: 266,000 sq km
Population Growth Rate: NA
Life Expectancy At Birth: NA
GDP Per Capita: NA

Figure Morocco 1. Geology, Major Cities, and Transportation Network

Atlas and Rif area. Ordovician and Silurian age sediments in Morocco are mainly composed of sandstones and mudstones. In southern Morocco, the Lower to Middle Devonian consists of four sedimentary cycles, each containing a limestone unit. In northern Morocco a shallow water environment dominated, and clastic sediments and volcanics are present. Sandstone, mudstone, and crinoidal limestones were deposited during the Carboniferous period. Permian age sediments are coarse clastics in Morocco.

In the Triassic, small basins developed north of the present Anti-Atlas. These basins contain conglomerates, sandstones, mudstones, and evaporites. Red beds were deposited continentally at the same time. Basalts were also intruded. Several deep basins developed during the Jurassic; deep-water limestones were formed in the central parts of basins, reef limestones near the edges, and dolomitic rocks on stable blocks between basins. During the Late Jurassic age, the High Atlas area and the Moroccan Meseta area were emergent and continental red beds were formed. The term meseta is from the Spanish word for table (mesa) and refers to a high plain.

During the Cretaceous age, several transgressions occurred in northwest Africa. In the Upper Cretaceous, a transgression resulted in the deposition of marls; at the end of the Upper Cretaceous, the deposition of the economically important phosphate deposits began in the western Meseta area. In the Cretaceous, marls with minor limestone beds were deposited in the area in northern Morocco now known as the Rif.

Phosphate deposits were also formed in the Lower Eocene in the western Meseta area, followed by gastropodal limestones. A significant marine transgression occurred in the Upper Eocene. During the Oligocene, a terrestrial environment prevailed in Morocco. Small occurrences of limestones are found in Miocene age sediments. The main Alpine mountain-building deformation occurred at the Miocene/Pliocene transition, resulting in the development of flysch deposits.

The Coastal Basin of Western Sahara is an asymmetrical structure located to the south and west of the main deformation that occurred in Morocco in the Mesozoic and Cenozoic. The base of the basin is formed by Precambrian rocks and folded Paleozoic sediments. Triassic sediments form the base of the unfolded sediments that fill the basin. The basin has experienced numerous transgressions and regressions of the sea. Similar to occurrences in Morocco, formation of the phosphate deposits began in the late Cretaceous.

The entire area of Morocco and Western Sahara has been mostly emergent during the Quaternary. Shorelines have fluctuated, with the resulting formation of beach deposits. Dunes have formed, particularly in Western Sahara. Geologic processes are ongoing in the area as the Atlas Mountains and the Rif area are seismically active.

Nitrogen Resources

Morocco currently produces small amounts of natural gas and oil from the Essaouira (or Essaouria, Essaouiria, Essqouira) Basin and gas from the Gharb Basin in the north. In 2000 an oil and gas discovery in the Talsint region near the border with Algeria raised hopes that the oil and gas sector would significantly develop. However, further work was not encouraging. Many of the Moroccan offshore basins are only now being explored. Firms engaged in exploration include PETRONAS, Kerr-McGee, Total, and Energy Africa. Contracts with Total and Kerr-McGee that included acreage off Western Sahara caused considerable controversy. Offshore Western Sahara is believed to contain the most potentially viable hydrocarbon reserves in the area (EIA, 2005).

Oil production in Morocco in 2005 was 300 barrels per day (bpd) (World Factbook, 2006). Oil consumption was 158,000 bpd in 2005. Natural gas production was 5 million m^3 (2003 estimate). Natural gas consumption was 650 million m^3 (2003 estimate).

Proven oil reserves are 100 million barrels (2005 estimate; World Factbook, 2006). Proven natural gas reserves are 1.218 billion m^3 (2005 estimate).

In 2004 Morocco had two oil refineries—the Samir Oil Refinery at Mohammedia and the Sidi Karem Refinery. In November 2002 the Samir Oil Refinery was damaged by a massive fire. In 2000 the total amount of refinery products produced in

Morocco was 48,000,000 barrels. In 2003 the estimated production was 20,000,000 barrels (Mobbs, 2003).

The majority of Morocco's electricity is produced by thermal units that burn oil and coal (EIA, 2005). All of the oil is imported, and most of the coal comes from South Africa. A mine at Jerada produced 129,200 tons of coal in 1999 (Mobbs, 2003). In 2003 Moroccan coal output was 214 tons.

Phosphate Resources

Phosphate rock was first discovered in Morocco in 1908 (Office Chérifien des Phosphates [OCP], 1989). In 1917 large deposits were discovered between Oued Zem and El Borouj near Khouribga, about 120 km southeast of Casablanca. Phosphates formed in four main basins in northwestern Africa, from north to south: the Oulad Abdoun Basin, the Ganntour Basin east of Safi, the Meskala Basin east of Essaouira, and the Oued Eddahab Basin (or Aaiun Basin) in Western Sahara.

Numerous studies performed on the Moroccan phosphate deposits have established a Late Cretaceous to Middle Eocene age range (Boujo, 1976, 1980; Salvan, 1953, 1960). The basic type sequence, particularly of the deposits in the Moroccan Meseta, is as follows, from bottom to top: phosphatic limestone or dolomite, coarse-grained phosphate, medium-grained phosphate, fine-grained phosphate, medium-grained phosphatic marl, fine phosphatic marl, friable or undurated marl, and clay (OCP, 1989). These sediments are believed to have been deposited in warm shallow marine to lagoonal conditions. The sequence varies considerably from one basin to the next. In most areas in Morocco, the sequence is capped by a gastropodal limestone.

The phosphatic sequence is extremely attenuated or condensed in the richest mining zones (Savage, 1987). The entire Cenomanian-Lutetian succession in the Khouribga area is about 100 m thick and may be as thin as 25-30 m. The phosphate facies may be transgressive in age, becoming younger from southern to northeastern Morocco.

The Oulad Abdoun Plateau—The Oulad Abdoun Plateau, also known as the Plateau des Phosphates, is the site of the richest and most extensively exploited deposits in Morocco (Figure Morocco 2). The plateau covers an area of 1,950 km^2 and extends 100 km from east to west and about 60 km north to south. It is bounded to the west and north by an escarpment. The main phosphatic suite varies considerably. Sandy oolitic phosphate beds alternate with marls, clay, phosphatic limestone, and occasional flint beds. Seven beds are distinguished in the area, from top to bottom: Horizon B, Horizon, A, Bed O, Bed O´, Bed 1, Bed 2, and Bed 3 (OCP, 1989; Gharbi, 1998). The beds have the following thicknesses and P_2O_5 contents:

Phosphate Rock Beds	Thickness (m)		% P_2O_5	
	Minimum	Maximum	Minimum	Maximum
Horizon B	0.1	3.0	29	35
Horizon A	0.1	2.5	27	34
Bed O	0.0	2.0	24	33
Bed O´	0.0	1.5	23	31
Bed 1	0.4	6.0	22	34
Bed 2	0.4	12.8	14	30
Bed 3	2.2	46.7	11	25

Exploitation of the Oulad Abdoun Plateau phosphates began in the Khouribga area in 1922. The oldest beneficiation center is located at Khouribga. The second treatment center was established at Oued Zem in 1961 adjacent to the Sidi Daoui area about 30 km east of Khouribga. The Beni Idir plant was built between the two areas. The explored sectors and mining areas are shown in Figure Morocco 3.

Until 1956 all mining was underground. Blocks or "recettes" were established between the outcrop and the water table. Each block contained about 20 million tons of ore. The first open pit was established in 1956 at Sidi Daoui Nord. A modern underground operation was established at Hatane Nord in 1964. In 1965 a pit was established at Mera (or Meraa) El Arech. The new treatment center was built at Beni Idir to process the ore from these mines. The mine at Sidi Daoui Sud was established in 1971.

Currently there are three open-pit mines in the Khouribga area. Production from Sidi Daoui was about 2.6 million tpy in 2004 (Sendal, 2004), down from about 10 million tpy in the 1980s. The Sidi Chenanne Mine was developed in 1994 to replace Sidi Daoui and increase production in the area. Annual production was 6.2 million tons in 2004 with projected increases in production to 10-12 million

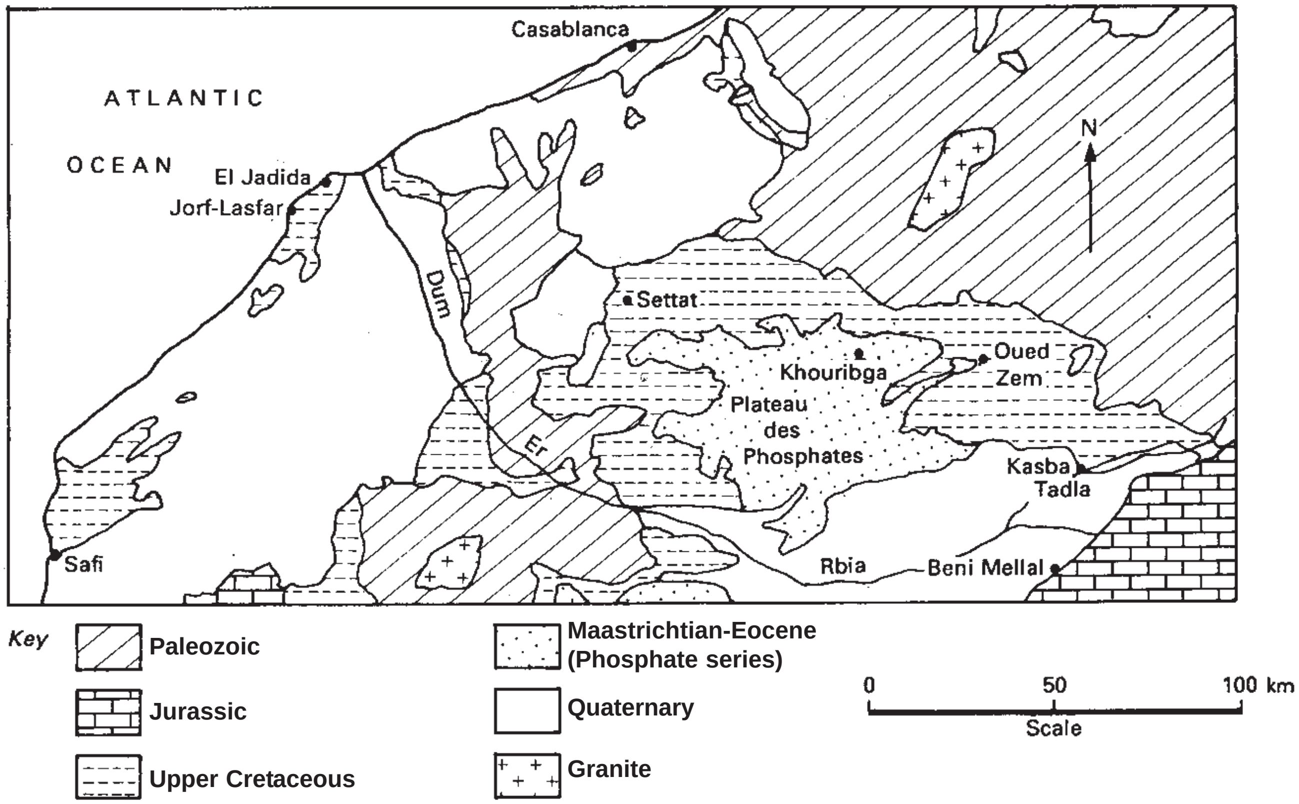


Figure Morocco 2. Generalized Geology of the Oulad Abdoun Plateau Area (Adapted From OCP, 1989)

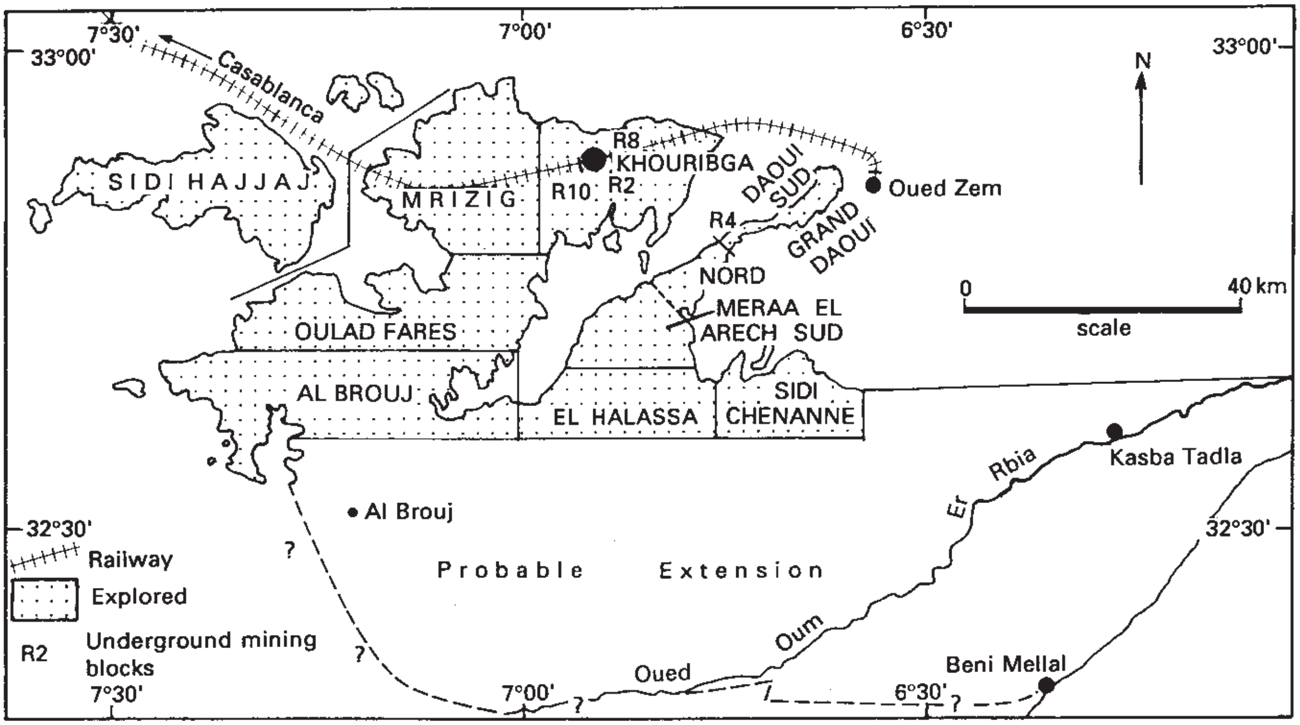


Figure Morocco 3. Explored Sectors of the Oulad Abdoun Plateau Area (Adapted From OCP, 1989) tpy by 2010. Production from Mera El Arech was about 6 million tpy in 2004 with projected increased production to 8-9 million tpy by 2010.

Mining is quite complicated and selective in the area. Figure Morocco 4 depicts a scenario in the area where six to seven phosphate beds are mined. Not all of the beds are present in some areas, nor is it economically or technically feasible to mine this selectively in some areas. Overburden and interbed waste is drilled and blasted. Phosphate beds are generally soft and friable and are selectively removed. The equipment used is sized to the specific operation on individual beds. There are several large Marion draglines deployed in the area; smaller draglines, power shovels, and front-end loaders are also used. Trucks range from 15 tons to 170 tons in capacity.

Depending on the characteristics of individual phosphate beds, the beds are processed differently. Higher grade ore is only screened and dried. Some ores may be washed, screened, cycloned, and dried. A washing/flotation unit has been installed to treat low-grade ore. The capacity of the first flotation unit is 1 million tpy. There is a calcination unit to treat 250,000 tpy at Beni Idir. Total drying capacity at the Beni Idir and Oued Zem beneficiation plants is over 18 million tpy (Sendal, 2004).

Khouribga phosphate rock has traditionally been well known in world trade because of its very high quality. Several samples of the Khouribga rock have been analyzed at IFDC (Table Morocco 1). These samples ranged from 31.7% to 34.2% P_2O_5. Khouribga rock has been marketed as high as 82 BPL. The unit cell $\underline{a}$-values of four samples of Khouribga rock analyzed at IFDC indicate an average of $\underline{a} = 9.337 \pm 0.002$. Based on previously established statistical models, this unit cell $\underline{a}$-value would indicate a maximum P_2O_5 content in the francolite of about 36.7 wt % and a maximum CO_2 content of about 4.3 wt %.

Production from the Khouribga area is exported or delivered to the OCP complex at Jorf Lasfor.

Ganntour Plateau—The Ganntour Plateau lies to the southwest of the Oulad Abdoun Plateau and is separated by the valley of the Oued Om er Rebia (or Oum Er Rbia) and tributaries. Paleozoic massifs bound the plateau to the north and south. The Ganntour Plateau is about 120 km long in an east to west direction and about 25-40 km wide. Phosphate beds outcrop on the north and west sides of the plateau.

Similar to the Oulad Abdoun Plateau deposits, the phosphates are found in Maastrichtian, Montian,

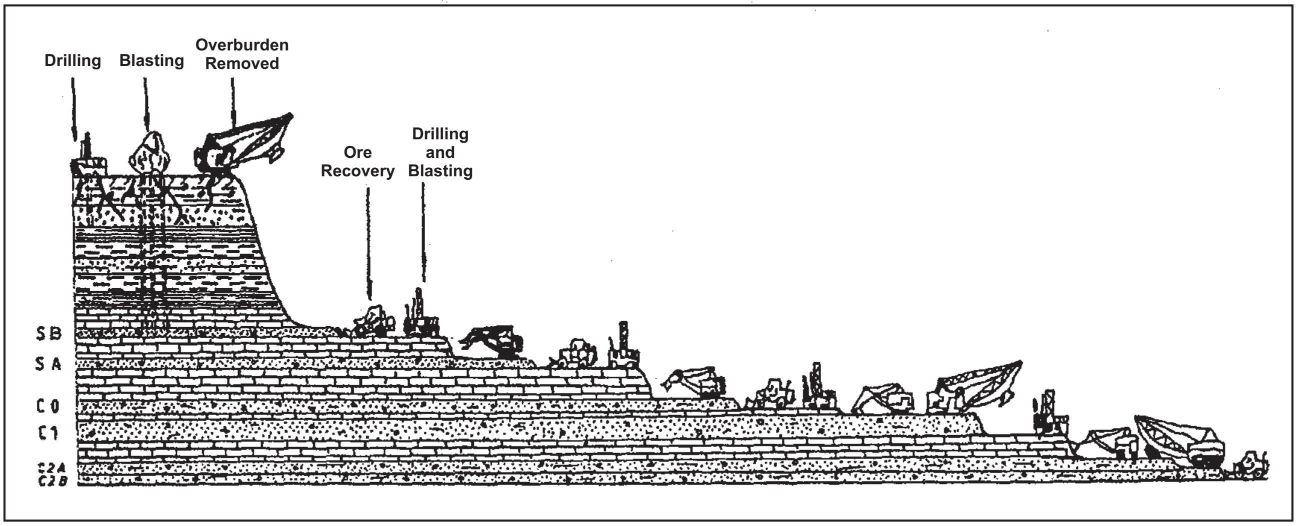


Figure Morocco 4. Selective Mining, Khouribga Area (Adapted From Gharbi, 1998).

Table Morocco 1. Chemical Analyses, Khouribga and Youssoufia Phosphate Rock

	Khouribga Product (R230.08)	Khouribga Product (R230.67)	Khouribga Product (R231.48)	Youssoufia Bed 1	Youssoufia Bed 6
	(wt %)				
P_2O_5	33.4	34.2	31.7	27.6	31.8
CaO	52.2	52.3	53.8	30.7	52.1
F	4.1	4.6	4.0	3.5	3.9
Fe_2O_3	0.21	0.25	0.20	0.31	0.29
Al_2O_3	0.46	0.41	0.30	0.32	0.47
SiO_2	1.0	2.2	1.8	2.9	4.5
MgO	0.27	0.29	0.44	1.1	0.39
K_2O	0.06	0.05	0.03	0.06	0.10
Na_2O	0.76	0.83	0.84	0.74	0.98
S	0.70	0.75	0.84	0.98	0.76
Cl (ppm)	121	135	233	124	281
CO_2	4.3	4.6	6.6	7.3	4.6
C (organic)	0.23	0.3	1.1	2.0	0.3
Free H_2O[a]	NA[b]	1.20	0.81	11.5	9.1
LOI[c]	NA	6.5	8.8	21.8	14.6

a. Free H_2O = weight loss, 1 h, 105ºC.
b. Loss on ignition = weight loss, 1 h, 1000ºC.
c. Not analyzed.

Thanetian, and Ypresian age beds. The deposits are capped by a fossiliferous Lutetian (Middle Eocene) limestone. The sequence is covered to the south by Quaternary sediments of the Plaine de la Bahira (Figure Morocco 5).

In the Youssoufia area, as many as 15-16 phosphate beds are recognized (OCP, 1989) (Figure Morocco 6). In the Benguerir (or Ben Guerir) area, as many as 20-23 individual phosphate beds are recognized. Chemical analyses of Youssoufia Bed 1 and Bed 6 samples are given in Table Morocco 1. The mining area at Youssoufia was opened in 1932. All mining on the Ganntour Plateau was by underground methods until the mine at Benguerir was opened. Underground mines are still in operation at Youssoufia. In 2003, 2.5 million tons of phosphate rock was produced, including 1 million tons of calcined phosphate rock and 1.5 million tons of dried phosphate rock. The underground mines are being replaced by production from open pits. All of the production from Youssoufia goes to the OCP complex at Safi. Chemical analyses of the Youssoufia product are given in Table Morocco 2.

The open-pit mine at Benguerir was established in 1980. The second stage of development began in 1994. Current production is 3.2 million tpy of 23.0%-27.5% P_2O_5 rock (Sendal, 2004). Production could be quickly raised to 6 million tpy in that much of the infrastructure is in place. Beneficiation at the mine is only by dry screening. A new washing/flotation unit is under development to upgrade part of the production from the open pits.

Currently, all of the output of the open pits is transported to Safi where it is washed with seawater and rinsed with freshwater before wet grinding and feeding the product to phosphoric acid and triple superphosphate (TSP) plants. The washing process raises the P_2O_5 content about 4%. A small amount of phosphate rock is produced at Benguerir for direct application.

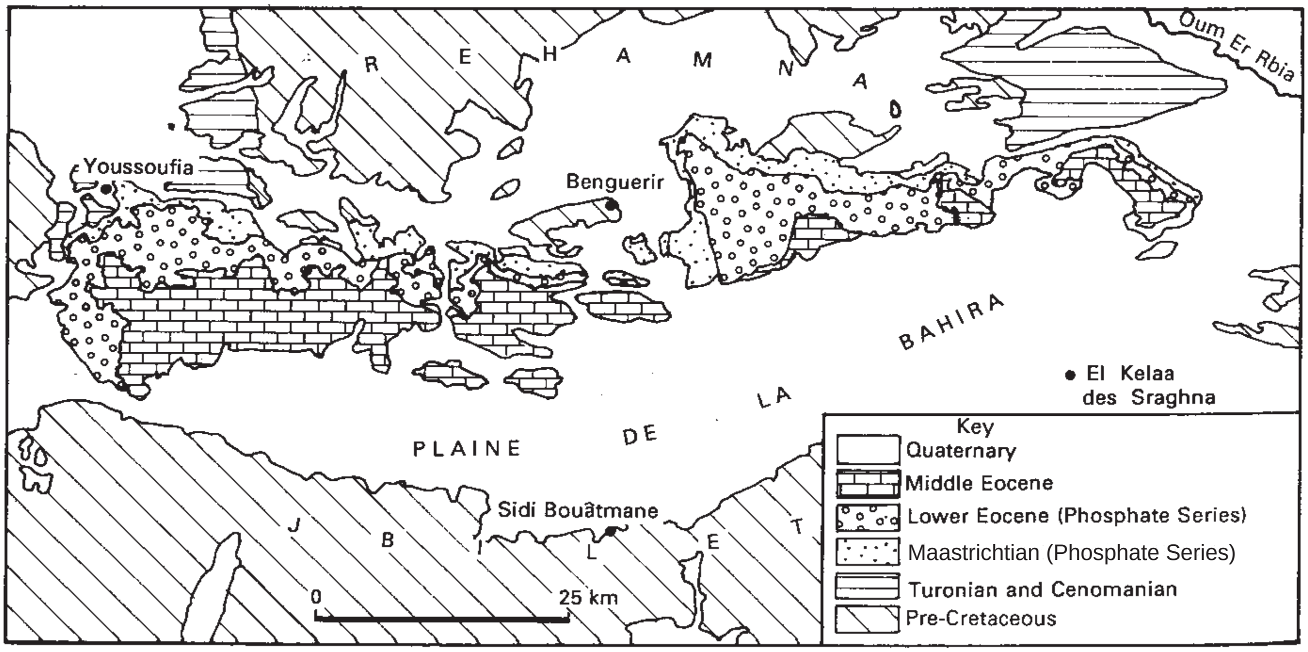


Figure Morocco 5. Generalized Geology of the Ganntour Plateau Area (Adapted From OCP, 1989)

Meskala Basin—The Meskala Basin covers an area of about 1,000 km^2 to the east of Essaouira and about 125 km south of Safi. The basin has been strongly affected by orogenic movements, and the phosphate beds are found in three synclines—Kémis Meskala, Oulad Bou Sbaa, and Imin-Tanout. Phosphate beds occur in the entire Maastrichtian to Lutetian succession, but the greatest concentration is in Maastrichtian and Montian-Thanetian rocks (OCP, 1989). Savage (1987) indicated that the average grade of the phosphate beds is 33% P_2O_5.

At one time, plans were drawn up to exploit the beds with Soviet assistance (Savage, 1987). A new mine was to be developed at Meskala, and a railway was to be built with a new port at Essaouira. The initial capacity of the mine was to be 3.5 million tpy, eventually rising to 10 million tpy. These plans were not realized.

Bou Craa (or Bu Craa) Deposit—Phosphate rock was discovered in the then-Spanish Sahara in 1947 (Savage, 1987). Between 1962 and 1964, studies by Empresa Nacional Minera del Sahara (ENMINSA) established that very large reserves of high-grade rock existed near Ouad Bou Craa, a dry river bed that cuts the deposit. The deposit became known as the Bou Craa Deposit, located about 120 km southeast of Laayoune (Figure Morocco 7). The basin in which the deposit is found is referred to as the Oued Eddahab Basin or the Aaiun Basin. In 1969 ENMINSA was dissolved and became Fosfatos de Bou Craa. Mining began in 1973. Mining was disrupted on many occasions between 1975 and the early 1980s. Shipments from stocks were made in 1977 by OCP. Phosbucraa (an OCP subsidiary) recommenced operations at Bou Craa in late 1982 (Savage, 1987).

The phosphate series in the basin is about 40-45 m in maximum thickness, ranging in age from Upper Maastrichtian to Thanetian. Maximum development was in the Lower Paleocene (Muñoz Cabezon, 1989).

The phosphate suite can be generally characterized as follows (Savage, 1987):

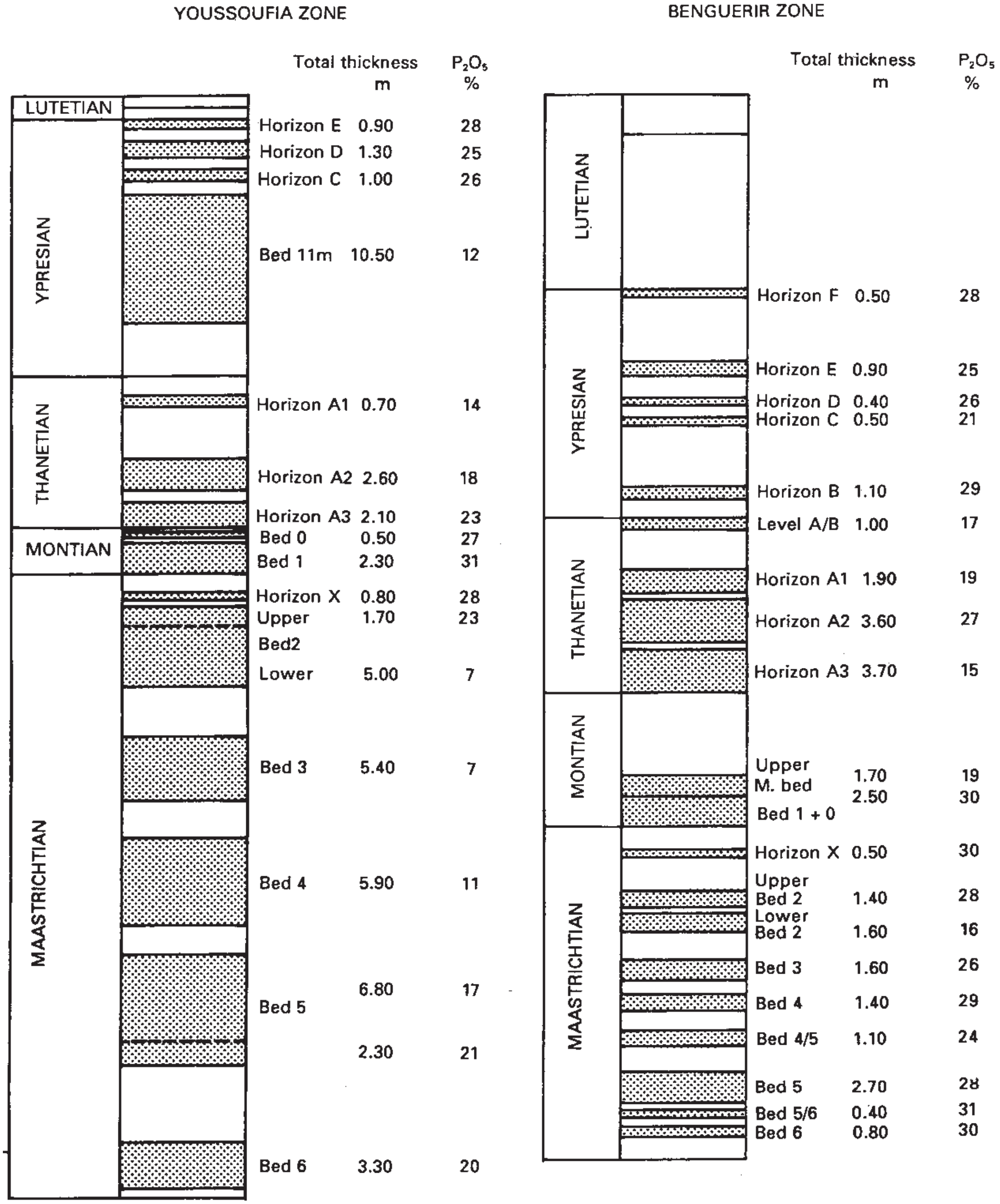


Figure Morocco 6. Stratigraphy of Phosphate Beds in the Youssoufia and Benguerir Zones, Ganntour Plateau, Morocco (Adapted From OCP, 1989)

Table Morocco 2. Chemical Analyses, Youssoufia Phosphate Rock

	Grade[a]	
	68%-69% BPL	73%-74% BPL
	(wt %)	
P_2O_5	31.17	34.14
CaO	51.17	53.84
Fe_2O_3	0.19	0.15
Al_2O_3	0.36	0.28
MgO	0.53	0.46
Na_2O	0.74	0.70
K_2O	0.07	0.07
SiO_2	4.04	2.76
CO_2	6.25	3.21
SO_3	1.18	2.32
F	4.05	4.13
Cl (ppm)	200	200
Organic carbon	0.29	0.16

a. BPL = bone phosphate of lime.

Source: Savage (1987).

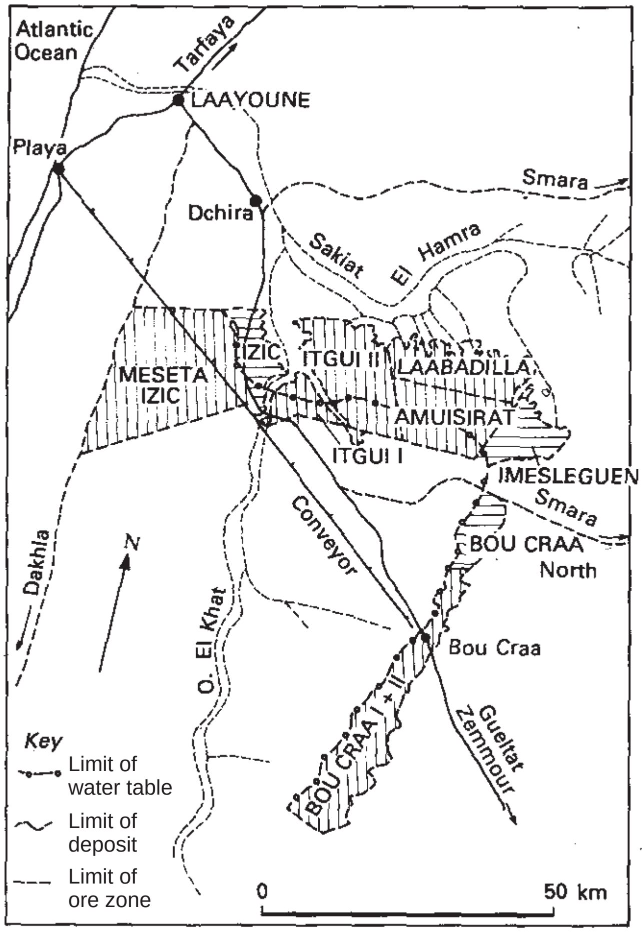


Figure Morocco 7. Phosphate Ore Zones in the Oued Eddahab Basin, Western Sahara (Adapted From OCP, 1989)

1. Upper siliceous complex (Paleocene) with a thin upper phosphate bed.
2. Clay and marls, phosphate level 1 (Paleocene).
3. Clays and marls with phosphate levels II, IIA, and IIB, characterized by silicious nodules up to 30 cm in diameter (Paleocene).
4. Lower siliceous complex with Phosphate Level III (Paleocene).
5. Clays and marls with Phosphate Level IV (Maastrichtian).

The deposit has been divided into sectors (Figure Morocco 7). The Bou Craa sector is the richest with average ore grades running from 28% to 32% P_2O_5. The phosphate series in this sector is about 13.5 m thick on average with relatively thin overburden (OCP, 1989). In this area Phosphate Beds II, IIA, and IIB form a single distinct unit 3-7 m thick (Muñoz Cabezon, 1989).

Structurally, the Bou Craa Deposit is a simple monocline dipping at a rate of 10-20 m/km to the west. The deposit is formed at the erosional outcrop of the Paleocene to Upper Cretaceous sediments.

The Bou Craa Mine is an open-pit operation. Overburden ranging from 10 to 30 m in thickness is removed by dragline. Phosphate ore is mined using bucket-wheel excavators or power shovels. The ore is transported by 100-ton trucks to the primary crusher where it is reduced to minus 10 mm. The ore is then conveyed to Laayoune. The conveyor belt system is built on pads across and above an area of shifting sand dunes near the coast.

The ore is composed of phosphate grains in a silt and clay matrix. The ore is crushed and pulped with seawater. The silt and clay are removed by screening at +1 mm and desliming at -60 microns (Savage, 1987). The product is dewatered and then washed with freshwater obtained from a desalination plant. The product is then dried.

Table Morocco 3 gives chemical analyses of Bou Craa ores and final products. Bou Craa product has one of the highest P_2O_5 contents of any phosphate rock available on the world market. Production capacity is over 2 million tpy of 80 BPL product. All the production is exported.

Table Morocco 3. Chemical Analyses, Bou Craa Deposit

	Average Aaiun Basin Phosphate Rock	Average Bou Craa Ore	Bou Craa Concentrates	
			(75% BPL)	(80% BPL)
	(%)			
P_2O_5	30.0	32.23	34.31	36.6
CaO	45.0	47.51	50.42	51.9
SiO_2	10.0	10.23	6.54	4.52
Al_2O_3	1.0	0.01	0.59	0.35
Fe_2O_3	0.8	0.4	0.31	0.14
MgO	1.5	0.2	0.11	0.06
Na_2O	1.8	–	0.26	0.24
K_2O	0.8	–	0.17	0.14
H_2O (free)	–	–	0.56	0.44
H_2O (comb.)	–	–	0.62	0.65
CO_2	–	–	2.17	1.83
Organic matter	–	–	0.13	0.06
TiO_2	–	–	0.06	0.04
SO_3	1.0	2.22	0.58	0.44
Cl	0.9	0.32	0.04	0.04
F	2.2	3.24	3.88	3.93
SrO	–	–	0.03	0.03

Source: Muñoz Cabezon (1989).

Offshore Deposits—Phosphate rocks of Upper Cretaceous to Miocene ages occur off the Moroccan coast between 31ºN and 33º 45' N at depths between 80 and 200 m. These occurrences have been studied by a number of groups (McArthur, 1978, 1980; Summerhayes and McArthur, 1990; Summerhayes et al., 1971, 1972). IFDC has analyzed several samples obtained off the Moroccan coast by dredging. Chemical analyses of selected samples are given in Table Morocco 4. The average unit cell a-value of seven samples from the Moroccan shelf was 9.323Å±0.002. This corresponds to a francolite with a maximum P_2O_5 content of 34.2 wt % and a maximum CO_2 content of over 6%. This composition is very similar to that of phosphate rocks from North Carolina (United States) and Gafsa (Tunisia) which are some of the most suitable phosphate rocks in the world for direct application.

Table Morocco 4. Chemical Analyses, Offshore Phosphate Rock Samples

	Sample P1	Sample P(FE)1	P(G1)1	Sample M79111
	(wt %)			
P_2O_5	14.0	26.0	27.7	31.6
CaO	25.9	40.3	51.1	50.3
F	1.7	3.3	3.9	4.1
Fe_2O_3	8.2	5.0	0.53	0.27
Al_2O_3	1.9	0.73	0.25	0.72
SiO_2	14.5	12.6	1.4	3.8
MgO	3.2	0.8	0.70	0.50
K_2O	1.4	0.22	0.08	0.07
Na_2O	0.85	1.1	1.6	0.90
S	0.57	0.67	1.2	0.71
Cl (ppm)	500	800	700	NA[a]
SrO	15.0	6.3	10.8	5.7

a. Not analyzed.

Moroccan Phosphate Rock Reserves and Resources—The total phosphate rock resources of Morocco have not been rigorously defined; however, reserves/resources have been defined far beyond any reasonable planning horizon for mining. There is a vast amount of phosphate rock in Morocco; it is simply a waste of effort to definitively quantify these resources other than to locate the best areas for mining and to plan mines for the reasonable foreseeable future.

The United States Geological Survey (USGS) indicates that Moroccan and Western Sahara reserves are 5.7 billion (5.7 x10^9) tons and the reserve base is 21 billion tons (USGS, 2006).

Table Morocco 5 indicates identified Moroccan phosphate resources by major fields as indicated by OCP (1989) based on Belkhadir and Chaoui (1985).

Table Morocco 5. Identified Moroccan Phosphate Resources by Major Phosphate Fields

Oulad Abdoun (Khouribga)	
Million tons	26,800[a]
Extent	100 km x 45 km
Number of beds	6-10 (7 mined)
Grade (% P_2O_5)	25.2-34.3 (55%-75% BPL)
Average thickness	16.5 m
Ganntour (Youssoufia)	
Million tons	8,020[b]
Extent	125 km x 30 km
Number of beds	6-23
Grade (% P_2O_5)	22.9-32.9 (50%-72% BPL)
Average thickness	18.85 m
Meskala	
Million tons	20,480
Extent	More than 100,000 ha
Number of beds	6-10
Grade (% P_2O_5)	20.6-29.8 (45%-65% BPL)
Average thickness	17.95 m
Sahara (Laayoune-Bou Craa)	
Million tons	950[c]
Extent	141,500 ha
Number of beds	2-6
Grade (% P_2O_5)	31.1-33.9 (68%-74% BPL)
Average thickness	3-7 m

a. Estimated to represent 36% of the deposit area.
b. Estimated to represent only 18% of the deposit area.
c. Mineable reserve, Bou Craa deposit.

Source: Belkhadir & Chaoui (1985); OCP (1989).

In this compilation, total resources are about 56 billion tons. Note that only 36% of the deposit area of the Oulad Abdoun Plateau and 18% of the deposit area of the Ganntour Plateau were included in the total.

Fertilizer International (2006) indicates that Moroccan reserves are 85 billion m^3 of phosphate rock. This is a rather loose use of the term “reserves,” and the word “resources” probably should have been used. This estimate may have been based on a paper by Gharbi (1998) in which in situ reserves/resources were estimated based on the work of several other individuals and institutions. Gharbi’s analysis was quite detailed and considered 45% of the areal extent of the Oulad Abdoun Plateau and 38% of the areal extent of the Ganntour Plateau. Adding Gharbi’s estimates for all the areas indicates a total of 84.12 billion m^3 of phosphate ore in situ. Using an assumed average of 2.0 tons/m^3 for phosphate ore in situ indicates a total of approximately 168 billion tons of phosphate ore. This is a considerably higher resource estimate than any previous estimate. The amount of phosphate rock concentrate that ultimately will be economically recoverable far into the future is a matter of speculation.

Phosphate Fertilizer Production—OCP has chemical complexes at Safi and Jorf Lasfar. The Safi complex initiated production in 1965. The Jorf Lasfar site came onstream in 1986. Combined phosphoric acid production capacity for OCP is 3,568,000 tons P_2O_5 (IFDC, 2006a) (Table Morocco 6). Much of the acid is used within the complexes to produce diammonium phosphate (DAP), monoammonium phosphate (MAP), and NPKs (Table Morocco 7). Total DAP and MAP production capacity is 1,605,000 tons of P_2O_5, and NPK production capacity is 250,000 tons of product (IFDC, 2006b). OCP also produces about 800,000 tpy of TSP at Safi (*Fertilizer International*, 2006). In order to bring production of phosphoric acid to current levels, OCP has undertaken and completed several debottlenecking projects in the last few years. The DAP plants at Jorf Lasfar are being revamped with new preneutralizers and screening sections. A new DAP plant is under construction at Jorf Lasfar that will provide 850,000 tpy of additional capacity. Up to three more DAP plants may eventually be added.

Table Morocco 6. Morocco Phosphoric Acid Capacity Listing by Plant

	Plant Status[a]	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	Indefinite
Morocco										
OCP										
Maroc Phosphore III & IV, Jorf Lasfar	OPR	1,650	1,730	1,730	1,730	1,730	1,730	1,730	1,730	1,730
Maroc Phosphore, IMACID	OPR	330	330	330	330	330	330	330	330	330
Maroc Chimie I, Safi	OPR	163	163	163	163	163	163	163	163	163
Maroc Chimie II, Safi	OPR	170	170	170	170	170	170	170	170	170
Maroc Phosphore I, Safi	OPR	695	695	695	695	695	695	695	695	695
Maroc Phosphore II, Safi	OPR	480	480	480	480	480	480	480	480	480
Company Total	OPR	3,488	3,568	3,568	3,568	3,568	3,568	3,568	3,568	3,568
OCP and Bunge jv										
Jorf Lasfar	UCT						375	375	375	375
Pak-Maroc Phosphate Societe Anonyme										
Jorf Lasfar	UCT	–	–	–	–	–	375	375	375	375
Morocco Total		3,488	3,568	3,568	3,568	3,568	4,318	4,318	4,318	4,318

a. OPR = operating; UCT = under construction.

Table Morocco 7. Morocco DAP, MAP, and NPK Capacity Listing by Plant

	Plant Status[a]	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	Indefinite
DAP and MAP (tons P_2O_5 x 1,000)										
Morocco										
OCP										
Maroc Chimie I, Safi (TSP/DAP)	OPR	460	460	460	460	460	620	620	620	620
Maroc Phosphore I, Safi, (MAP)	OPR	165	165	165	165	165	165	165	165	165
Maroc Phosphore 3 and 4, Jorf Lasfar	OPR	980	980	980	980	980	980	980	980	980
Company Total		1,605	1,605	1,605	1,605	1,605	1,765	1,765	1,765	1,765
OCP and Bunge jv										
Jorf Lasfar	UCT	–	–	–	–	–	–	300	300	300
Morocco Total		1,605	1,605	1,605	1,605	1,605	1,765	2,065	2,065	2,065
NPK (tons x 1,000)										
OCP										
Moroc Chimie I, Safi	UCT	250	250	250	250	250	250	250	250	250
Morocco Total		250	250	250	250	250	250	250	250	250

a. OPR = operating; UCT = under construction.

OCP and Bunge Fertilizers of Brazil have formed a 50:50 joint venture to produce phosphoric acid and MAP at Jorf Lasfar. Startup is scheduled for 2007-2009. Indo Maroc Phosphore (IMACID) is a joint venture between OCP and Chambal Fertilizers to produce phosphoric acid for shipment to India. The Zuari Group and Tata Chemical also hold equity shares in the venture. The design capacity is 370,000 tpy P_2O_5. OCP has also bought into the Paradeep Phosphates Ltd. Complex in Orissa, India, with Chambal Fertilizers. This plant has a design capacity to produce 225,000 tpy of P_2O_5 as phosphoric acid and 1 million tons of finished fertilizers. Apparently OCP will provide phosphate rock for the plant.

Pakistan Maroc Phosphore S.A., a joint venture with the Fauji Group of Pakistan, was formed to build a 375,000-tpy P_2O_5 phosphoric acid plant at Jorf Lasfar. The estimated cost was US $235 million. The plant is scheduled to come onstream in 2007/08 (Table Morocco 6). OCP is also developing trading agreements with the Iran Petrochemical Corporation (IPC). OCP may ship phosphate rock and phosphoric acid to Iran. IPC may ship sulfur and ammonia to Morocco.

Potassium Resources

Potash was first discovered in Morocco during a drilling program by Sté Chérifienne des Petroles in the Meknes area in 1939 (British Sulphur, 1985). From 1954 to 1960, the Moroccan Bureau de Recherches et Participations Minières (BRPM) and Mines Domaniales de Potasse d'Alsace explored for potash in Morocco, These entities formed Cie des Potasses des Zemmours to exploit the deposits in the Khemisset Basin. An annual capacity of 200,000 tons was proposed. This project was never implemented. Polish interests have also looked into means of processing the ores.

There are two basins in the Meknes area—the Khemisset Basin and the Boufekrane Basin. The basins are joined in the north in the subsurface. The Khemisset Basin covers an area of 1,000 km in a graben apparently formed during the Variscan Orogeny. Salt deposition occurred during the Triassic. There are two salt beds separated by basalt flows, submarine dolerite lavas, and anhydrite beds. The lower salt bed contains the most significant potash beds. Continental deposits occur on the edges of the basins. Carnallite is found in a central zone with some bischofite. The potash zones are found in the upper part of the lower salt. The carnallite averages 5-6 m thick and can reach 9 m. Sylvite borders the carnallite but can occur on the top of the carnallite. A sylvite body, known from a borehole near the Khemisset village, is 2.5-3.0 m thick at a depth of 500 m. The carnallite generally occurs at depths of 700-800 m. British Sulphur (1985) noted an announcement made in 1968 that the carnallite reserves had been estimated at 200 million tons and sylvinite reserves at 40 million tons following a UN-financed drilling program. Barodi et al. (1998) indicated that the reserves of the sylvinite zone are 17 million tons at 11% K_2O and the reserves of the carnallite zone are 180 million tons at 9.5% K_2O.

The Doukala Basin east of Safi has an inconsistent sylvite layer at the base of the upper salt with a maximum K_2O content of 6%. The lower salt has a thicker carnallite zone at a depth of 900-1,000 m (British Sulphur, 1985). In the Berrechid Basin east of Casablanca, carnallite is present in the evaporite sequence but does not form a discrete horizon. In the region between the Ziz and Guir Rivers near the Morocco and Algerian border, potash has been found in both Upper Triassic and Cretaceous evaporites.

Sulfur Resources

Elemental sulfur is imported to produce sulfuric acid for OCP phosphoric acid operations. No sulfur production in Morocco is indicated by Mobbs (2003). There are copper and lead smelting operations in Morocco; treatment of offgases could provide a minor amount of sulfuric acid.

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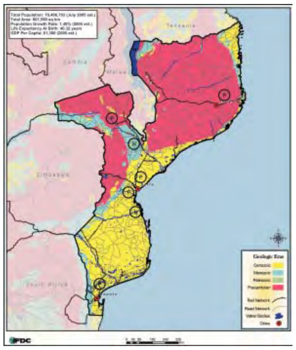
MOZAMBIQUE



The Republic of Mozambique is bordered to the north by Tanzania; the west by Malawi, Zambia, Zimbabwe, South Africa, and Swaziland; and the south and east by the Indian Ocean (Figure Mozambique 1). The total area is 801,590 km^2 and 5.1% of the land is arable. The population was estimated in mid-2005 as approximately 19.4 million inhabitants. Annual population growth was estimated at 1.48% (World Factbook, 2006). Agriculture occupies 81% of the labor force.

The transportation network consists of 5,685 km of paved roads, 24,715 km of unpaved roads, 2,933 km of 1.067-m-gauge railway, and 140 km of 0.762-m-gauge railway. There are 22 airports with paved runways and 136 airports with unpaved runways. Mozambique has 649 km of gas pipeline and 292 km of pipeline for refined products. There is 460 km of waterways. The Zambezi River is navigable to Tete. The main ports are Beira, Maputo, and Nacala.

More than 60% of the land surface of Mozambique is Precambrian age rock. Precambrian rocks in Mozambique can be divided into three units. Archean and Lower Proterozoic rocks outcrop near the Zimbabwe border and are composed of the greenstones, gneisses, and granites of the Zimbabwe Craton. The Middle Proterozoic to Upper Proterozoic is represented by the Irumide Belt and the Mozambique Belt. The Irumide Belt is located at the eastern margin of the Zimbabwe Craton and western Mozambique as a prolongation of the Irumide Belt of Zambia. The Mozambique Belt covers an extensive area of the country in the north. The Irumide Belt was metamorphosed about 1,300 million years ago and again during the Mozambiquian Orogeny (1,100-900 million years ago) (Mozambique Ministry of Mineral Resources and Energy, 2003). The third unit of the Precambrian is the Panafrican Cycle represented by rocks formed during the Katangian Orogeny (800-600 million years ago) and an intense thermo-tectonic event (500 million years ± 100 million years) with the emplacement of granites and pegmatites.

During the carboniferous period, rifting began, associated with sedimentation and widespread igneous activity. In Mozambique three main sedimentary basins formed. The intracratonic basin of the Zambezi Valley, Lunho River, and Lugenda River is filled with continental deposits and some volcanics. The southern coastal basin at the mouth of the Zambezi River to the Save/Limpopo River areas and the Rovum coastal basin at the border with Tanzania are filled with Mesozoic to Cenozoic age sediments.

Nitrogen Resources

Petroleum—Although natural gas fields were discovered in Mozambique in the 1960s by Gulf Oil, they remained unexploited due to the civil war and lack of a market. Three main onshore gas fields have been established—Pande, Temane, and Buzi Divinhe. Reserves are indicated by various sources as 63.71 billion m^3 (2002, estimated) (World Factbook, 2006) to 127 billion m^3 (Yager, 2003). In mid-2004 Sasol, South Africa, opened an 865-km pipeline from the Pande and Temane fields. The gas will be used to generate electricity at Sasol's Secunda plant and for applications at chemical plants.

Mozambique had its first offshore licensing round in March 2000—for an area covering 14 blocks mainly in the Mozambique Basin, which includes the shallow and deep Zambezi Delta

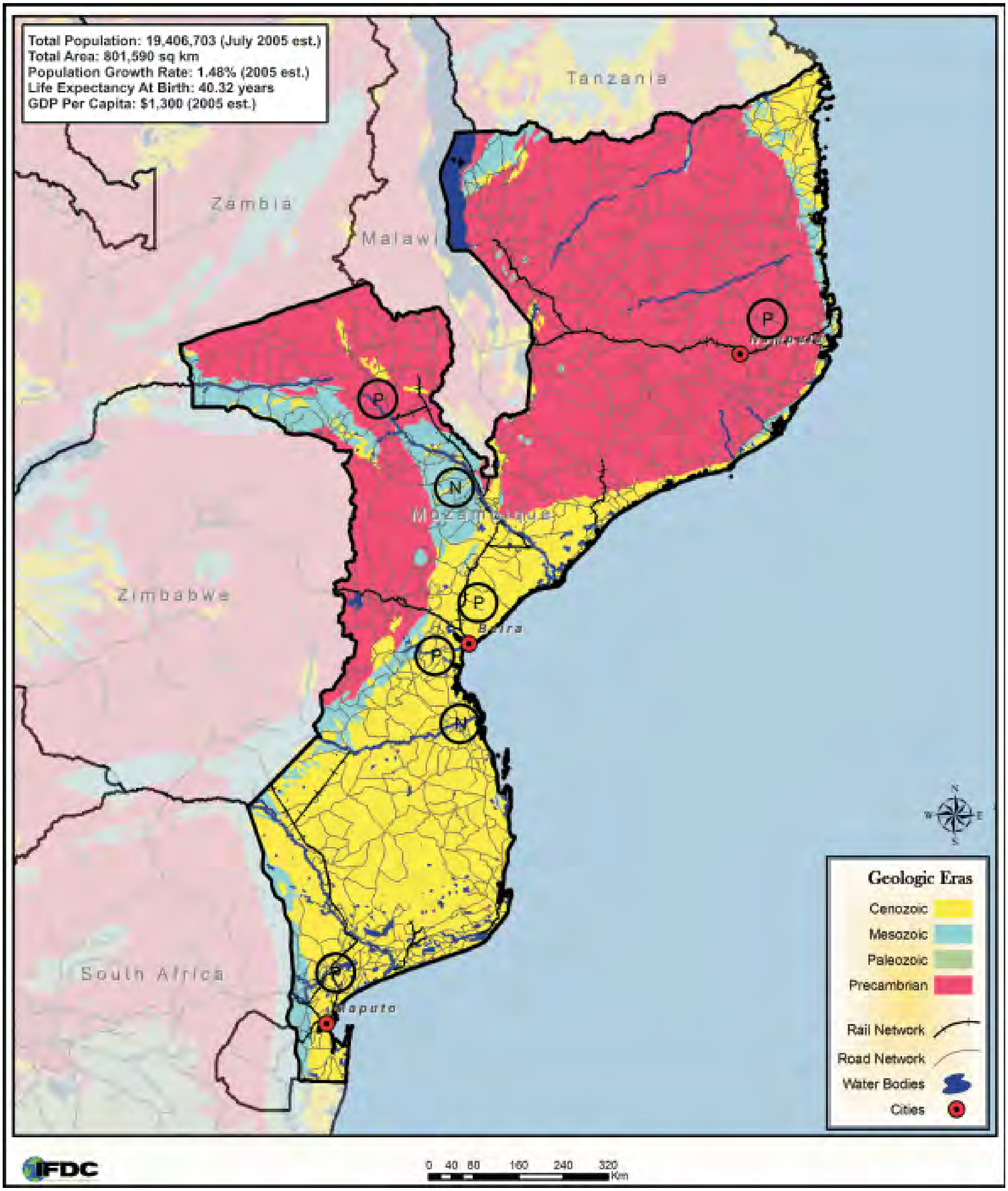


Figure Mozambique 1. Geology, Major Cities, and Transportation Network

(MBendi, 2006). The main oil and gas industry participants are Sasol Petroleum International, Enron Oil and Gas Resources Inc., Anadar KO, Energy Africa, Leapardus Resources Limited, Zarara Petroleum Resources, Total Fina Elf S.A., Trefoil Ltd., Lonrho de Provuma Petroleum, PETRONAS, British Petroleum, and Norsk Hydro. Western Geophysical has conducted several offshore seismic surveys. In 2006 Norsk Hydro signed an Exploration and Production Concession (EPC) contract for 14,500 km^2 offshore northern Mozambique in the Rovum Basin (Norsk Hydro, 2006).

Although no oil reserves have been established, the offshore Mozambique basins are considered good prospect areas by several experts (Matthews et al., 2001; Pawlowski et al., 2003). The area of the Mozambique Channel, and to the north, is also generating significant interest (Explorer, 2003).

Coal—Production of coal from the Moatize Coalfield in central Mozambique has been very limited because damage to the rail line cut off access to overseas markets. Output was 36,742 tons in 2003; 43,512 tons in 2002; and 8,753 tons in 1999 (Yager, 2003). Production fell off in the first half of 2003 due to problems with aging equipment. Coal was exported to Malawi in previous years. In 2003 the state-owned railway, Caminhos de Ferro de Mozambique (CFM), started the rehabilitation of the rail line.

In November 2004 Companhia Vale do Rio Doce (CVRD), Brazil, won the bid for rights to explore and develop the Moatize Coal Deposit (International Finance Corporation [IFC], 2004). The winning bid was US $122.8 million. CVRD is one of the largest steel producers in the world. Coal from the Moatize Deposit is prized because it is coking quality coal. The proposal includes an exploration program, feasibility study for a mine-mouth, coal-fired power plant with a capacity of 1,500 MW, a rail link to the intended port, and the development of port facilities. CVRD will also assess various other domestic potential industries linked to the mine including coking, steel, cement, aluminum, and ferroalloy plants. The expected annual production is 21 million tons of run-of-mine coal.

The prefeasibility study was to take 24 months at a cost of approximately US $35 million (CVRD, 2004). Preliminary estimates indicate production could start in 2009. Preliminary studies indicate that the deposit has a working life of 70 years at 21 million tons of raw coal per year from the mine. The project would produce 6.5 million tpy of coal suitable to produce coke, 3.5 million tpy of thermal coal for export, and 4.0 million tpy of coal for use in the power station at the mine.

An Indian company, Coal India Limited (CIL), is also interested in developing coal resources in Mozambique (*The Telegraph*, 2005).

Phosphate Resources

Igneous Deposits—Igneous phosphate deposits in Mozambique occur in metamorphic rocks, carbonatites, and within pegmatites.

Monte Muande—The Monte Muande Deposit is located about 30 km northwest of Tete on the northern bank of the Zambezi River. The deposit continues across the river and is known as the Monte Fema Deposit. Magnetite and apatite are associated near the top of Monte Muande Deposit and occur within marbles in a 4.5-km^2 area as stratiform bodies concordant with the foliation (Manhica, 1991). The magnetite deposits were studied by Nissko Company in 1960 and a Yugoslavian team in 1984.

Analysis of a composite sample from the deposit indicated a P_2O_5 content of 4.03% (Manhica, 1991). The Yugoslavian team divided the deposit into three primary zones (as indicated by Manhica, 1991):

High-grade iron (Fe) deposit
    Average Fe = 34.52%
    Average P_2O_5 = 5.12%
Moderate-grade Fe deposit
    Average Fe = 21.11%
    Average P_2O_5 = 5.25%
Low-grade Fe deposit
    Average Fe = 9.95%
    Average P_2O_5 = 4.02%

An eluvial deposit covers the marble area and averages 5.01% P_2O_5. The reserves were calculated as:

Eluvial deposit = 2,680,000 tons Fe and 295,000 tons P_2O_5
Primary deposit = 14,620,000 tons Fe and 3,855,000 tons P_2O_5
Total reserves = 17,300,000 tons Fe and 4,150,000 tons P_2O_5

Reserves of the primary zone were calculated to a depth of 140 m.

Evate Deposit—The Evate Phosphate Deposit is found within the Monapo Complex in Nampula Province of northern Mozambique near the port of Nacala and about 50 km from the coast. While Manhica (1991) describes the deposit as occurring as a marble and van Straaten (2002) indicates there is a metasedimentary sequence, Siegfried (1999) indicates the Monapo structure is one of the largest alkaline complexes on the earth. Siegfried refers to the apatite deposit as a carbonatite and indicates that all the rocks within the structure have been metamorphosed to the pyroxene amphobolite facies (Figure Mozambique 2). Although metasediments are recognized in the complex, Siegfried (1999) indicates the presence of enriched thorium and rare earth elements, and a potassium-fenite aureole around the Evate Carbonate occurrence suggests it is a carbonatite. Manhica (1991) indicated the following reserves at Evate:

Apatite—Category C2: 92 million tons
Apatite Ore—Category C1: 31 million tons, 9.59% P_2O_5

Manhica (1991) indicates that the eluvial enriched zone (14%-18% P_2O_5) represents over one-fourth of the reserves. The apatite content of the carbonatite is 15%-30%. Some layers are richer and some are poorer, and only in the contact zones with the gneisses does the apatite content reach 40% to 50%.

A later study further explored the deposit and included ore-dressing studies (Manhica, 1991). Reserves were indicated as 155,413,000 tons of apatite at 9.32% P_2O_5, 5.76% Fe, 1.12% TiO_2, and 47.69% CaO to a level 100 m above sea level.

Norsk Hydro was investigating the Evate Deposit in 2000. Reports at this time indicated reserves of 60-70 million tons of loose ore containing 33% apatite (Nacala Development Corridor, 2006) and 200 million tons at 9.8% P_2O_5 (MBendi, 2000). It was reported that Norsk Hydro was performing beneficiation tests and looking for a cost-effective mechanism for “liberating” the chlorine. When chlorine-containing apatites are acidulated, the resulting phosphoric acid is generally very corrosive. No further details concerning the Norsk Hydro study were available.

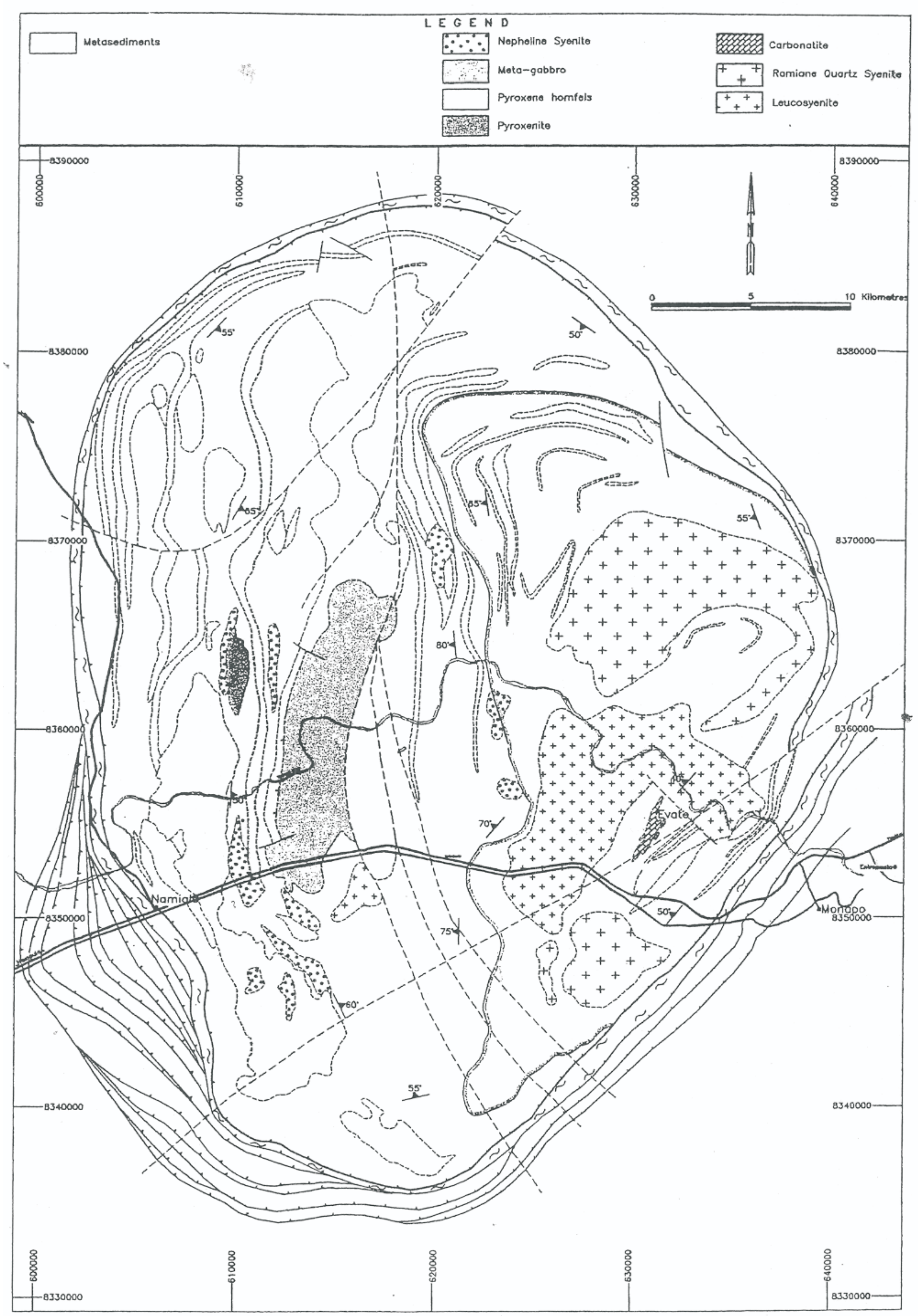
Analyses of two composite samples from Evate are given in Table Mozambique 1. The high CaO/P_2O_5 ratio of the samples indicates that calcite and dolomite are present and the samples are from the carbonatite.

Table Mozambique 1. Composite Samples From the Evate Deposits, Mozambique[a]

Chemical Analysis	Sample 1	Sample 2
P_2O_5	10.96	6.29
Fe_2O_3+FeO	7.8	2.86
CaO	46.25	47.17
MgO	4.26	2.90
TiO	1.63	0.52
SiO_2	1.50	0.67
Al_2O_3	0.70	0.37
CaO/P_2O_5	4.22	7.50

a. Data from Manhica (1991).

Other Igneous Occurrences—Apatite is found in hydrothermically affected zones of the Xiluvo carbonatite. The P_2O_5 content of selected samples ranges from 1.39% to 6.08% P_2O_5. Apatite is associated with buff carbonates in the Cone Negose carbonatite of Middle Jurassic-Upper Cretaceous age. The average P_2O_5 content is only 1%-2%, but zones containing up to 60% apatite occur (Manhica, 1991).



Source: Siegfried (1999).

Figure Mozambique 2. Geological Map of the Monapo Complex

Fracture zones in the Luicuisse carbonate, situated about 240 km northeast of Lioninga in Niasse Province, contain apatite. In some sectors the eluvial deposit is over 30 m thick. Apatite was determined in about 34% of the samples (Manhica, 1991). The mean P_2O_5 content was 2.34% in 84.4% of all samples containing apatite.

Apatite also occurs in several pegmatites in Mozambique, including the Nahora, Morrua, Ilodo Nuaparra pegmatites. While chemical analyses indicate that individual samples are essentially pure apatite (Manhica, 1991), these appear to be very limited occurrences.

Sedimentary Deposits—Manhica (1991) reported that sediments containing 0.7% to 3.1% P_2O_5 are located near Magude, north of Maputo. Davidson (1986), Cilek (1989), Manhica (1991), and Notholt (1994) speculated on locating sedimentary phosphate in Mozambique; however, no distinct deposits have been found.

Manhica (1991) reported that exploration for bat guano had been conducted in all areas of Mozambique with karst topography. The following chemical analyses and reserves are indicated:

Chemical Analysis	Vilanculos Area	Buzi Area	Cheringoma
		(%)	
NO_3	5.22	3.26	2.74
P_2O_5	3.32	3.88	5.14
K_2O	2.95	1.52	1.37
Reserves (tons)	30,000	132,700	600,000

Between 1953 and 1960, about 6,000 tons of guano was extracted at Vilanculos and 1,000 tons was extracted from the Buzi area.

Sulfur Resources

Cilek (1989) indicated that gypsum/anhydrite beds occur at depth (150-200 mm) in an evaporite sequence in the Temane Formation. The beds are 10-15 m thick.

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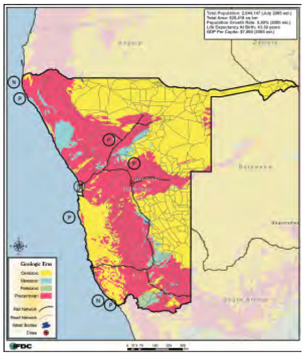
Namibia



The Republic of Namibia (Figure Namibia 1) is bordered by Angola and Zambia to the north and northeast; Botswana to the east; South Africa to the east and south; and the Atlantic Ocean to the west. The total area is 825,418 km^2 and approximately 1% of the land is arable. The population was estimated in mid-2005 as 2.0 million inhabitants. Annual population growth was estimated at 0.59% (World Factbook, 2006). Agriculture occupies about 47% of the labor force.

The transportation network comprises 5,406 km of paved roadways, 36,831 km of unpaved roadways, and 2,382 km of 1.067-m-gauge railway. There are 21 airports with paved runways and 115 airports with unpaved runways. Luderitz and Walvis Bay are the main ports.

Precambrian rocks are exposed over large areas of western Namibia (Figure Namibia 1). Large areas of eastern and northern Namibia are covered with Khalihari sands.

The Precambrian rocks of Namibia can be divided into the Vaalian (>2000 Ma) to Lower Mokolian (2000-1800 Ma), the Mokolian (1800-1000 Ma), and the Namibian (1000-570 Ma). The Vaalian to Lower Mokolian age rocks, composed of undifferentiated metamorphic complexes and an anorthite complex, are located primarily in the southern third of the country. Mokolian age rocks are mainly metamorphics and volcanoclastics and are located in the southern half of the country.

Namibian age rocks are represented by the Richtersveld Granite/Syenite Complex in the north, the Damara Sequence (mainly sedimentary rocks) in the north and central Namibia, the Gariep Complex in extreme southern Namibia, and the Damaran Granites. The Damaran Granites cover an extensive area in the center of the country and extend to the north to the border with Angola.

The Nama Group may transcend the Precambrian and is thought to be mainly Cambrian in age (Dierks, 1994). The group is situated in southern and southwestern Namibia. It consists of a relatively unmetamorphosed succession of marine sandstones, limestones, and shales. Several intrusions of granites, carbonatites, and other rock types intruded the sequence at about 500 Ma.

The Karroo (Karoo) sequence has a geological age of 400 to 120 Ma from the Carboniferous to Cretaceous. The main rocks encountered in this sequence are tillites, dolomites, mudrocks, shales, and sandstones. At the end of the Karroo, extensive volcanics (basalt flows) were laid down in northwestern Namibia. Post-Karroo intrusive complexes are mainly found in west-central Namibia. Numerous kimberlites were implanted in southern Namibia at the end of the Cretaceous. Cenozoic sedimentary deposits are found in the coastal basins and offshore. The Kalahari sequence of Tertiary to Quaternary ages forms an extensive cover of terrestrial origin in the eastern and northern parts of the country.

Nitrogen Resources

Offshore exploration in Namibian waters began in 1968 in areas held by various operators and resulted in the discovery of the Kudu Gas Field by Chevron in 1973 (MBendi, 2005). Shell Exploration and Production Namibia B.V. (75%), ChevronTexaco (12.5%), and Energy Africa Ltd. (12.5%) held the rights to the field. The government and the consortium tried to work out a plan to develop the field.

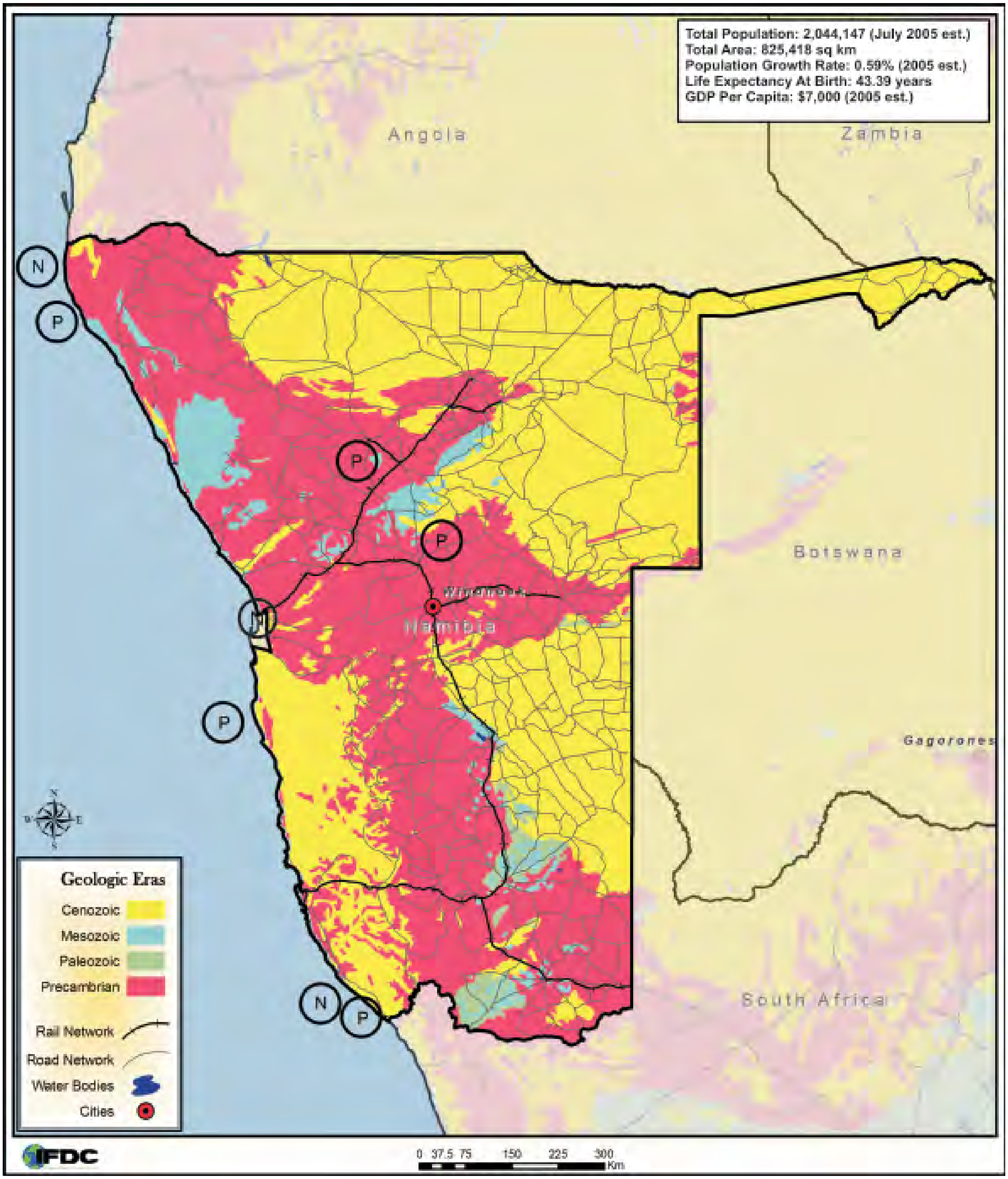


Figure Namibia 1. Geology, Major Cities, and Transportation Network

Shell withdrew from the project in September 2002, and ChevronTexaco relinquished its interests in December 2003 (Coakley, 2003). Proven natural gas reserves at Kudu were estimated at 36.8 billion m^3, which was well short of the 142 billion m^3 needed to justify a proposed floating liquefied natural gas (LNG) facility at a cost of US $2.5 billion.

Currently, Tullow Oil holds a 90% operating interest in Production License 001 over the Kudu Gas Field (Tullow Oil, 2006). In 2004 a Joint Development Agreement was signed with National Petroleum Corporation of Namibia (NAMCOR) for development of the field as part of a gas-to-power project. The project involves offshore development and piping of the gas to shore for treatment and delivery to an 800-MW power station to be developed and operated by Nam Power at Oranjemund. The front end engineering design (FEED) study for a four-well subsea development and onshore gas-conditioning plant has been completed; invitations to bid for various construction contracts have been prepared and were expected to be issued in early 2006. The Environmental Impact Assessment for the upstream development has been approved by the Ministry of Mines and Energy.

Other oil companies that have been or are currently working offshore Namibia include Norsk Hydro, Ranger Oil, ExxonMobil, Vanco Energy, INA Industrija Naffe (the Croatian oil company), EnerGulf Resources, Sonangol (the state oil company of Angola), and Hunt Oil. It was reported (Coakley, 2003) that Vanco Energy drilled in block 1711 (Kunere Prospect) where reserves were estimated to be 700 million barrels of oil and 170 billion m^3 of gas. The Vanco website (www.vancoenergy.com) does not offer any information on Namibia exploration.

Limited amounts of nitrates have been found in areas of the coastal Namib Desert (Schneider and Genis, 1992a).

Phosphate Resources

Igneous Deposits—Carbonatite complexes in northern Namibia occur in a belt that extends from Cape Cross to the northeast for about 400 km. These complexes of Late Karroo age intrude metamorphic rocks of the Damara System and the Salem Granite. These carbonatites have been correlated with similar intrusions in Brazil (Marsh, 1972).

The Ondurakorume Carbonatite Complex is located about 13 km northeast of Kalkfeld. The carbonatite plug, about 1.4 m in diameter, has beforsite ring dikes that contain apatite. Sampling by African Metals Corporation Limited in 1964 showed up to 17.3% P_2O_5 and averaged about 7% P_2O_5 (Savage, 1987).

The P_2O_5 contents of several other complexes are indicated in the following table, based on data in McManus and Schneider (1994), Pirajno (1994), and Savage (1987).

Complex	Location	P_2O_5 Content
		(%)
Epembe Carbonatite	Southwest of Swartbooisdrif	3.5
Okorusu Carbonatite	Ofjiwarongo District	3–4
Kalkfeld Carbonatite	Near the Village of Kalkfeld	6.7
Osongombe Carbonatites	Southwest of Kalkfeld	6.5
Otjisazu Pyroxenite	Southeast of Kalkfeld	3–9

Schneider and Schreuder (1992) note that the Otjisazu Pyroxenite Complex contains indicated reserves of 35 million tons of 3% to 9% P_2O_5 to a depth of 30 m.

Sedimentary Deposits—Sedimentary phosphates occur offshore on the Namibian shelf. Bremmer and Rodgers (1990) have divided these sedimentary phosphorites into three types: (1) phosphorite sands, (2) rock phosphorite, and (3) concretionary phosphorite. The phosphorite sand occurs in three principal deposits in the north, central, and southern areas (Figure Namibia 1). The northern deposit, which measures about 400 km in length and 40 km in width, lies mainly on the landward side of the 200-m isobath. The central deposit, which lies off and to the south of Walvis Bay, is the largest; it measures 550 km in length and 70 km in width, and it is located between the 100- and 500-m isobaths. The southern deposit is approximately 100 km long and 30 km wide; it lies mainly between the 100- and 200-m isobaths.

X-ray analysis indicates that the apatite of the offshore deposits is the carbonate-substituted variety francolite. Age dating places the formation of the deposits between Miocene and Recent times. Young phosphorites with high carbonate substitution are among the most suitable of all phosphates for direct application (Van Kauwenbergh, 2001).

Bremmer and Rodgers (1990) indicate 3,020 million tons of total resources in the offshore deposits for sandy and concretionary phosphorite at a thickness of 10 cm in areas with greater than 5% apatite. A breakdown of these resources is given in Table Namibia 1. Schneider and Schreuder (1992) indicate 1,430 million tons of P_2O_5 with grades exceeding 4.6% P_2O_5 in the offshore sediments between Walvis Bay and Luderitz.

Table Namibia 1. Phosphate Resources on the Namibia Shelf[a]

Deposit/Type	P_2O_5	Resources[b]
	(%)	(tons x 10^8)
Northern Phosphorite Sand Deposit		
Pelletal	9.1	1.7
Glauconitized pelletal	14.4	3.2
Central Phosphorite Sand Deposit		
Pelletal	21.6	20.0
Glauconitized pelletal	9.5	2.5
Southern Phosphorite Sand Deposit		
Pelletal	7.4	1.8
Concretionary Phosphorite Deposit	10.8	1.0

a. In areas with >5% apatite in samples.
b. To a depth of 10 cm.

Guano has been produced since the 1800s from 13 islands off the Namibian coast (Hutchinson, 1950). In 1931 artificial roosting platforms were erected on the islands. Total production from 1844 to 1991 was approximately 870,000 tons (Schneider and Schreuder, 1992). The guano typically analyzed 20% to 40% N and 21% to 29% P (van Straaten, 2002).

Small amounts of bat guano have been harvested from caves in the Windhock District and near Karibib (Schneider and Schreuder, 1992).

Sulfur Resources

North of the Walvis Bay area limited amounts of gypsum were produced in the late 1960s from a bed less than 1 m thick. The total reserves in the Tumas area amount to approximately 4 million tons (Schneider and Genis, 1992b). Several million tons of material containing between 30% and 90% gypsum have been located in the Walvis Bay coastal area.

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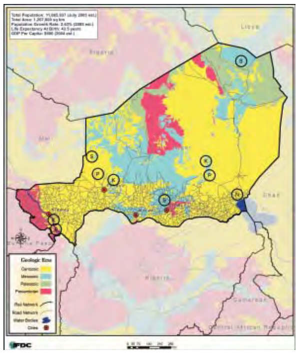
NIGER



The Niger Republic is landlocked by Benin and Nigeria on the south, by Algeria and Libya on the north, by Mali and Burkina Faso on the west, and by Chad on the east. The total area is 1,267,000 km^2; 3.5% of the land is arable. The population was estimated in mid-2005 at 11.7 million inhabitants (World Factbook, 2006); most of the population is concentrated in the more fertile southern part of the country that represents 10%-12% of the entire territory. Approximately 90% of the population is involved in agriculture and herding. The annual population growth rate is estimated to be 2.6%.

The road network (Figure Niger 1) consists of 798 km of paved roads and 9,302 km of secondary roads. Access to the sea is either through Burkina Faso to Togo and Côte d'Ivoire or through Benin. The Trans-Saharan international road runs through Agades and Zinder and allows Niger to be in contact with Algeria to the north. Desert roads also link Niger to Libya. The Niger River is navigable only between Tillaberi and Niamey (95 km) and between Niamey and Gaya (185 km) from June to October. There are no railroads in Niger.

Geologically, Niger is formed by two sedimentary basins containing Cambrian to Recent formations that are bordered by granitic and metamorphic basement complexes. To the west, north, and east the Iullemenden (or Iullemmeden, Iullemeden, Iullmedden) Basin (Figure Niger 2) is bordered by the Hoggar Chain and its southern extensions—the Adrar of Iforas and Aïr Massifs. To the south the Iullemenden Basin is bordered by the Nigerian Massif. The Precambrian massifs of Gourma and Liptako form the southwestern boundary and the Damagaran and Mounio Massifs form the southeastern boundary. In the extreme southwest border with Benin and Burkina Faso, the Iullemenden Basin is bordered by Precambrian sediments and intrusives. The Iullemenden Basin is filled with sediments of Paleozoic to Recent ages. During the Paleozoic, Mesozoic, and Tertiary ages, marine transgressions from the northeast and northwest crossed the area and overlapped previous transgressions.

To the east of the Aïr and north of the Damagaran and Mounio Massifs is the Chad Basin, which contains Cretaceous to Recent age sediments. The northwest part of the Chad Basin is known as the Djado Basin in Niger.

Nitrogen Resources

Petroleum—In 2005 Petroliam Nasional Berhad (PETRONAS) and ExxonMobil announced the discovery of oil in the Agadem Basin in the Agadem Block 1 permit area (PETRONAS, 2005). Each of the companies owns a 50% interest in the permit, and PETRONAS is the operator. The Jaouro-1 exploration well was drilled to a total depth of 2,462 m. Production tests resulted in a maximum flow rate of 2,540 barrels per day (bpd). Confirmed recoverable oil resources on the permit thus far amount to 300-350 million barrels (Bermúdez-Lugo, 2003; ExxonMobil, 2006)

Coal—The Anou Araren Deposit is the only coal deposit recognized in Niger. Discovered in 1964 by the Commissariat à l'Energie Atomique (CEA), detailed prospecting was carried out by CEA-Compagnie Générale des Materiès Nucléaires (COGEMA) (Franconi et al., 1981). In 1976 Société Française d'Etudes Minières (SOFREMINES) studied the exploitation of the deposit for Société Nigériene de Charbon (SONICHAR) in order to build a power plant to provide 32 MW to the

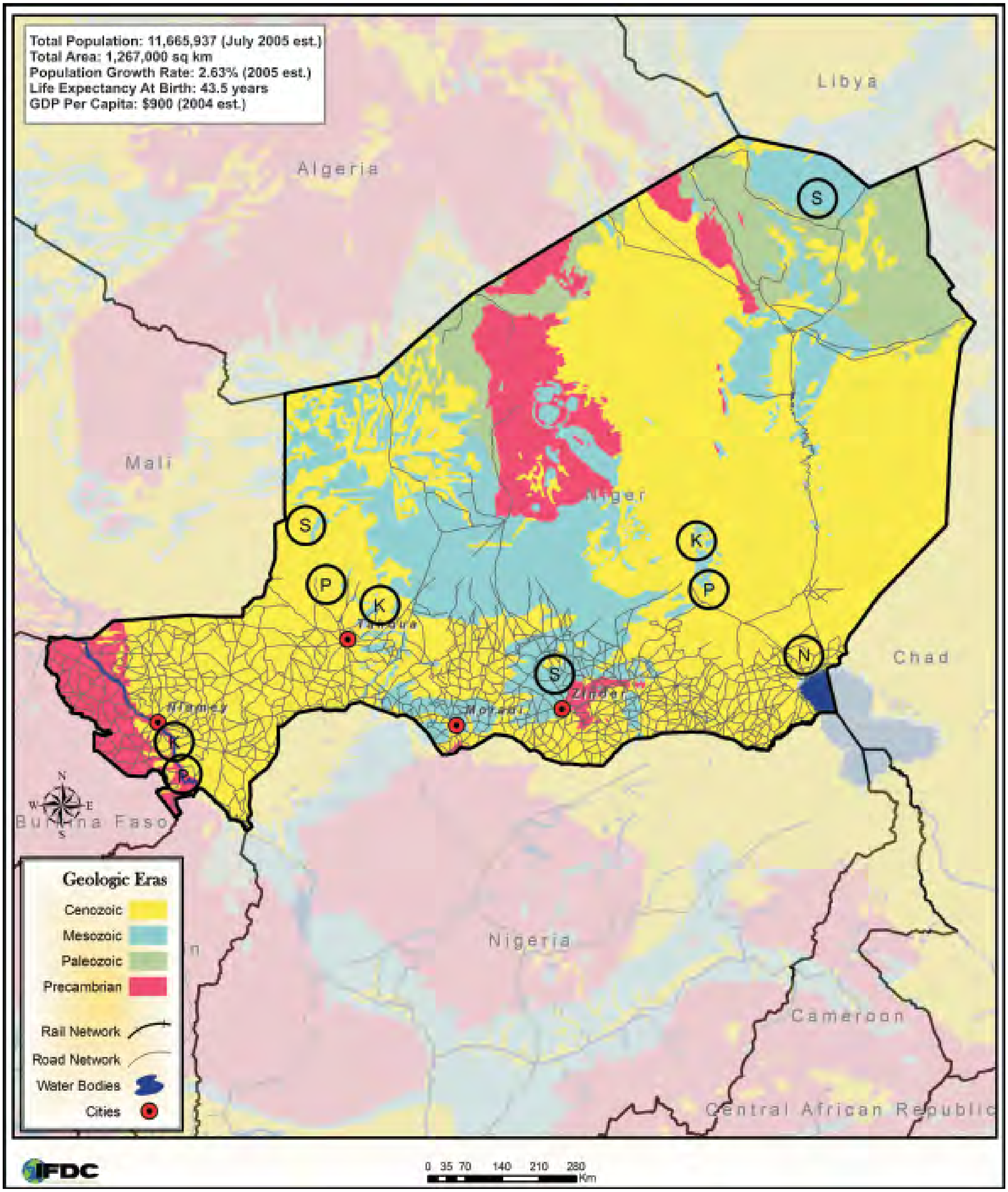


Figure Niger 1. Geology, Major Cities, and Transportation Network

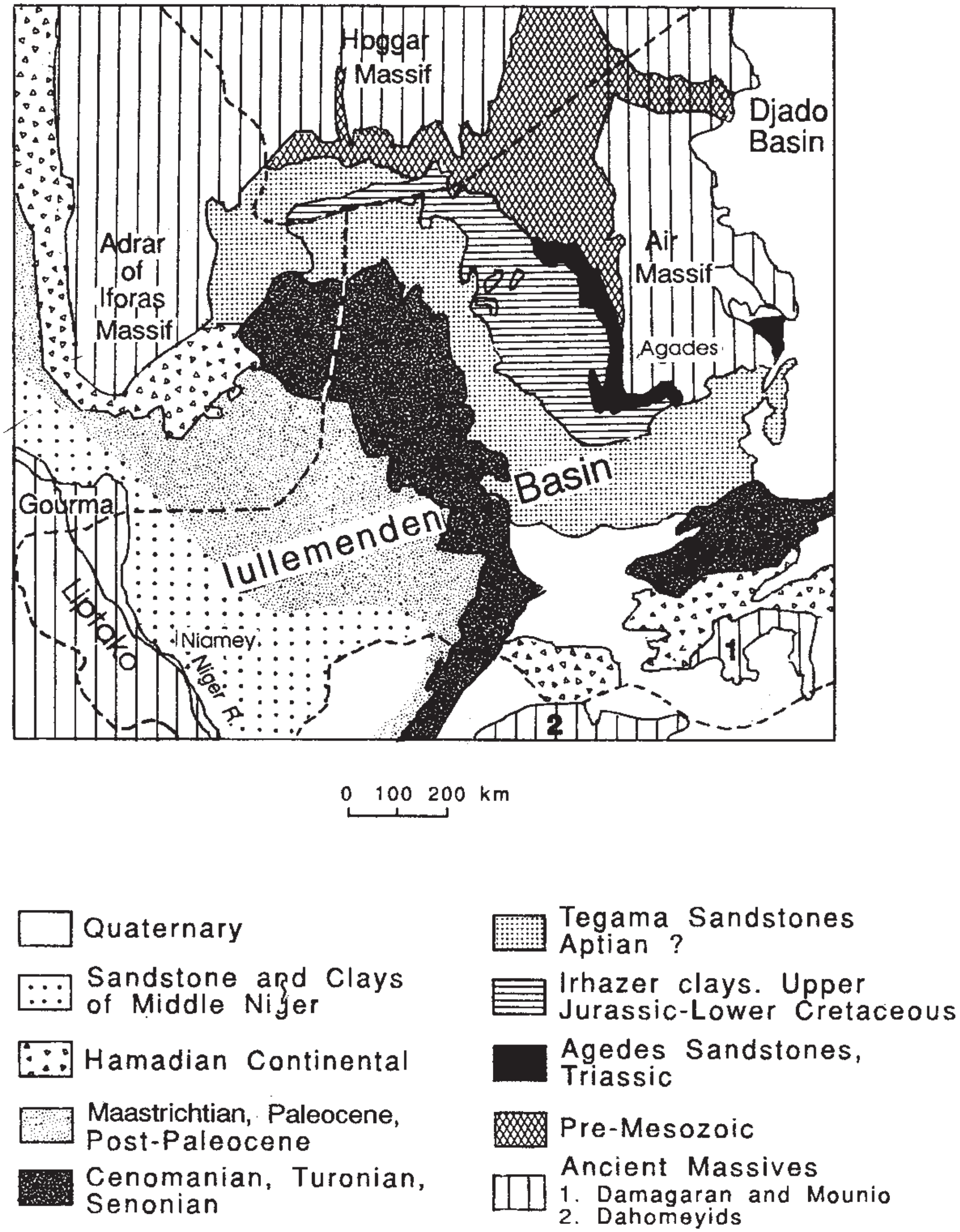


Figure Niger 2. General Geologic Map Showing the Post-Paleozoic of Niger

uranium industry located in the Doulingen Basin. The Anou Araren Deposit is 35 km north of Agades and 180 km south of Arlit. The coal is of Visean age, and reserves were estimated in 1983 at 14 million tons. Coal production in 1985 was 150,635 tons. Bituminous shale occurs in the Djado Basin and Kao area in Cretaceous formations (Greigert, 1966).

Phosphate Resources

The phosphate deposits of Niger contain resources of more than 1.2 billion tons. The Tapoa Deposit is the largest single phosphate deposit in West Africa. The Tahoua Deposit has been exploited and other deposits have been studied in the Ader Doutchi (or Adar Doutchi) area.

Ader Doutchi Area Phosphates—Roure (1948) described coprolitic phosphate beds in the Iullemenden Basin (Figure Niger 2) near Barmou, northeast of Tahoua. Greigert (1966) confirmed that the Cenozoic phosphate beds reported at Annekeur (or Innakeur, In Akker, Anekeur, Anneker) and in the Gaoy (or Gaoye, Gaweye) sector (600 km northeast of Niamey and 65 km north of Tahoua) shared similar characteristics with the occurrences known in the Tilemsi Valley of Mali. This discovery established the continuity of these phosphate beds for more than 600 km (Greigert, 1966; Hanon, 1985). To the south these phosphates may be correlated to phosphate beds in the Sokoto area of Nigeria.

Figure Niger 3 shows a reconstruction of the lithostratigraphy of phosphate-bearing formations of the Ader Doutchi area. The phosphates formed in marine and confined environments and are associated with carbonates and fissile-laminated clays, which contain palygorskite. There were two phosphogenic episodes in the Iullemenden Basin. The main phosphate-producing period occurred after marine transgressions T4 and T5 (Figure Niger 4). Emersion periods are marked by the occurrence of evaporites and karstification. The Lower Eocene phosphate occurrences in the Ader Doutchi area are the most important.

Tahoua Area Phosphates—Greigert and Pougnet (1967) examined the Lower Eocene beds north of Tahoua near Annekeur and provided some analyses (31%-33% P_2O_5). The Nigerien and Canadian governments became interested, and Dumas (1971) prospected with pits and trenches for the Canadian International Development Agency (CIDA) in a 500-km area near Tawaswas (Annekeur sector).

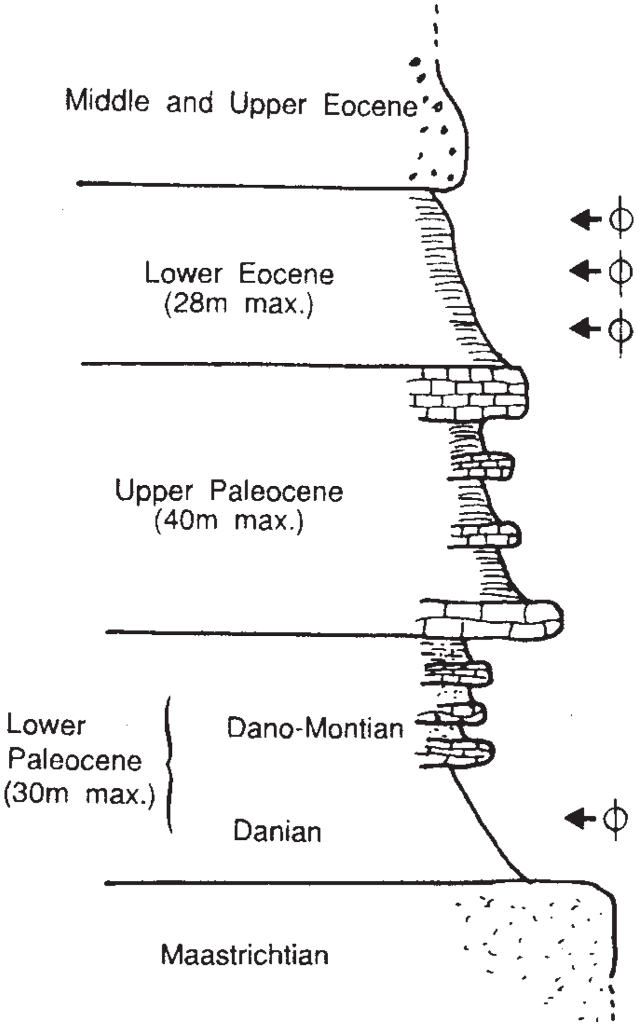


Figure Niger 3. Synthetic Stratigraphic Column of the Cenozoic in the Iullemenden Basin (Tahoua Area) and Location of Phosphate (Φ) Occurrences

The phosphatic Garadoua Formation is composed of alternating clays, marls, and limestones of Lower to Middle Eocene age and is overlain by superficial formations (dunes, sands, eluvium, laterites) of the so-called “Continental Terminal.” Phosphate nodules of variable size and morphology are mostly located in the upper middle part of the formation within a clay sequence. The phosphate nodules are found in discontinuous beds that are somewhat randomly distributed within the clays. The

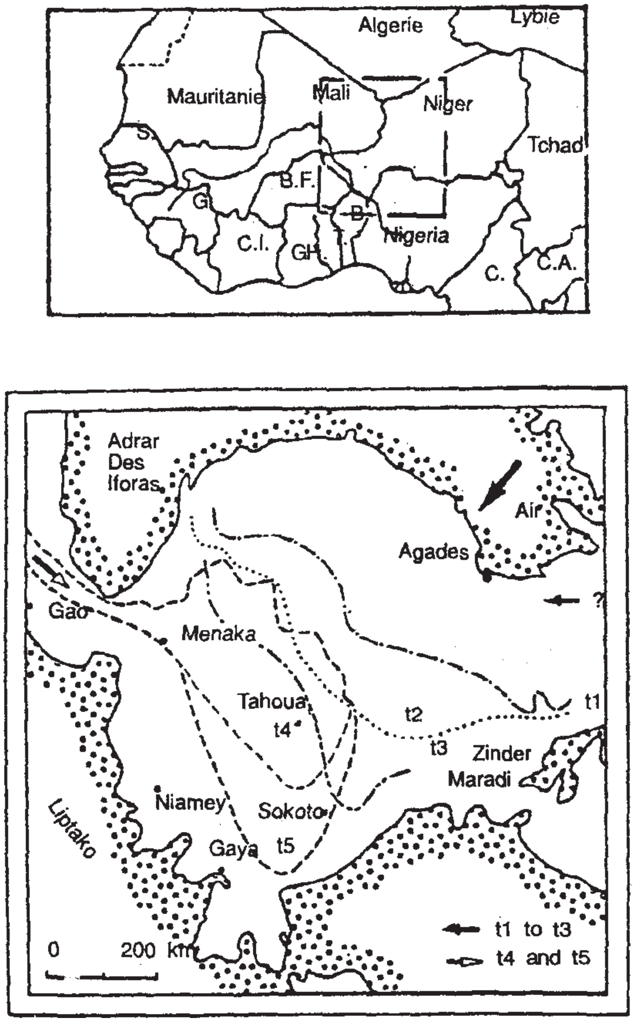


Figure Niger 4. Marine Post-Paleozoic Transgressions in the Iullemenden Basin (After Greigert, 1966 and Petters, 1979). T1, Upper Cenomanian Transgression With Neolobites; T2, Lower Turonian Transgression With Neolobites and Nigericeras; T3, Maastrichtian Transgression With Libycoceras; T4, Dano-Montian Transgression With Libycoceras; T5, Upper Paleocene Transgression

shape of the phosphate nodules ranges from spherical to discoidal to elongate. The length of some nodules may reach 75 cm. The nodules are light yellow or white in color and are generally covered by a goethic/limonite pedicule. Five beds containing nodules are recognized, and the average total thickness of the entire formation is 6 m either without overburden or with very thin overburden.

Chemical analyses by the United States Agency for International Development (USAID) and Office National des Ressources Minières (ONAREM) on Gaoy nodules (Table Niger 1) indicate 28.7%-32.7% P_2O_5. Several phosphate samples were collected from the Gaoy area by a joint IFDC-Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) mission during 1989 and chemically analyzed (Table Niger 2). Two samples of nodules from Tahoua were previously analyzed at IFDC (Table Niger 3).

Samples WANTA1, R231.90, and R232.08 are weathered nodules collected at or near the surface. The P_2O_5 contents of these samples range from 23.0 to 30.4 wt %. The main impurities are SiO_2 (8.5-25.8 wt %) and Fe_2O_3 (5.7-10.3 wt %).

Sample WANTA2 is higher in grade (33.8 wt % P_2O_5) (Table Niger 2) and was collected from a steep-sided ravine near Gaoy. The phosphate nodules were encased in bluish clays about 2 m below the surface of the land and about 1 m below the iron-stained oxidation zone. The nodules were white and without the characteristic iron staining or pedicule that typifies nodules collected at or near the surface. The nodules are soft and difficult to extract from the clays without breakage. Nodules at or near the surface are highly indurated. The chemical analysis indicates that the nodules in the clay matrix have a much lower Fe_2O_3 content (2.4%) than nodules from the surface.

Table Niger 1. Chemical Analyses of Tahoua Phosphate Nodules

	USAID Analysis	ONAREM Analysis
	(%)	
P_2O_5	28.7	32.7
CaO	43.9	27.98
SiO_2	7.9	6.3
Fe_2O_3	13.0	1.57
Al_2O_3	2.1	2.17
MgO	0.2	0.58
Na_2O	–	0.10
K_2O	–	0.05
U_3O_8, g/ton	–	26.0

Table Niger 2. Chemical Analyses of Phosphate Rock From the Tahoua Area[a]

	WANTA1 Nodules at Surface, Near Gaoy	WANTA2 Fresh Nodules in Shale, Near Gaoy	WANTA 3 Base of Section, Transition to Limestone[b]
	(wt %)		
P_2O_5	30.4	33.8	14.5
CaO	42.1	46.1	24.0
F	3.4	3.6	1.8
SiO_2	8.5	7.1	25.0
Fe_2O_3	5.7	2.4	5.0
Al_2O_3	2.9	2.5	4.5
K_2O	0.2	0.1	0.2
Na_2O	0.1	0.2	0.3
MgO	0.3	0.8	3.8
$C1^-$ (ppm)	35	35	60
S	0.1	0.3	0.2
CO_2	1.7	1.4	5.4
Free H_2O[c]	1.2	1.3	5.5
LOI[d]	5.5	5.2	16.6
NAC P_2O_5[e]	1.9	2.3	3.6[f]

a. Collected during joint IFDC-BGR mission, 1989.
b. About 5 km south of Gaoy, non-nodular samples.
c. Free H_2O = weight loss, 105°C, 1 h.
d. Loss on ignition = weight loss, 1000°C, 1 h.
e. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).
f. Second extraction.

Crystallographic analysis of the apatites of nodular phosphates from the Tahoua area indicates a range in unit-cell a-values from 9.352 Å ± 0.001 to 9.358 Å ± 0.001 (Table Niger 4). Sample WANTA2, collected from below the land surface, has crystallographic properties similar to surface samples. At an average a-value of 9.356 Å ± 0.001, based on established statistical models, the composition of the apatite would be:

$$Ca_{9.87}Na_{0.09}Mg_{0.04}(PO_4)_{5.61}(CO_3)_{0.39}F_{2.16}$$

The apatite is a carbonate-substituted francolite. The maximum P_2O_5 content in a 100% francolite concentrate is predicted to be 39.96 wt % and the CO_2 content would be about 1.7 wt %.

The measured neutral ammonium citrate (NAC) solubilities of the nodular samples of 1.9%-2.5% P_2O_5 are at or slightly below predicted NAC solubili-

Table Niger 3. IFDC Analyses of Tahoua Phosphate Rocks

	Sample No. R231.90	Sample No. R232.08
	(wt %)	
P_2O_5	27.90	23.0
CaO	39.00	30.1
F	2.8	2.4
SiO_2	11.7	25.8
Fe_2O_3	10.3	8.5
Al_2O_3	2.1	2.3
K_2O	0.12	0.08
Na_2O	<0.01	0.21
BaO	–	0.28
MgO	0.20	0.19
MnO	–	0.62
Cl^- (ppm)	50	19
S	0.8	0.20
CO_2	1.5	1.1
Free H_2O[a]	0.7	–
LOI[b]	5.1	4.7
NAC P_2O_5[c]	2.5	2.3

a. Free H_2O = weight loss, 105°C, 1 h.
b. Loss on ignition = weight loss, 1000°C, 1 h.
c. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).

Table Niger 4. Chemical and Crystallographic Analyses of Niger Phosphate Rocks

Deposit/ Sample Number	Total P_2O_5	R_2O_3	Apatite Unit Cell a-Value	Predicted NAC P_2O_5	Measured NAC P_2O_5
	(wt %)		(±0.001 Å)	(%)	
Tahoua					
WANTA1	30.4	8.6	9.352	3.3	1.9
WANTA2	33.8	4.9	9.356	2.8	2.3
WANTA3	14.5	9.5	9.331	5.6	3.6
R231.90	27.9	12.4	9.357	2.7	2.5
R232.08	23.0	10.8	9.358	2.6	2.3
Tapoa					
WANT3	27.5	3.5	9.362	2.1	1.8
WANT4	13.1	2.3	9.358	2.6	1.4
R231.63	29.0	2.2	9.357	2.7	2.1
R231.56	28.7	2.2	9.359	2.5	2.3
R231.64	33.5	2.3	9.356	2.8	2.8
Mekrou					
WANM1	26.8	4.4	9.365	1.8	1.5

ties of 2.6%-3.3% P_2O_5 (Table Niger 4). The crystallographic properties and measured NAC solubilities are typical of apatites from highly weathered or metamorphosed sedimentary phosphate rocks and are approaching the NAC level of igneous apatites without carbonate substitution (0.4%-1.6% NAC P_2O_5). Phosphate rocks with such low levels of NAC solubility are not generally recommended as direct-application P_2O_5 sources.

Sample WANTA3 was collected about 5 km south of Gaoy from a bed that was said to be the transition to the carbonates below the main phosphatic clay beds. The apatite particles of this sample range from brown to light gray in color and may be up to 5 mm in diameter. The phosphate particles in this bed are relatively fine compared to the nodular phosphates in the area. The P_2O_5 content is 14.5 wt % and the apatite content would be about 40%. The gangue minerals are palygorskite, quartz, and carbonates.

Crystallographic analysis of the apatite of sample WANTA3 (Table Niger 4) indicates it is a highly carbonate-substituted francolite (a-value = 9.331 Å). Based on previously established statistical models, the composition of the apatite would be:

$Ca_{9.62}Na_{0.27}Mg_{0.11}(PO_4)_{4.98}(CO_3)_{1.02}F_{2.41}$

The maximum P_2O_5 content in a 100% francolite concentrate is predicted to be 36.26 wt % and the CO_2 content would be about 5 wt %.

The analyzed NAC solubility on a WANTA3 sample, extracted twice to remove free carbonates, was 3.6% P_2O_5 (Table Niger 4). This is well below the predicted NAC solubility of 5.6% P_2O_5. However, this level of solubility is generally above the level of NAC solubility for nodular phosphates in the area of 1.9%-2.5% P_2O_5. The NAC solubility of this sample is approaching the level of NAC solubility of Tilemsi Valley (Mali) phosphate rock, a rock that has been successfully used for direct application.

It is not known how extensive these beds are in the area. Although some prospecting has been done, the primary focus was on coarse nodular phosphates associated with laminated clay beds. Fine-grained phosphates, at or below the base of the clay section, may have been overlooked.

The CIDA study (Dumas, 1971) analyzed samples from over 30 pits and trenches in the Annekeur area and determined that the average percentage of nodules in the beds (+11.1 mm) was less than 2% (Table Niger 5). The average P_2O_5 content of the nodules ranged from 21.2% to 24.6%. Dumas (1971) did not give an estimate of the resources of the area.

Table Niger 5. Results of Canadian Prospecting in Annekeur Area

Bed	Number of Samples	Percentage of Nodules[a]	P_2O_5 Content of Nodules
			(wt %)
e^{2b}	1	0.0	–
e^{2c}	10	1.7	23.2
e^{2d}	9	0.3	23.8
e^{2e}	26	1.8	24.6
e^{2f}	9	1.7	21.2
e^{2g}	2	0.6	22.0

a. Weight percent of total weight of samples, +11.1-mm fraction.

Source: Dumas (1971).

Based on the results of the Dumas (1971) study, Franconi et al. (1981) estimated the resources of the area. The criteria for the estimate were (1) an area of 65,937,500 m^2; (2) the P_2O_5 contents of beds e^{2f}, e^{2e}, and e^{2c}; (3) bed thickness; and (4) a bulk density of 2 tons/m^3. On this basis the resources of the area were considered to be about 7.4 million tons at an average of 23% P_2O_5.

This estimate does not appear to be an indication of minable resources but rather of total resources in this area. The literature is not clear whether the area in question is the total area investigated or the area of the outcropping phosphatic formation. The calculations of Franconi et al. (1981) indicate that this is a total area estimate, not considering overburden or interbed waste. Franconi et al. (1981) indicate it is necessary to excavate 0.8 km^3 of marls and clays in the area to realize the important reserves.

It is important to note that the resource estimate was based on the percentage of nodules measuring more than 11.1 mm in diameter. The joint IFDC-BGR mission observed the stockpiles of nodules at Tahoua and Gaoy. Most of the nodules stockpiled were several centimeters in diameter, and there was very little material as fine as 1 cm. The hand picking of nodules favors the procurement of larger nodules. There are no data to assess the actual recovery of nodules by this method. Any future reserve estimates should include some realistic estimates of the potential recoverable amount of nodules.

Beginning in 1975, local labor was used to collect nodules near Gaoy and Annekeur from the surface and after scraping the surface of the phosphate formation with a bulldozer. ONAREM then transported the nodules by truck to Tahoua. From 1976 to 1977 the nodules were ground at the Malbaza cement plant.

In 1979 a grinding-bagging unit (2.5 tph) was installed at Tahoua for ONAREM. About 400 workers collected nodules at the height of production. ONAREM bought nodules from the workers for 15 CFA/kg and sold the ground and bagged product for 2,650 CFA/50-kg bag (53 CFA/kg). From 1975 to 1984 about 14,500 tons of nodules was collected and about 6,000 tons was processed. Approximately 8,500 tons of nodules was stockpiled at Tawasnas, Gaoy, and Tahoua in 1989. Figures Niger 5, 6, 7, 8, 9, and 10 illustrate the mining area and grinding facility.

According to L'Aot (1984), the Tahoua phosphate operation was bound to fail. Several reasons were cited for failure:

- The ground phosphate rock product was not highly soluble, and effects were minimal in areas with less than 500 mm rainfall. The effects in well-watered areas were not immediate.
- Farmers did not like the powdered product because it was difficult to apply to the soil.
- Smuggled subsidized Nigerian fertilizers were readily available.

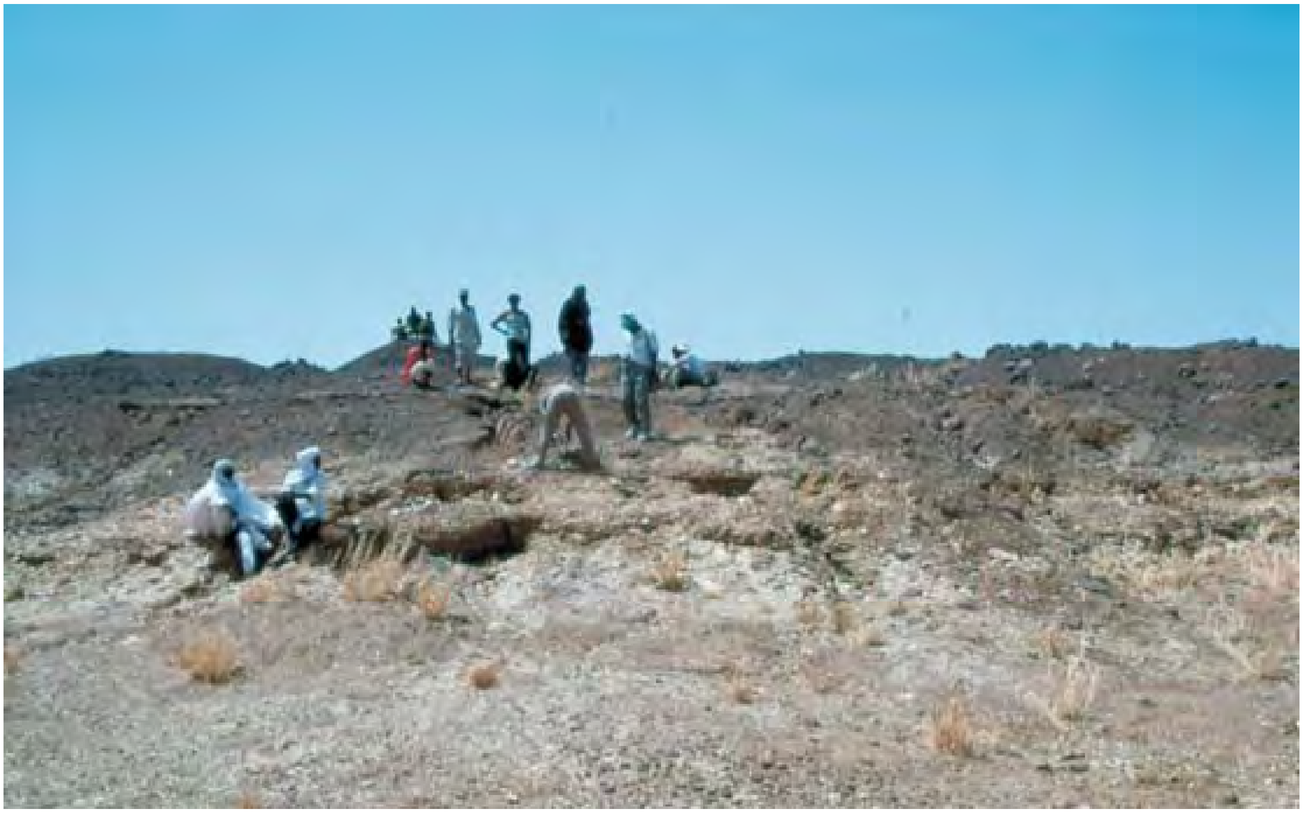


Figure Niger 5. Area of Outcropping Garadoua Formation, Tahoua Area

Figure Niger 6. Phosphate Nodules in Clay, Tahoua Area

Figure Niger 7. Stockpiled Phosphate Nodules and Grinding Facility, Tahoua

Figure Niger 8. Feed Station, Grinding Facility, Tahoua

Figure Niger 9. Grinding Mill, Cyclone and Bagging Station, Tahoua

Figure Niger 10. Storage Facility for Bagged Tahoua Direct-Application Phosphate Rock

Several studies to investigate the agronomic effectiveness of Nigerien phosphate rocks and phosphate rock products, including partially acidulated phosphate rock (PAPR), were conducted by IFDC in liaison with National Institute of Agronomic Research (INRAN) and International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). Beginning in 1984, field trials were conducted at Gobery to compare the effectiveness of Tahoua phosphate rock and Tahoua phosphate rock acidulated at the 50% level (PAPR 50) with that of triple superphosphate (TSP) and single superphosphate (SSP) (IFDC, 1986; 1987; 1988). Several field experiments have shown that the use of finely ground Tahoua phosphate rock can result in mean yields that are 83% and 90% of the mean yields obtained with SSP and TSP, respectively. Tahoua phosphate rock also was about 60% more effective agronomically than Tapoa phosphate rock. Laboratory and field experiments indicated that Tahoua PAPR 50 did not perform as well as finely ground rock, possibly because of a reversion to highly insoluble phosphate compounds due to high Fe_2O_3 and Al_2O_3 in the Tahoua phosphate rock (IFDC, 1988).

An IFDC prefeasibility study of a PAPR production unit for Niger was funded by USAID (IFDC, 1984a). Although this study recommended the use of Tapoa phosphate rock with the PAPR plant at Say, the Tahoua deposit was not considered favorable for development because of a lack of information on reserves and the quality of the ore.

Madaoua Area Phosphates—The Maastrichtian Farin-Doutchi Formation outcrops in the hills north of Madaoua. During the joint IFDC-BGR mission to the area in 1989, samples of phosphatic nodules and a phosphate hardground were collected from gypsum-bearing shales near the base of the formation. Chemical analyses (Table Niger 6) indicated that the phosphatic nodules had a very low P_2O_5 content (l.8 wt %). X-ray diffraction (XRD) analysis indicated the nodules are composed of

Table Niger 6. Chemical Analyses of Phosphate Samples From Farin Doutchi Formation[a]

	Nodules	Phosphatic Hardground With Gypsum
	(wt %)	
P_2O_5	1.8	11.4
CaO	ND	19.4
F	0.1	0.1
SiO_2	1.6	11.7
Fe_2O_3	1.5	8.7
Al_2O_3	36.5	4.0
K_2O	9.7	0.6
Na_2O	0.2	<0.1
MgO	0.1	0.7
Cl^- (ppm)	65	50
S (total)	0.5	15.4
SO_4	–	35.1
CO_2	0.1	0.2
Free H_2O[b]	0.3	6.5
LOI[c]	42.5	32.3
NAC P_2O_5[d]	0.1	1.6

a. Collected during the joint IFDC-BGR Mission, 1989.
b. Free H_2O = weight loss, 105°C, 1 h.
c. Loss on ignition = weight loss, 1000°C, 1 h.
d. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).

alunite ($KAl_3(SO_4)_2OH_6$) and quartz. Apatite could not be detected by XRD, and the P_2O_5 cannot be present as apatite because no CaO could be detected by chemical analysis.

The phosphatic hardground has a much higher P_2O_5 content (11.4 wt %). XRD analysis indicated that the samples were composed of hydroxylapatite (note the low fluorine [F] analyses), gypsum, and quartz. There were some indications in the XRD pattern of secondary phosphate and sulfate minerals. Apatite crystallographic unit-cell measurements were not possible because of interferences in the pattern. The analyzed NAC solubility of the sample was low at l.6% P_2O_5.

Aschia Tinamou Area Phosphates—The Bureau de Recherches Géologiques et Minières (BRGM) reported phosphate rock from the Aschia Tinamou (or Achétinamou) area south of the Termit Massif (BRGM, 1966). The phosphate occurs in the Senonian Aschia Tinamou Formation and is associated with palygorskite clays and carbonates. Chemical analysis (Table Niger 7) indicates the rocks contain 20% P_2O_5. The mineralogical composition of the sample is given as apatite (45%), calcite (28%), pyrite (14%), quartz (3%), gypsum (3%), and other minerals (7%) (BRGM, 1966).

Table Niger 7. Chemical Analyses of Phosphate Rock From Near Aschia Tinamou (Sample No. 3075)

	Wt %
P_2O_5	20.0
CaO	42.1
MgO	1.05
MnO	0.65
SiO_2	3.1
Al_2O_3	Trace
Fe	7.35
S	6.75
CO_2	12.60
SO_3	1.90
Free H_2O	1.0

Source: BRGM (1966).

The phosphate particles are reported to occur primarily as fish teeth and bone fragments. There has been no in-depth mineralogical study of this deposit. The apatite from this deposit could be very interesting, both mineralogically and agronomically. The presence of pyrite (if primary) indicates the deposit has not been oxidized, and the presence of calcite (if primary) may indicate the beds have not been decalcified. Apatites from unoxidized carbonate-containing beds may have a high degree of carbonate-substitution and high levels of NAC solubility. The apatite, composed of organically derived particles, may also be hydroxyl (OH^-) substituted, and these types of apatites may be highly NAC soluble.

There are no resource estimates for the area. The thickness and extent of the phosphate beds are not known.

Parc W Phosphate Deposits—The phosphate deposits in the Parc W area are located near the Tapoa and Mekrou Rivers in the extreme southwestern part of the country near the Benin and Burkina Faso borders within the Parc W National Wildlife Reserve. The distance from Niamey is about 150 km. Discovered by Pascal (1972), the phosphates occur in Middle Voltaian Formations (Upper Precambrian) that are equivalent to the phosphate-bearing formations in Burkina Faso (Kodjari, Arly, and Aloub Djouana) and Togo (Bassar).

The Upper Proterozoic age Volta Basin sediments that are flat lying and extensively developed in Ghana (~200 km wide) narrow northward through Niger in the 3,500-km^2 area bordered by the “W” of the Niger River (Figure Niger 11). Within the Parc W area is the transition zone to the Buem and Atakora Units of the Dahomeyids Chain.

From 1973 to 1980, work by Donnot (1974), Dion (1973), BRGM-OFREMIG (1976a, 1976b), Kuhn and Zajackkowski (1975), Souley and Boureima (1979), Souley and Filion (1980), and The SNC Group of Canada (SNC, 1983) led to delineation of a total resource of 1.254 billion tons of phosphate rock grading 23.0% P_2O_5 in the Tapoa sector and 10 to 20 million tons in the Mekrou sector.

Tapoa Deposit—The Tapoa Deposit occurs in a plunging asymmetric syncline with the axis oriented north/northeast-south/southwest (Figure Niger 12). The eastern and western flanks of the syncline dip at 20°-30°W and 10°-20°E, respectively. Phosphate beds outcrop on the borders, and the depth to the phosphate beds in the center of the syncline is about 200 m. Phosphate rock at the surface can range from relatively unaltered to highly weathered at depths to 20 m.

The lithology of the phosphate-bearing formation, from the top to the base, is as follows:

1. Upper shale formation.
2. Massive phosphatic sandstones with a thickness varying from 20 to 70 m.
3. Fine phosphatic sandstones and shales.
4. Basal siltstones and cherts.

The Tapoa Deposit is an upward-coarsening sandstone sequence that is up to 70 m thick. At the top of the sequence, coarse phosphatic sandstones with massive or cross-bedded structure assay 10%-15% P_2O_5. Below the coarse-grained phosphatic sandstones, beds of massive fine-grained phosphatic sandstone grade 20%-32% P_2O_5. This portion represents the highest grade of the deposit. The overlying slate is approximately 200 m thick, and the underlying siltstones are at least 400 m thick.

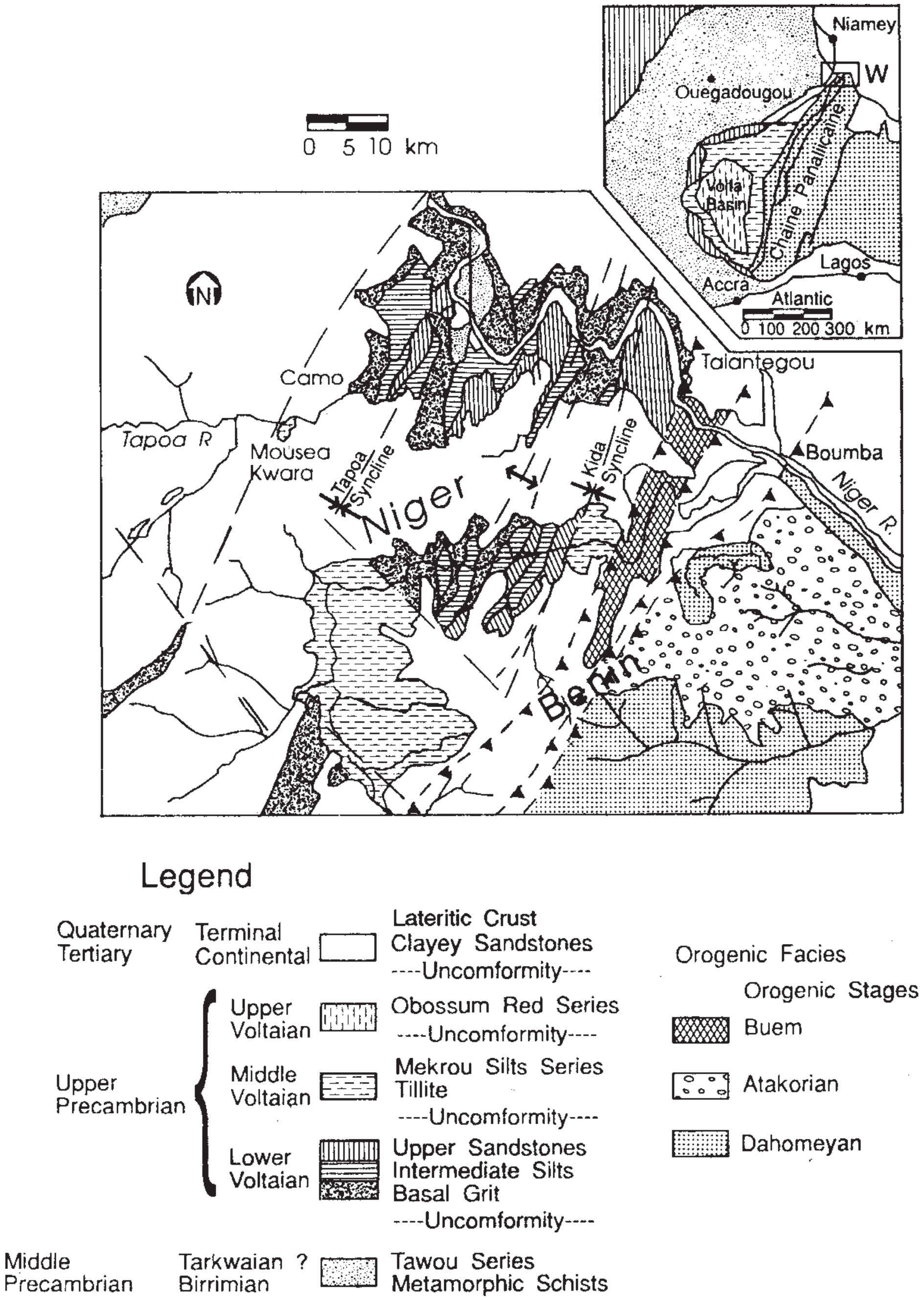
In the phosphate beds, the grain size decreases from top to bottom while the P_2O_5 content increases. Petrographically, the sandstones are composed of grains of feldspars and quartz (200 to l,800 μm) and apatite. The apatite grains are dominantly pellets with some ooids that range in size from 150 to 500 μm in the coarse sandstones. The cement is generally a heterogeneous mixture of quartz, chalcedony, and clays. The clay fraction is made up of chlorite, smectite, and illite. Minor amounts of carbonate cement have been detected in samples from far below the surface (50-90 m) (BRGM-OFREMIG, 1976a).

The mineralogical composition of some of the phosphatic sandstones as determined by Jacob and Marsal (1977) is:

	Coarse Sandstones	Medium Sandstones	Fine Sandstones
		(%)	
Apatite	45.6	56.3	53.5
Carbonate ($CaCO_3$)	l.4	5.4	4.3
Pyrite	0.8	1.8	l.0
Silica and silicates	52.2	37.3	41.2

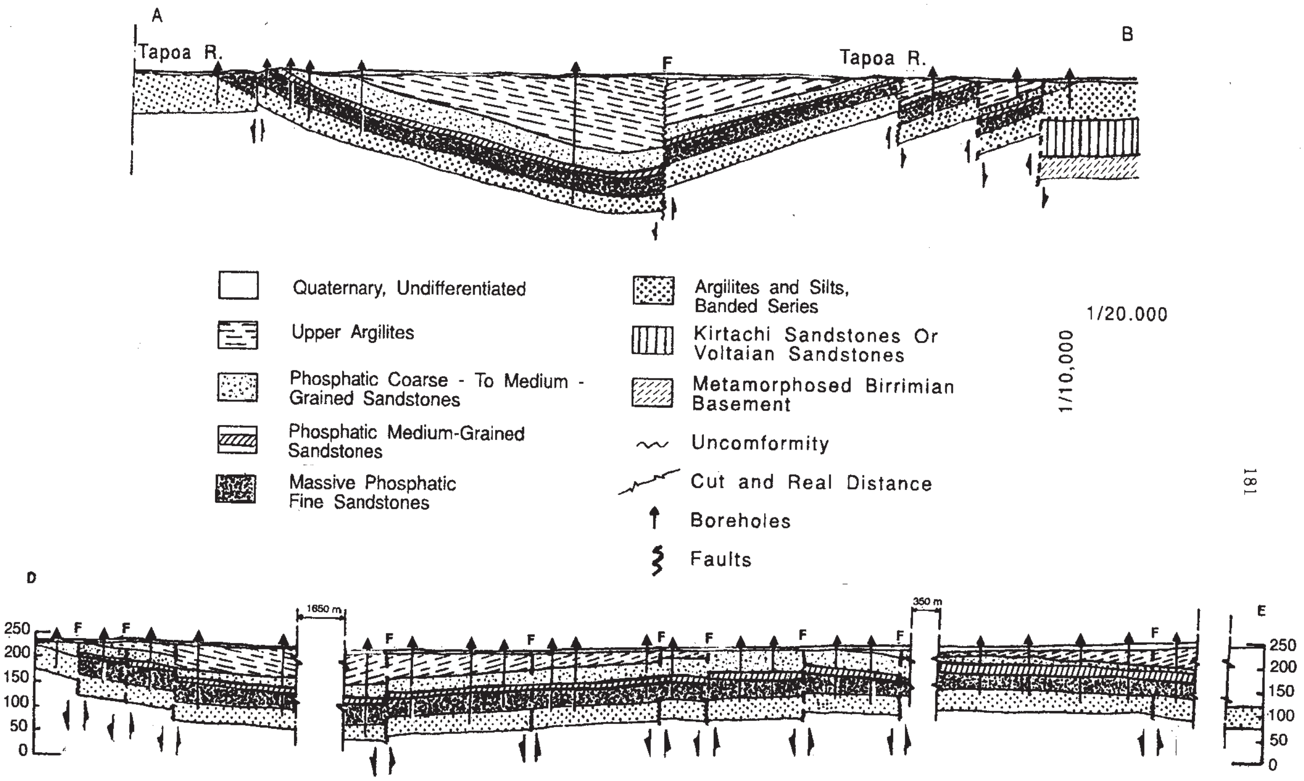
This analysis apparently considered all the CO_3 present as free carbonate and did not assign CO_3 to the apatite component. Free carbonates have never been detected in Tapoa samples analyzed at IFDC.

Several samples of Tapoa phosphate rock were collected by the joint IFDC-BGR fact-finding mission of 1989 and chemically analyzed (Table Niger 8). Two samples of Tapoa ore and a



Source: SNC (1983).

Figure Niger 11. The Geology of the Voltaian Sequence in the Parc “W” of Niger



Source: SNC (1983).

Figure Niger 12. Geological Cross Sections of the Tapoa Syncline

Table Niger 8. Chemical Analyses of Parc W Tapoa Phosphate Rock[a]

	Sample No.			
	WANT1 (Trench 1, 1 m)	WANT2 (Trench 1, 2 m)	WANT3 (Trench 1, 3–4 m)	WANT4 (Trench 1 Area, Surface)
	(wt %)			
P_2O_5	28.5	24.6	27.5	13.1
CaO	1.0	0.7	35.3	17.7
F	<0.1	<0.1	2.7	1.2
SiO_2	37.0	34.1	27.6	63.6
Fe_2O_3	0.4	3.0	2.2	1.8
Al_2O_3	22.0	22.2	1.3	0.5
K_2O	0.1	0.1	0.1	0.1
Na_2O	<0.1	0.1	0.2	0.1
MgO	<0.1	0.1	0.1	<0.1
Cl^- (ppm)	50	60	40	60
S	<0.1	<0.1	<0.1	<0.1
CO_2	0.1	0.2	1.1	0.7
Free H_2O[b]	4.3	1.4	0.4	0.2
LOI[c]	14.4	14.9	2.3	1.0
NAC P_2O_5[d]	5.9	–	1.8	1.4

a. Collected during the joint IFDC-BGR Mission, 1989.

b. Free H_2O = weight loss, 105°C, 1 h.

c. Loss on ignition = weight loss, 1000°C, 1 h.

d. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).

concentrate sample were previously analyzed by IFDC (1984b) (Table Niger 9).

Samples WANT1 and WANT2 (Table Niger 8) were collected from the upper 2 m of Trench 1 (Figures Niger 13 and 14). The bulk samples previously taken from the Tapoa Deposit for beneficiation and fertilizer tests were taken from the bottom of Trench 1. Trench 1 was located in the high-grade middle zone of the formation. Although Samples WANT1 and WANT2 have relatively high P_2O_5 contents of 28.5 and 24.6 wt %, respectively, the chemical analyses show 1% or less CaO, indicating the phosphate is not present as apatite. XRD analysis indicates the main phosphate mineral in these samples is varisite [$Al(PO_4)\cdot 2H_2O$], and there are traces of crandallite [$CaAl_3(PO_4)_2(OH)_5\cdot H_2O$]. Quartz was the only other mineral detected in Samples WANT1 and WANT2.

Table Niger 9. IFDC Analyses of Tapoa Phosphate Rocks and Concentrate

	R231.63 (Ore)	R231.56 (Ore)	R231.64 (Concentrate)
	(wt %)		
P_2O_5	29.0	28.7	33.50
CaO	41.3	39.00	45.50
F	1.70	2.80	3.20
SiO_2	25.2	23.70	12.5
Fe_2O_3	1.1	1.0	1.4
Al_2O_3	1.1	1.2	0.88
K_2O	0.03	0.03	0.04
Na_2O	0.15	0.14	0.16
MgO	0.03	0.06	0.03
$C1^-$ (ppm)	40	54	72
S	0.04	0.05	0.07
CO_2	1.2	1.5	1.3
Organic C	0.08	NA[a]	0.20
Free H_2O[b]	0.32	0.44	0.55
LOI[c]	2.1	2.2	2.7
NAC P_2O_5[d]	2.1	2.3	2.8

a. Not analyzed.
b. Free H_2O = weight loss, 105°C, 1 h.
c. Loss on ignition = weight loss, 1000°C, 1 h.
d. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).

Source: IFDC, 1984b.

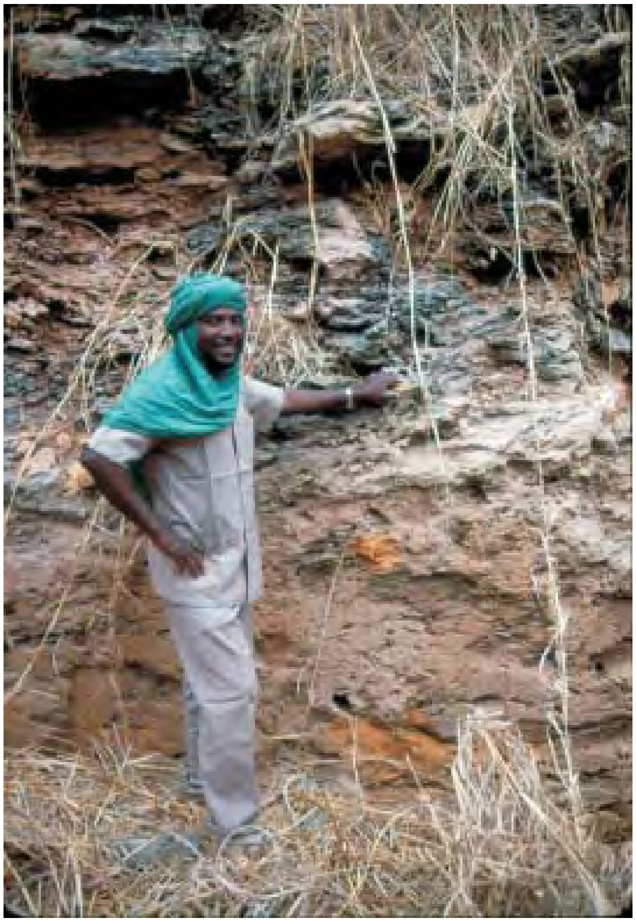


Figure Niger 13. Trench 1, Tapoa Deposit, Niger

Sample WANT3 was taken from near the bottom of Trench 1 (3-4 m). XRD analysis indicates that quartz and apatite are the major mineral phases present in this sample. The chemistry of Sample WANT3 is very similar to the chemistry of the Tapoa ore Samples R231.56 and R231.63 previously analyzed at IFDC (Table Niger 9).

Sample WANT4 was collected from an outcrop of the coarse-grained upper phosphate beds about 200 m from Trench l. In contrast to the highly weathered and altered nature of the phosphate in the samples from the surface near Trench l, chemical analyses (Table Niger 8) and XRD analyses indicate the phosphate is present as apatite. The P_2O_5 content is low (13.1 wt %) and the quartz (silica) content is high (63.6 wt %).

Figure Niger 14.Crossbedded Phosphatic Sandstone, Trench 1, Tapoa Deposit, Niger

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Crystallographic analysis of the apatite of unweathered Tapoa samples (Table Niger 4) indicates a range in unit-cell a-values from 9.356 Å ± 0.001 to 9.362 Å ± 0.001. At an average a-value of 9.358 Å, based on established statistical models, the composition of the apatite would be:

$Ca_{9.89}Na_{0.08}Mg_{0.03}(PO_4)_{5.66}(CO_3)_{0.34}F_{2.13}$

The apatite is a low-carbonate-substituted francolite. The amount of carbonate in a 100% francolite concentrate is predicted to be about 1.5 wt %, and the maximum P_2O_5 content would be 40.29 wt %.

The measured NAC solubilities of l.4%-2.8% P_2O_5 for the apatitic samples (Table Niger 4) are below or at the solubilities of 2.1%-2.8% predicted by models based on the a-value. These unit-cell a-values and low NAC solubilities are typical of weathered, metamorphosed, or Precambrian sedimentary phosphate rocks.

The NAC solubility of 5.9% P_2O_5 of Sample WANT1 would be considered high for an apatitic phosphate rock. Agronomic potential for direct application also would be considered very high under suitable agroclimatic conditions. Apatite was not detected in the sample, and the dominant phosphate is variscite. The agronomic potential of this type of phosphate for direct application is not known.

The mineralogic properties of variscite indicate that most of the water in the structure can be driven off at 180°C (Palache et al., 1951). A sample of WANT1 was heated to 200°C for 1 h. The weight loss at 200°C was 10.1 wt % and the P_2O_5 content increased to 31.3 wt %. The NAC solubility of the sample further increased to 16.4% P_2O_5. Calcium-aluminum phosphates from Senegal and Christmas Island have been thermally treated to destroy the crystal structure and increase NAC solubility. The product from Senegal was marketed under the name Phos-Pal. The temperature required to process these phosphates is much higher (500°-600°C). The agronomic potential of low-temperature thermally processed variscite is not known. The measured NAC solubility indicates this material has high potential. The extent of this type of mineralization in the deposit and possible resources are not known.

Approximately 375 boreholes (31,247 m) have been drilled, and 28 pits have been dug in the area to determine the resources of the Tapoa Deposit. The prospecting grid on the limbs of the Tapoa syncline was 100 x 200 m.

Total phosphate resources throughout the area are estimated as l,254,552,817 tons at 23.0% P_2O_5. Proven reserves on the western flank of the Tapoa syncline structure (Figure Niger 12) were calculated in Zones A and B where conditions permit open-pit mining. There are proven minable reserves of 70 million tons grading 27.8% P_2O_5 and an additional 47 million tons at 24.8% P_2O_5. These ore reserves occur under less than 7.4 m of overburden. These reserves are supplemented by possible reserves totaling 92 million tons averaging 27.0% P_2O_5.

Beneficiation tests by The SNC Group (1983) used a treatment to float the silica gangue and produced fine and coarse concentrates, which were combined to average 34.4% P_2O_5 with 72.4% phosphate recovery. Beneficiation tests by IFDC (1984b) produced concentrates at about 30 wt % P_2O_5 with 70%-80% P_2O_5 recovery.

The SNC Group (1983) carried out a detailed prefeasibility study on the Tapoa Deposit. This study included a detailed mining plan, market and transportation study, and an order of magnitude estimate for a phosphate fertilizer complex. The potential market was determined to be 160,000 tons of concentrates at 34% P_2O_5/year. Of this total, 100,000 tons was for the Kaduna phosphate plant in Nigeria (SSP) and 60,000 tons was for local consumption and in surrounding countries.

Pilot plant beneficiation tests by the Ontario Research Foundation for SNC indicated that coarse and fine concentrates (34.8% P_2O_5 and 33.4% P_2O_5) could be produced. To meet the market demand and in light of the recovery ratios determined by the beneficiation tests, mine production was determined to be about 1,000 tpd.

Capital costs for the mine and beneficiation plant were estimated at US $37.5 million (error margin given as +25% and -10%). Total investment, including capital and startup costs, was estimated as US $43.2 million.

In the SNC study, the Tapoa concentrate must sell at Kaduna for the same price as Togo rock, which was US $91.26/ton including transport to Kaduna. The Tapoa rock would have to be sold at US $11.26/ton f.o.b. Niger to adjust for the US $80/ton transportation fee to Kaduna. Furthermore, the 60,000 excess tons would then have to be sold on the local market at US $95.90/ton.

A financial analysis was done based on 100% equity financing and a tax exemption covering the first 10 years of operation. The analysis indicated that at the then-current world selling price of similar concentrates (US $43/ton), the project would yield a minus l.5% return on investment (ROI).

An order-of-magnitude capital cost estimate was done for a phosphate fertilizer complex. This complex included a sulfuric acid plant, a phosphoric acid plant, and a granulation plant to process the entire production of 160,000 tpy from the beneficiation plant. This estimate amounted to US $76 million.

IFDC (1984a) investigated several scenarios in a prefeasibility study for a PAPR plant in Niger. Unbeneficiated Tapoa rock (28% P_2O_5) was to be used to produce a product with 20 wt % total P_2O_5, 10 wt % water-soluble P_2O_5, and about 12 wt % available P_2O_5. Scheme A_1 investigated the scenario of a 100-tpd PAPR plant producing run-of-pile (ROP)-PAPR. Scheme A_2 used a 100-tpd plant to produce granular PAPR. Scheme B used a 200-tpd plant to produce ROP-PAPR. Capital investments were estimated as $9.6 million, $12.4 million, and $13.6 million in mid-1984 U.S. dollars for Schemes A_1, A_2, and B, respectively.

The internal rates of return (IRR), calculated on 100% equity financing with no income tax and equivalent P_2O_5 on an SSP price basis, were 21.2%, 14.8%, and 29.7%, respectively, for Schemes A_1, A_2, and B. The IRR at a 50% income tax level and an equal P_2O_5 in SSP price basis were 13.4%, 9.0%, and 19.4%. The IFDC study concluded that using Tapoa rock and sulfuric acid from imported sulfur is economically viable when compared with SSP imported from the international market under the conditions assumed for the study.

The Autorité de Développement Intégré de la Région du Liptako Gourma (ALG, 1989) investigated the possibility of producing 21,428 tpy of PAPR 50 made from Tapoa rock (26.05% P_2O_5) at a plant located in Say, about 112 km from the Tapoa Mine and on the Niger River. The calculated IRR, based on the price of imported SSP to Say and hypothetical available P_2O_5 in the product (14%), was 32.3% without taxes. Including taxes, the IRR dropped to 16.6%. The initial fixed investment for the project was about US $7 million.

Since 1982, trials have been conducted in Niger comparing finely ground Tapoa phosphate rock and PAPR acidulated at 25% and 50% with SSP and TSP (IFDC, 1986; 1987; 1988; Bationo, 1989). Results of several experiments show that Tapoa PAPR 50 at the level of 40 kg P_2O_5 per hectare can be as agronomically effective as TSP. Acidulation of Tapoa rock at

25% did not improve its initial effectiveness compared with unacidulated rock. Tapoa rock acidulated at the 50% level performed agronomically as well as SSP. Although the ground Tapoa rock did not perform as well as Tapoa PAPR 50 and PAPR 25, it did increase yields dramatically over the control (in some cases more than doubling the yield), indicating that its direct application may be economically feasible.

Mekrou Area Phosphates—This phosphate deposit is located about 30 km south of Tapoa near the Mekrou River and border with Benin. The deposit was first studied by BRGM-OFREMIG in 1976. Nine boreholes were drilled at this time for a combined total depth of 494.55 m.

The joint IFDC-BGR mission to the area observed two phosphate beds (2 m thick each) separated by about 3 m of shales (Figure Niger 15). The dip of the beds was near 90°. The Precambrian rocks in this area are very deformed because this is the transition area to the Panafrican Dahomeyids Chain. A grab sample from ore of the beds indicated a P_2O_5 content of 26.8 wt % (Table Niger 10). XRD analysis indicated the presence of apatite and quartz.

Crystallographic analysis (Table Niger 4) indicated the unit-cell a-value of the apatite was 9.365 Å ± 0.001. The composition of the apatite, based on established crystallographic models, would be:

$Ca_{9.96}Na_{0.03}Mg_{0.01}(PO_4)_{5.87}(CO_3)_{0.13}F_{2.05}$

The apatite is a low-carbonate-substituted francolite approaching a fluorapatite composition. The predicted P_2O_5 content of a pure apatite concentrate would be 41.49 wt %, and the predicted CO_2 content is 0.56 wt %. The chemical analysis (Table Niger 10) indicates 1.0 wt % CO_2, and some free carbonate may be present.

The analyzed NAC solubility is 1.5% P_2O_5 (Table Niger 4) and is only slightly below the predicted solubility of 1.8% P_2O_5. This Mekrou phosphate rock sample is less soluble than samples from Tapoa and near the range of NAC solubilities of igneous apatites of 0.4%-1.6% P_2O_5 (IFDC unpublished data).

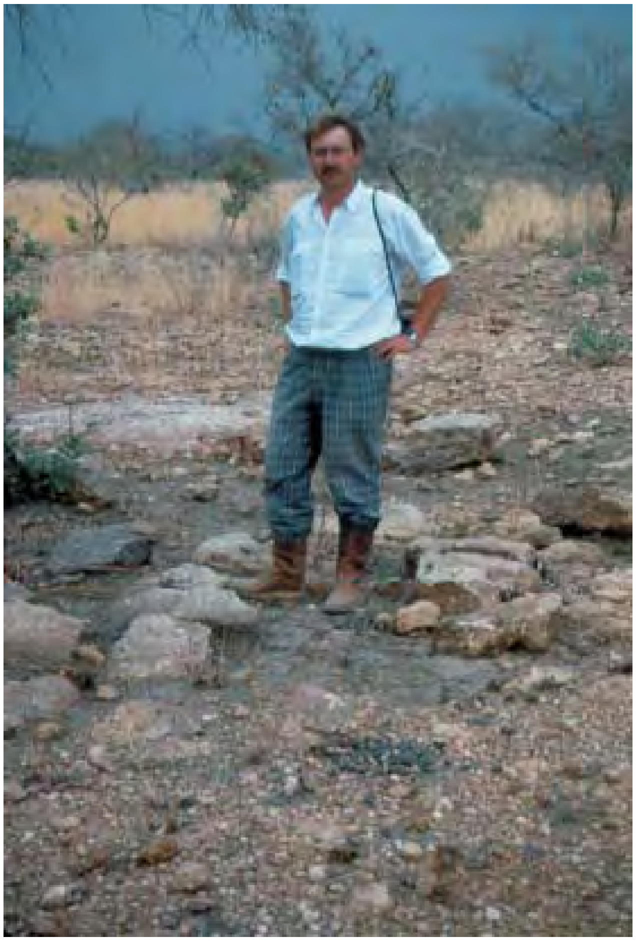

Figure Niger 15.Outcropping Mekrou Area Phosphate Rock, Parc W, Niger

BRGM-OFREMIG (1976a, 1976b) estimated the resources of the Mekrou area at 10-20 million tons with 11%-26% P_2O_5. This is not a firm estimate due to the stratigraphic and structural complexity of the area and limited amount of drilling data. Given the existence of the Tapoa Deposit to the north, it is doubtful if any further detailed work will be carried out in the Mekrou area.

Other Potential Phosphate Deposits in Niger—Phosphate occurrences of unknown significance exist in several areas including:

- The Afasto area (CEA-COGEMA, 1977).
- The Iullemenden Basin in Senonian and Maastrichtian formations (Greigert, 1966, pp. 78, 116).

Table Niger 10. Chemical Analysis of Parc W, Mekrou, Phosphate Rock, Sample No. WANM1[a]

	Wt %
P_2O_5	26.8
CaO	35.5
F	2.5
SiO_2	30.0
Fe_2O_3	3.6
Al_2O_3	0.8
K_2O	0.1
Na_2O	0.1
MgO	0.1
Cl^- (ppm)	90.0
S	0.1
CO_2	1.0
Free H_2O[b]	0.2
LOI[c]	1.3
NAC P_2O_5[d]	1.5

a. Collected during joint IFDC-BGR Mission, 1989.
b. Free H_2O = weight loss, 105°C, 1 h.
c. Loss on ignition = weight loss, 1000°C, 1 h.
d. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).

- The Djado area, Wouringai Mountain (B.R.P., 1960, p. 8).
- Eastern Niger in Cretaceous formations (Faure, 1966, pp. 119, 164, 166).

Potassium Resources

Alunite [$KAl_3(SO_4)_2(OH)_6$], a double sulfate of potassium and aluminum, occurs in the Maastrichtian-Paleocene Termit Formation near the Termit Massif in 15- to 25-cm-thick lenses with kaolinite and natro-alunite [$NaAl_3(SO_4)_2(OH)_2$]. Alunite sometimes forms nodules in fine clayey sandstones. In the Liptako region (Parc W) along the Katyanyahya River, lenses of pure alunite occur under altered oolitic phosphatic sandstone (lateroids). In both of the deposits, the occurrence of alunite is interpreted to be the result of meteoric weathering of an ancient erosion surface. No resource evaluations have been done (Faure, 1966; Dion, 1973).

Salt is produced at many locations in Niger. Salt (halite) is typically found in association with saltpeter (KNO_3), thenardite (Na_2SO_4), and natron ($Na_2CO_3 \bullet 10H_2O$). The salt produced at Teguidda In Tessoum, Manga Foga, and Bosso is rich in natron and sulfates. There apparently have been no studies to assess the sulfate- and potassium-bearing minerals associated with the deposits.

Sulfur Resources

Gypsum deposits are numerous in Niger and have been reported in sedimentary rocks of Devonian to Lower Eocene ages. The gypsum occurs as beds of variable extent, as nodules concentrated in thin beds, or as crystals of varying sizes.

In the Djado region in the northern part of the country, gypsum occurs as massive beds in clay and carboniferous formations (B.R.P., 1960; S.M.D., 1976). The reserves have not been assessed. However, the outcropping of primary gypsum occurs in an area of about 100 km^2. The In Arridal Deposit, discovered in the northwestern part of the country (Lambert, 1935), is characterized by the frequency and by the regularity of gypsum beds within Lower Senonian marls. First estimations by Joue and Vadon (1967) and by Albert et al. (1967) indicated 28 million tons of gypsum ore, of which 576,000 tons is potentially exploitable. The beds have a cumulative thickness of 90 cm. The site is remote and difficult to reach.

In the Ader Doutchi area, gypsum occurs in Maastrichtian age marls (Lambert, 1935; Greigert, 1966; Joue, 1967; Hanon, 1985; Diallo, 1981, 1982). The Farin-Doutchi Formation contains gypsum beds and veins (millimeters to several centimeters) that are concordant with the bedding or that crosscut the stratification. At least a portion of the gypsum is of secondary origin. The main occurrences of gypsum are north of Madoua and in the Keita and Kao regions. Resources are estimated to be 48,000 tons. Near Madoua, the gypsum was mined by hand by local people and sold to the Société Niger Gypse (SNG) in the village of Azarori. SNG sold the raw product to the cement plant at Malbaza.

In the Tanout area, gypsum occurs in marls and clays dated from Upper Cenomanian to the Lower Turonian ages. No specific work has been done to assess the resources of this occurrence.

Pyrites occur in small quantities in Maastrichtian clays in the Tegama area. Barite ($BaSO_4$) occurrences are reported in the Djado area (Silurian sandstone), south of the Aïr Massif at Tazole in the Tegama Group, and in the Tefidet Trough in sandstones of the Angornakouer Formation. The most important occurrences are located north of Agadez (Agades).References

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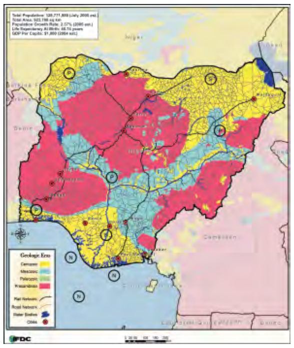
NIGERIA



Nigeria is bordered on the north by Niger, on the west by Benin, and on the east by Chad and Cameroon. There is approximately 853 km of coastline formed mainly by the delta of the Niger River. Total area is 923,768 km^2. The amount of arable land is 31.3%. Nigeria is the most populous country in Africa with approximately 128.8 million inhabitants (mid-2005; World Factbook, 2006). The annual population growth rate is approximately 2.4%. Approximately 70% of the population is employed in agriculture.

The transportation network (Figure Nigeria 1) consists of 60,068 km of paved roads and 134,326 km of unpaved roads, as well as 3,505 km of narrow-gauge railways and 52 km of standard-gauge railways. Waterways (8,600 km) include the Niger and Benue Rivers and smaller rivers. Pipelines are significant and include pipelines for condensate (105 km), gas (1,896 km), oil (3,638 km), and products (3,626 km). There are 70 airports; 36 of these airports have paved runways.

The geology of Nigeria is defined by the Benue Trough. The southwest-northeast striking Benue Trough is part of a down-faulted "failed arm" of a triple-junction rift zone that formed when Africa and South America separated in the Cretaceous (Figures Nigeria 1 and Nigeria 2). Cretaceous sediments extend to the northwest in the Bida Basin. Cretaceous and younger sediments blanket the Niger Delta and the Dahomey Basin across Benin and Togo. Transgressive marine sediments of Mesozoic to recent ages of the Iullemenden and Chad Basins are found to the northeast and northwest of the country. Precambrian rocks of the basement complex, including gneisses, amphibolites, marbles, and granites, underlie large parts of Nigeria. Younger granites of late Paleozoic to Mesozoic ages exhibit ring structures. Volcanic rocks, including basaltic lava flows, trachytic plugs, volcanoes, and basaltic cinder cones occur in the Jos Plateau and Benue Trough.

Nitrogen Resources

Nigeria is the largest oil producer in Africa and eleventh largest oil producer in the world. Since 2003 Nigeria has produced over 2.0 million barrels of oil per day according to the Energy Information Administration (EIA) and others (World Factbook, 2006; EIA, 2005; Mobbs, 2003; D'Souza, 2004). Plans were to increase oil production to 3 million barrels per day (bpd) in 2006 and 4 million bpd in 2010. However, Nigeria is a member of the Organization of Petroleum Exporting Countries (OPEC) and is subject to quotas. OPEC increased the Nigerian production quota from 2.1 to 2.6 million bpd in August 2004.

The reserves are mainly found along the Niger River Delta in approximately 250 small (i.e., less than 50 million barrels each) fields. At least 200 other fields contain undisclosed reserves. Several large deep-water off-shore fields are under development.

The Nigerian government has two major funding arrangements for oil production in the country: joint venture (JV) and production-sharing contract (PSC) arrangements. Production from JVs accounts for approximately 95% of Nigeria's crude oil production. The largest JV, operated by Shell Petroleum Development Company of Nigeria Ltd. (SPDC) and majority owned by the Nigerian National Petroleum Corporation (NNPC), produces about half of Nigeria's crude oil.

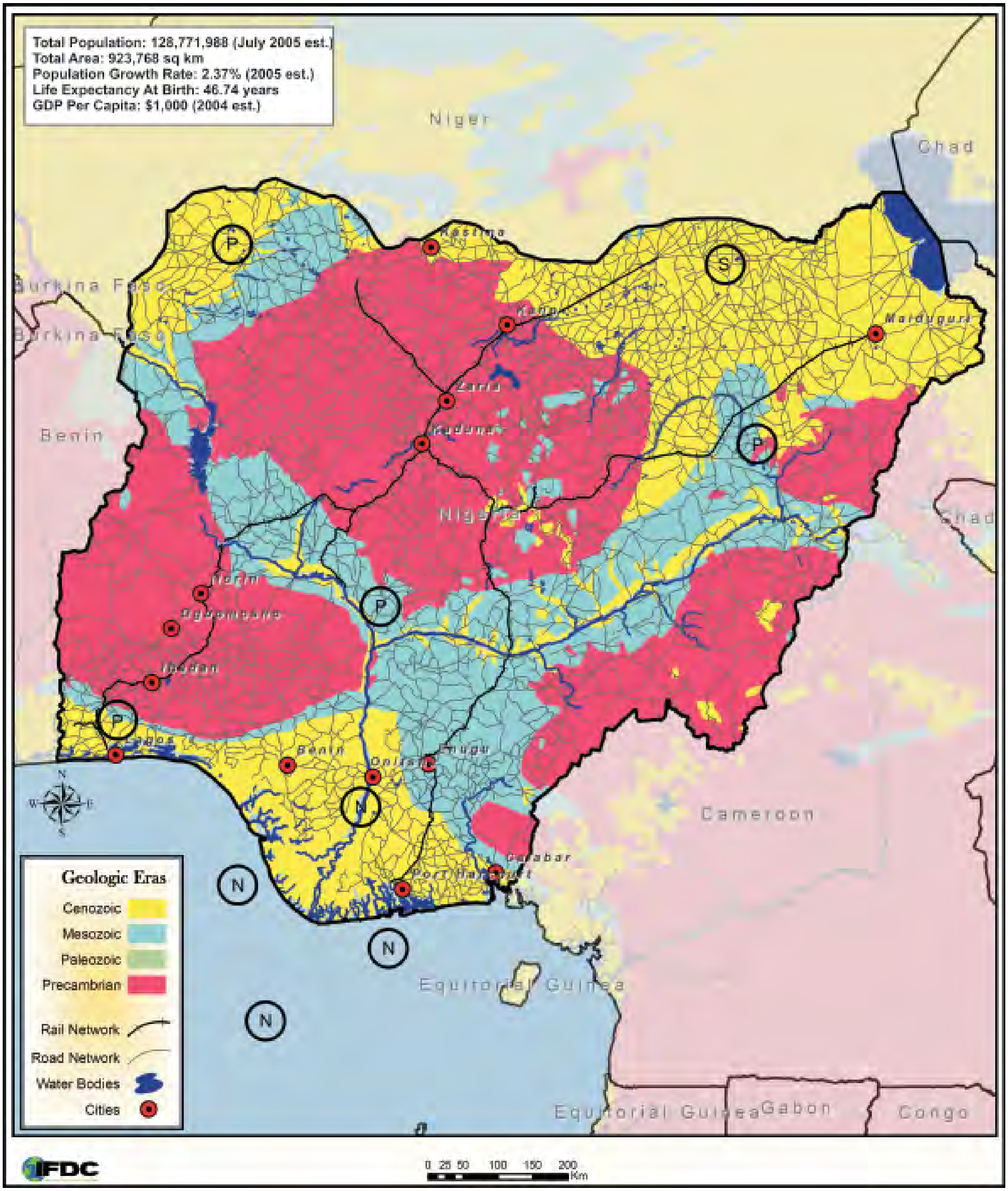


Figure Nigeria 1. Geology, Major Cities, and Transportation Network

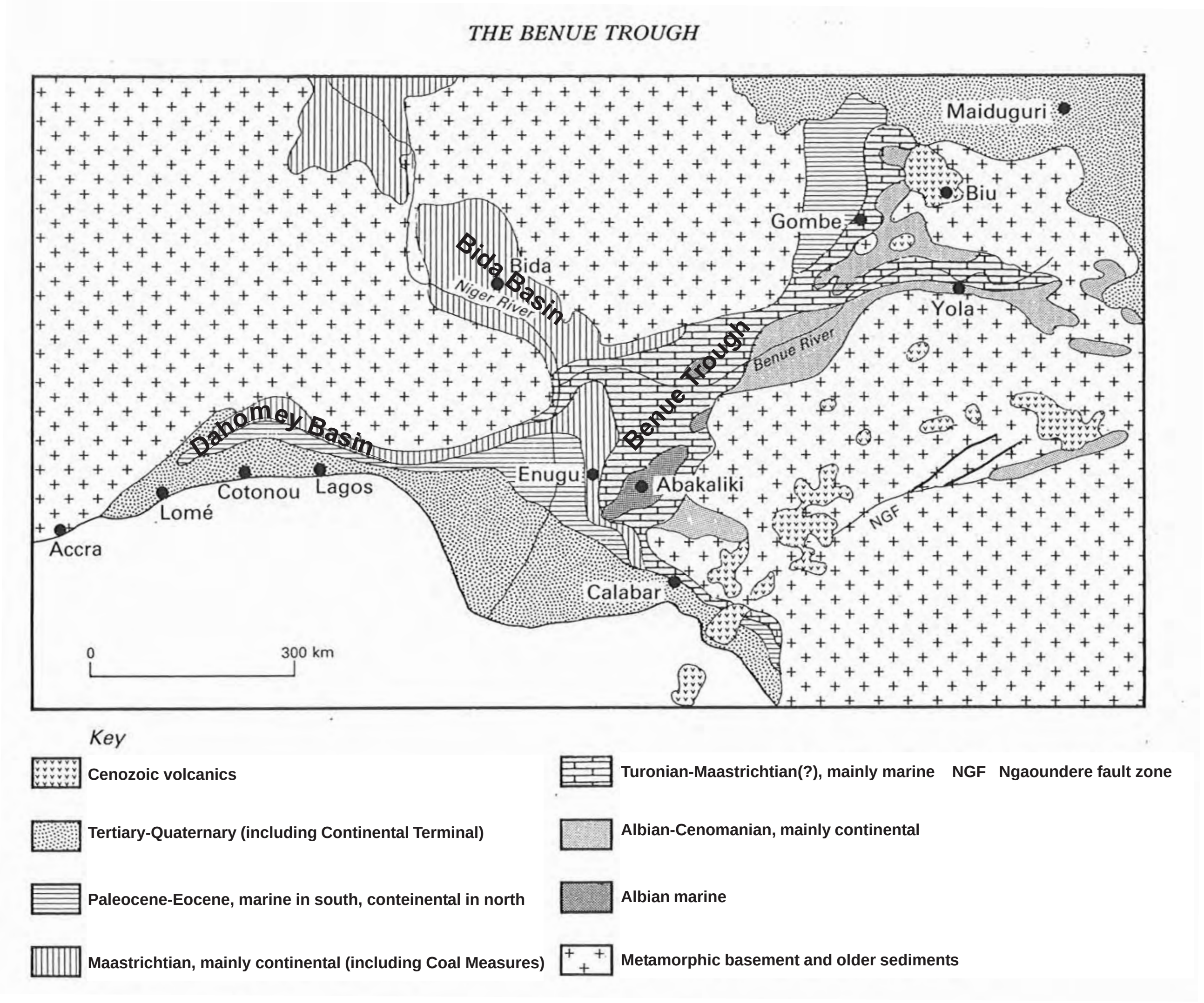


Figure Nigeria 2. The Geology of the Benue Trough, Bida Basin, Niger Delta, and Dahomey Basin
(Adapted From Wright et al., 1985)

Approximately 65% of Nigerian crude oil production is light (35° API or higher) and sweet (low sulfur content). Nigerian crude oil is generally prized for its low sulfur content. Nigeria has four state-held refineries (Port Harcourt I and II, Warri, and Kaduna) with a combined nameplate capacity of approximately 440,000 bpd (EIA, 2005). The Nigerian government is promoting the development of privately owned refineries; three more refineries are planned by 2008. In October 2004 the Nigerian government issued 13 licenses for the construction of additional private refineries. Proven reserves of oil are 34-35 billion barrels (EIA, 2005; World Factbook, 2006). The Nigerian government hopes to increase proven reserves to 40 billion barrels by 2010.

Nigeria has one of the top 10 natural gas endowments in the world. Proven reserves are in excess of 4 trillion m^3 (World Factbook, 2006). Nigeria flares a significant amount of the natural gas it produces; estimates run between 40% and 75% (EIA, 2005). The Nigerian government wants to reduce and eventually end gas flaring. The US $3.8 billion liquefied natural gas (LNG) facility on Bonny Island was completed in September 1999. Three trains were initially under operation. Trains 4 and 5 were scheduled to start up in 2005, and plans for a sixth train had been approved; the sixth train was to be operational in 2006. In January 2005 ExxonMobil signed a Memorandum of Understanding (MOU) with NNPC to study the possibility of constructing a second LNG plant on Bonny Island to come online in 2010. ConocoPhillips, Chevron Corporation, and Agip signed an agreement for a US $3.0 billion Brass River LNG plant which would be operational in 2008. In January 2005 ChevronTexaco announced the possibility of constructing a US $6.0 billion LNG plant at Olokola in Western Nigeria. ChevronTexaco's $1.9 Escravos gas-to-liquids project was scheduled to come online in 2006; the project was halted in 2005. The West African Gas Pipeline Project was implemented in 2005. There are several projects concerned with distributing natural gas within Nigeria.

Urea was produced in Nigeria between 1987 and 1995 by the National Fertilizer Company of Nigeria Ltd. (NAFCON), which also produced diammonium phosphate (DAP) and urea-based NPKs at an associated plant. Both plants were located at Port Harcourt. The ammonia/urea plant was established as a joint venture between the Federal Government of Nigeria (FGN) and M. W. Kellogg. Kellogg withdrew from the venture and ownership passed to FGN. In 2003, NAFCON was sold for US $75 million to Sino Africa Petrochemical Co. Ltd. (a Chinese-Nigerian consortium, 70% interest) and Foskor Ltd. (30% interest). The transaction was not completed and was terminated.

A study by IFDC in 2004, "Prefeasibility Study on the Establishment of an Ammonia/Urea Plant in Nigeria," considered both the rehabilitation of the existing NAFCON plant, which had been in maintenance mode for 7-8 years, and the building of an entirely new plant (IFDC, 2004b). The new plant would be located adjacent to the existing plant on land designated for NAFCON.

The study concluded that rehabilitating the existing NAFCON plant represents an attractive investment opportunity that would generate a good rate of return for the private investor. The rehabilitation of NAFCON was estimated to cost a maximum of US $150 million and would take 18 months from the date the project was initiated. Based on 2004 market prices for urea, an attractive simple internal rate of return (IRR) of around 25% could be achieved if the total "price of NAFCON" including rehabilitation did not exceed US $200 million and if an existing gas agreement remained in force. The urea product selling price used for the evaluation was US $200/ton of urea, which was some US $100/ton lower than the 2004 market price in Nigeria. The existing NAFCON plant with some relatively minor low-cost debottlenecking could produce around 650,000 tpy.

A new urea production facility with natural gas availability and with access to export markets would generate good rates of return for investors. The total investment for a large-scale urea plant with a yearly capacity of 1,155,000 tons would be in the order of US $550 million and would generate an unleveraged rate of return of around 24% based on established gas pricing and 2004 product market price of US $200/ton. Such a facility would be competitive in both the domestic Nigerian market and the international export market when located in the greater Port Harcourt area.

O-Secul bid US $152 million for the NAFCON plant in August 2005, outbidding three other bidders (*Business Day*, 2005). O-Secul has a technical partnership with Engro, a Pakistani company that operates urea production units. A timeframe for rehabilitation and restarting the plant had not been established at the initial announcement of the winning bid for the plant.

Phosphate Resources

Ifo Junction-Oshosun—Lower Eocene sedimentary phosphate deposits containing between 22% and 32% P_2O_5 were discovered in 1921 by W. Russ of the Geological Survey of Nigeria (GSN) near Ifo Junction and Oshosun, between 43 and 48 km north of Lagos (Russ, 1924). High percentages of aluminum phosphates were indicated, suggesting the deposits are highly weathered. Investigations conducted in the area by the GSN after World War II did not indicate they were commercially significant (Jones, 1964). In the Oshosun area, about 30,000 tons of phosphate rock and intercalated shale, averaging 1.5 m in thickness, was delineated. Field surveys and a drilling program to the west of the Oshosun-Ifo Junction indicated there were no significant occurrences between this area and the Benin border.

The occurrences are equivalent in age to the deposits worked in Togo. These lenticular beds of phosphate rock are assigned to the Ilaro Formation and form a part of a succession of Tertiary sediments that are up to 100 m thick. Pitting indicated the phosphate beds may range from only a few centimeters to slightly over 1 m thick. Three or four phosphate beds can be recognized. For the uppermost bed, the greatest development occurs near Oshosun and Balogun, where it reaches a thickness of approximately 1.3 m. Laboratory tests on granular phosphate rock samples from Ifo Junction indicate that significant increases in grade can be achieved by gravity separation (McClellan and Notholt, 1986). McClellan and Notholt (1986) estimated total resources of the Ifo Junction-Oshosun area at a little over 1 million tons. Van Straaten (2002) indicated that the Ifo Junction deposit was being mined, the resources estimate was 40 million tons, and the resource estimates needed updating and confirmation. These observations concerning the mining and the reserve estimate could not be verified.

Sokoto Phosphate Deposits—The occurrence of phosphate in the Sokoto Basin was first reported by Jones (1948) of GSN. The phosphate occurrence is mainly restricted to the Dange Formation, which is widely distributed in the basin. These phosphate occurrences near Sokoto are related to the phosphate occurrences of the Iullemenden Basin to the north in Niger. Five marine transgressions have been identified in the history of the Iullemenden Basin. The Dano-Montian transgression is associated with phosphate occurrences near Tahoua in Niger. The final Upper Paleocene transgression in the basins is apparently associated with the phosphate occurrences in the Sokoto Basin. The phosphate occurrences of the Tahoua and Sokoto areas are very similar; phosphate nodules appear to occur as discontinuous lenses within siltstone and shale beds.

Detailed investigation of the Sokoto phosphate did not begin until 1980 when radiometric surveys of the basin indicated that uranium deposits may be present. Investigation of the radiometric anomalies in an area about 100 km long indicated the anomalies were due to the presence of phosphate nodules rather than other types of uranium mineralization.

Seven of the anomalies were identified as phosphate prospects. Investigations focused on two of the phosphate prospects—the Dilingu Prospect 1 and the Kansawasa Prospect 2. GSN drilled boreholes and did extensive pitting to evaluate the prospects. At the Dilingu Prospect, the investigations led to identifying 3,525,000 tons of concentrated phosphate nodules in a 5,087-ha area to a depth of 10 m. At the Kansawasa Prospect, 10,969 tons of reserves was proven over 12 ha to a depth of 10 m in Block 1; in Block 2, 1,020,000 tons of reserves was inferred to a depth of 10 m over 600 ha (Oyeka and Ukeha, 1991a, 1991b).

Inspection of figures representing drill logs indicates that generally two and as many as five phosphatic beds may be present in an area of the deposit. While some reports suggest the phosphate rock contains 20% to 40% P_2O_5, it should be noted that these numbers are for handpicked nodule concentrates. The P_2O_5 content of a sample of nodules analyzed at IFDC (Table Nigeria 1) was 34.2% (IFDC, 1985). It is very difficult to determine

Table Nigeria 1. Chemical Analysis, Phosphate Nodules, Sokoto State, Nigeria

	Chemical Analyses
	(wt %)
P_2O_5	34.2
CaO	47.9
F	3.4
SiO_2	4.2
Al_2O_3	1.7
Fe_2O_3	3.0
Na_2O	0.24
MgO	0.10
K_2O	0.08
CO_2	1.9
S	0.19
Cl^-	109 ppm
C (organic)	0.1
LOI[a]	5.30
Free H_2O[b]	0.77
NAC P_2O_5[c]	3.5

a. Loss on ignition = weight loss, 1000°C, 1 h.
b. Free H_2O = weight loss, 105°C, 1 h.
c. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).

the P_2O_5 content of individual phosphate beds based on the way the data are presented in the GSN reports (weight of nodules per ton excavated). However, calculations indicate that some beds may have a total P_2O_5 content of about 5%.

Following a directive from the Nigerian government indicating that a trial mining operation should be started in 1990, the Nigerian Mining Corporation (NMC) evaluated the Dilingu and other prospects. The findings of the NMC can be summarized as follows:

1. Phosphate occurs as nodules in shales and siltstones in narrow bands no more than 0.5 m thick.
2. There may be up to three phosphate-bearing layers at any one location.
3. The P_2O_5 content of the nodules ranges from 19% to 40%.
4. The best mining method would be by hand labor.

Local people gather the phosphate nodules during 5 months in the wet season (November-June) when there is little employment. Pits up to 1 m deep may be excavated in the outcropping formation. Phosphate nodules less than 1 cm in maximum dimension may be picked. Phosphate-producing companies purchase and pick up the piles of nodules. The phosphate-producing companies grind the rock to specification, approximately 64% passing 149 microns, and transport the material in bulk to Kaduna.

The Federal Superphosphate Company in Kaduna is currently the only company in Nigeria manufacturing phosphate fertilizer and the only potential buyer for the phosphate rock. IFDC studied the Federal Superphosphate Company in 1989 for the Economic Community of West African States (ECOWAS). At that time a new sulfuric acid plant was needed if production was to continue.

According to the Raw Materials and Research and Development Council (RMRDC) data, 1997 was the first year that Federal Superphosphate purchased and used Sokoto phosphate rock. The data in the following table were provided by the RMRDC and indicate the amount of Sokoto phosphate rock purchased.

	Ground Sokoto PR
	(tons)
1997	10,000
1998	<2,000
1999	0
2000	0
2001	3,000
2002	3,000

Apparently there were production problems in 1999 and 2000. Prior to using Sokoto phosphate rock, Togo phosphate rock was imported.

The new single superphosphate (SSP) plant at Kaduna was manufactured by Hitachi. The capacity of the new plant is 70,000 tons of SSP per year. The short-range production plan was to produce 50,000 tons of SSP per year. In 2003 the Kaduna plant intended to purchase the bulk of the supply of phosphate rock from the Sokoto area (30,000 tpy). This was a very ambitious plan considering that less than a total of 18,000 tons was purchased between 1997 and 2002. The tender for phosphate rock issued in February 2003 indicated that the minimum content of P_2O_5 required was 30.05%.

Based on pit data from the GSN reports, an IFDC study evaluated the potential cost of mining (IFDC, 2004a). The cost of moving rock or overburden by a contractor in Nigeria, as obtained by the IFDC consultant, is N185/m^3 (US \$1.46/m^3, US \$1 = N127). Based on actual recovery of nodule data from 24 pits in the Dilingu area, a stripping ratio of 0.75, and a 4.85-m-thick bed over the area, the cost of excavating to obtain 1 ton of nodules is N13,242/ton (US \$104.27/ton).

This cost does not include any costs to process the excavated material to obtain the nodules, costs of reclamation of the mined land, handling and grinding of the nodules, administrative costs, or transportation to Kaduna. Some of these costs are known; other costs could only be estimated by more detailed study in Nigeria. The following table summarizes the potential production costs based on available information.

	Cost per ton[a]	
	N	US $
Excavation costs[b]	13,242	104.27
Processing to obtain nodules[c]	3,000	23.62
Land reclamation[d]	662	5.21
Handling and grinding[e]	2,000	15.75
Transportation to Kaduna[f]	2,000	15.75
Administrative costs	–	–
Total[g]	20,904	164.60

a. N127 = US $1.
b. By contractor.
c. Assumes processing by hand at a cost similar to current costs.
d. Based on 5% of excavation costs. Typically 5% of total mining costs in North America is required for reclamation.
e. Estimated from information from current grinding operations; does not include any profit margin.
f. Based on current rates, 30-ton trucks.
g. Does not include any royalties to landowners.

The cost of processing to obtain nodules was assumed to be the current rate the miners are paid per ton of rock, as this is the only known processing method. There is simply no known effective method of beneficiating such phosphatic nodules in a shale/siltstone matrix; a method would have to be developed and tested. When nodules from such shale beds are excavated from below the surface, they are often moist and soft. It may not be possible to handle the nodules mechanically without significant losses. Handling and grinding is assumed to cost N2,000, based on conversations with current ground rock producers; a firm figure was not available. Administrative costs for such operations are highly variable, mainly depending on whether the operation is privately owned or government owned and operated. The table does not include any capital cost recovery for loans for infrastructure development, processing equipment, etc. Even if the nodules are picked by hand, some sort of conveying/sorting system must be designed and purchased. The potential product cost does not include any profit for the phosphate-producing company.

The Federal Superphosphate Company has paid from N9,000 to N13,000/ton (US $70.80 to US $102.36/ton) for ground Sokoto phosphate nodules delivered to the plant in Kaduna. Partially or wholly mechanizing the process may potentially double the cost. The current cost of Togo phosphate rock delivered to Kaduna is estimated as N11,303/ton (US $89.00/ton).

On the basis of IFDC test work (IFDC, 1985), the Sokoto phosphate rock has a neutral ammonium citrate solubility of 3.5% P_2O_5. The Sokoto phosphate rock is classified as a relatively low reactivity rock. Ground Sokoto phosphate rock could be valuable as a direct-application P_2O_5 source if used under appropriate cropping and agroclimatic conditions. Conditions conducive to the use of such a rock include highly acid soils, high rainfall, and long-term crops. Rocks similar in reactivity to Sokoto rock have been used successfully in Southeast Asia on oil palm, rubber trees, and coconuts. Agronomic testing would be required to determine the suitability of Sokoto phosphate rock for direct application under Nigerian cropping and agro-climatic conditions.

It is suggested that the areas in Nigeria that would be most appropriate for the use of Sokoto phosphate rock for direct application would be in the south of the country near the coast. Detailed studies would be required to determine the potential costs of producing Sokoto phosphate rock and distributing it for sale in the areas where it would be most conducive for successful adoption. However, in several similar cases studied in detail by IFDC, where long transportation distances to bring the ground phosphate rock to suitable market areas were involved, the cost of using ground phosphate rock (on a total P_2O_5 basis) was significantly higher than the cost of using traditional water-soluble fertilizers that were imported. In the Nigerian situation, the cost of Sokoto phosphate rock would increase as it is transported to the south. Conversely, the cost of imported fertilizer would decrease the closer the distribution point is to the coast and seaport.

IFDC reports (IFDC, 1992; Nashuni, 2002; IFDC, 2004a) indicate the best technically feasible use of the Sokoto phosphate rock is to produce SSP. Due to high impurity contents, use for other fertilizer processes is not suggested or recommended. The combined $Fe_2O_3 + Al_2O_3$ contents for the sample analyzed at IFDC was 4.7 wt %.

An effective beneficiation scheme for the Sokoto phosphate rock would have to be developed in order to use the material to make phosphoric acid.

Because phosphate deposits such as the Sokoto deposit have never been mined and beneficiated anywhere in the world, there is no established technique for processing this or similar phosphate ores.

Similar to the recommendation of the Nigerian Mining Corporation, IFDC suggested that the best mining method would be by hand labor. Based on potential cost calculations, hand labor appears to be the most cost effective option. The hand labor mining system also requires no investment and is very flexible. Sokoto rock could be used alone or blended with other phosphate rocks such as Togo phosphate rock.

Further exploration in the Sokoto Basin was suggested by IFDC (2004a). The results of the previous radiometric survey might be reviewed. The radioactive anomalies in this area should correspond to the highest phosphate concentrations.

Nape Basin—Phosphorus-rich ironstones containing kaolinite, pyrite, siderite, limonite hematite, and goyazite-crandallite occur in the Nape Basin near Lokoja (Akande et al., 1999). The P_2O_5 contents may range from 0.04% to 5.92%.

Pindinga and Dukul Area—In the upper Benue Basin near Pindinga and Dukul, mudstones and grainstones contain varying proportions of apatite (0.5%-49.2%) (Akande et al., 1999).

Phosphate Fertilizer Production—NAFCON produced DAP and NPKs at a plant in Port Harcourt between 1987 and the early 1990s. Inspection by an IFDC team (IFDC, 2004b) indicated the plant had been disassembled. As previously mentioned, the Federal Superphosphate Company produces SSP in Kaduna.

Sulfur Resources

The Nigerian RMRDC (2006), Federal Ministry of Science and Technology lists gypsum deposits in 14 states. A reserve of 141 million tons is listed in Yobe State.

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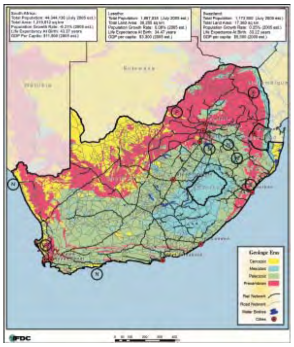
REPUBLIC OF SOUTH AFRICA



The Republic of South Africa is bordered to the north by Namibia, Botswana, and Zimbabwe; the east by Mozambique; and the south by the Atlantic and Indian Oceans (Figure South Africa 1). The total area is 1,219,912 km^2 and approximately 12.1% of the land is arable. The population was estimated in mid-2005 as 44.3 million inhabitants (World Factbook, 2006). Agriculture occupies 30% of the work force while industry and services occupy 25% and 45% of the work force, respectively.

The transportation network is composed of 57,568 km of paved roads, 218,403 km of unpaved roads, 20,872 km of 1.065-m-gauge railroad, and 436 km of 0.610-m-gauge railroad. There are 146 airports with paved runways and 582 airports with unpaved runways. Pipelines include 100 km for condensate, 1,052 km for gas, 847 km for oil, and 1,354 km for refined products. The main ports are Cape Town, Durban, East London, Port Elizabeth, Richards Bay, and Saldanha Bay.

Precambrian rocks form about one-third of the land surface of South Africa (Figure South Africa 1). These Precambrian rocks are mainly exposed in the north of the country. Some Precambrian rocks of the Namagualand and Natal Metamorphic Belts outcrop in eastern South Africa near the coast. Precambrian rocks also outcrop in the folded mountains in the south of Cape Province. Precambrian rock types include practically all types of metasediments, granitic intrusions, mafic intrusions, and various types of volcanics and carbonatites.

About half of the exposed rocks of the country are Paleozoic to Mesozoic in age. Paleozoic age rocks include sediments of the Cape System, mainly found in the Cape Fold Belt in the extreme south of the country. The Karroo (or Karoo) System ranges in age from late Permian through the Jurassic. Karroo System rocks include tillites in the Duiyka Series, extensive coal-bearing sediments of the Ecca Series, and sequences of volcanics found primarily in eastern South Africa at the border with Mozambique and to the south.

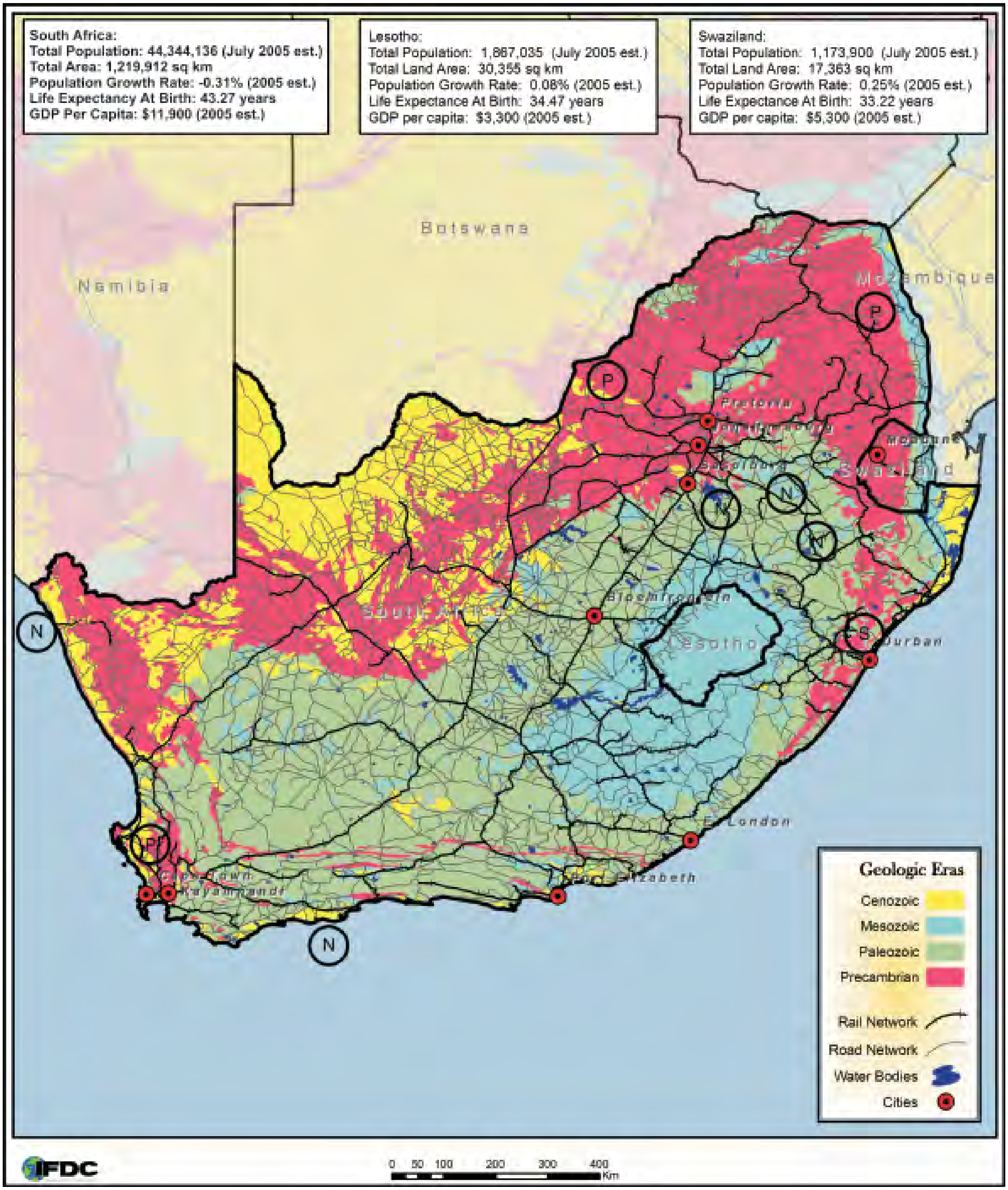
Cenozoic sediments are found in several coastal basins. Kalihari sands cover extensive areas in northwestern South Africa along the borders with Botswana and Namibia. Alkaline complexes, carbonatites, and kimberlites have penetrated the Precambrian basement and Karroo sediments.

South Africa is home to one of the most highly developed mining and mineral processing sectors in the world. Mines include both deep underground operations and surface mines for gold, copper, phosphate, platinum, diamonds, coal, and other materials.

Nitrogen Resources

Coal—Coal is the primary fuel produced and consumed in South Africa. South Africa is the world's sixth largest coal producer; the Energy Information Administration (EIA) reports production of 263.78 million tons in 2003 (EIA, 2005a). Over 80% of the production comes from Mpumalanga Province. Production also comes from the Free State, Limpopo, and Kwazulu-Natal.

Total recoverable coal reserves are approximately 4.88 x 10^{10} million tons (EIA, 2005b). Seventy percent of the recoverable reserves lie in the Highveld, Waterberg, and Witbank Coal Fields (EIA, 2005c). Anglo Coal (Anglo American), Ingwe Coal (BHP Billington), Eyesizwe Coal, Kumbwa



South Africa:
Total Population: 44,344,136 (July 2005 est.)
Total Area: 1,219,912 sq km
Population Growth Rate: -0.31% (2005 est.)
Life Expectancy At Birth: 43.27 years
GDP Per Capita: $11,900 (2005 est.)

Lesotho:
Total Population: 1,867,035 (July 2005 est.)
Total Land Area: 30,355 sq km
Population Growth Rate: 0.08% (2005 est.)
Life Expectance At Birth: 34.47 years
GDP per capita: $3,300 (2005 est.)

Swaziland:
Total Population: 1,173,900 (July 2005 est.)
Total Land Area: 17,363 sq km
Population Growth Rate: 0.25% (2005 est.)
Life Expectance At Birth: 33.22 years
GDP per capita: $5,300 (2005 est.)

Figure South Africa 1. Geology, Major Cities, and Transportation Network (South Africa, Swaziland, and Lesotho)

Resources, Sasol Mining, and Xstrata Coal South Africa (Swiss-based) are responsible for the majority of South Africa's coal production.

About one-third of South Africa's coal is exported, primarily to the European Union and South Asia. The Richards Bay Coal Terminal handles most of the tonnage and is the world's largest coal export facility with a capacity of 72 million tons yearly. Capacity increases were to be completed in 2005.

Oil and Natural Gas—South Africa imports oil from the Middle East and other African countries. Total oil production in South Africa only accounts for approximately 10% of domestic requirements.

Oil production in South Africa began in 1997 when Petroleum Oil and Gas Corporation (PetroSA) and Energy Africa developed the Oribi Field off the south coast. The Oryx Field, about 5-6 km from the Oribi Field, was developed to continue production in the block.

Development of the nearby Sable Field (PetroSA and Pioneer) began in 2003. Six subsea wells are connected to a floating production, storage, and offloading (FPSO) vessel with the capacity to produce 60,000 barrels per day (bpd) of oil.

Natural gas production is located in Block 11A, east of Block 9 where the Oribi, Oryx, and Sable Fields are located. The production platform at the FA Natural Gas Field, from which at least nine production wells have been drilled, is one of the largest structures ever constructed in South Africa. A 91-km pipeline conveys gas and condensate to the Mossgas synfuels plant at Mossel Bay, where gasoline, diesel, and kerosene are produced (MBendi, 2005). Development and exploration continue in the area.

South Africa's offshore west coast has been the focus of exploration in recent years. In March 2000, United States-based Forrest Oil Corporation and Anschutz discovered oil in Block 27 along the border with Namibia (EIA, 2005a). The AK-1 find flowed at a rate of 52.8 million ft^3 per day of natural gas and 342 bpd of condensate (Africa Energy, 2006). On the basis of two appraisal wells, Forrest Oil estimated that the Ibhubezi Field contained 2.5 trillion ft^3. The production will probably be channeled to regional energy production.

Oil prospecting leases and subleases have been signed by Soekor, Phillips Petroleum, PanCanadian Petroleum International, Energy Africa, and Sasol for blocks off South Africa's northeast coast. The blocks have potential for gas reserves, and a ready market exists onshore.

South Africa has a highly developed synthetic fuels industry. The major producers of synthetic fuel in South Africa are Sasol (150,000 bpd) and PetroSA (50,000 bpd) (EIA, 2005a). Sasol is the world's largest manufacturer of oil from coal and maintains coal liquefaction plants at Secunda (oil) and Sasolburg (petrochemicals). Sasol has been partially replacing coal with natural gas as feedstock. In 2004 natural gas became available from Mozambique's Temane Gas Field.

State-owned PetroSA began synfuel production in 1993. PetroSA receives natural gas and condensate from the gas fields in Mossel Bay and can process up to 8,000 bpd of imported condensate (EIA, 2005a).

South Africa has the second largest refining capacity in Africa (519,547 bpd) surpassed only by Egypt (EIA, 2005a). Major refineries include Sapref (172,000 bpd) and Enref (150,000 bpd) in Durban; Calref (110,000 bpd) in Cape Town; and Natref (87,547 bpd) at Sasolburg.

Phosphate Resources

Igneous Phosphate Deposits—Most of the igneous apatite deposits in South Africa are associated with carbonatites and pyroxenites.

Glenover Carbonatite—The Glenover Carbonatite is roughly oval in shape and outcrops over about 18 km^2 on two farms in northwestern Transvaal. Leaching of the carbonatite in the central portion of the plug resulted in a ferruginous brecciated rock consisting mainly of apatite, hematite, and goethite at the top of a small hill called Glenover Kopje. The upper and central portions of the orebody contained about 2.7 million tons of ore averaging 32.8% P_2O_5 and 9.3% Fe_2O_3 (Savage, 1987). Nb_2O_3 contents ranged from 0.03% to 0.32%.

The mine was operated from 1958 to 1982 by Glenover Phosphate (Pty.) Ltd., owned by Gold Fields of South Africa. Milling of the material continued until 1983. The only treatment was the screening of fine material. Most of the phosphate produced in the 1980s contained about 29% P_2O_5. The fine material contained from 30.6% to 33.1% P_2O_5. Due to the high Fe_2O_3 content, the material was not suitable for fertilizer processing. The entire production was sold to Chemfos for production of elemental phosphorus and use in its chemical plant at Kookfontein.

Considerable ore resources grading 20% to 25% P_2O_5 remain in situ below the workings in the northwestern section of the mine (van Straaten, 2002). Dumps from the previous mine contain 2.5 million tons of minus 12-mm material; it was reported that a company, Fer-Min-Ore, was planning to leach the fines, containing an average of 20% to 37% P_2O_5, to produce phosphoric acid for animal feed products (van Straaten, 2002). Currently the fine ore is being beneficiated by flotation to produce a concentrate at over 36% P_2O_5; the concentrate is used for animal feeds (van der Linde, 2006, personal communication).

Palabora Deposit—The Palabora Igneous Complex is located in northeast Transvaal about 6 km northwest of the confluence of the Selati and Olifants Rivers (Figure South Africa 1). The mining property borders on the Kruger National Game Park.

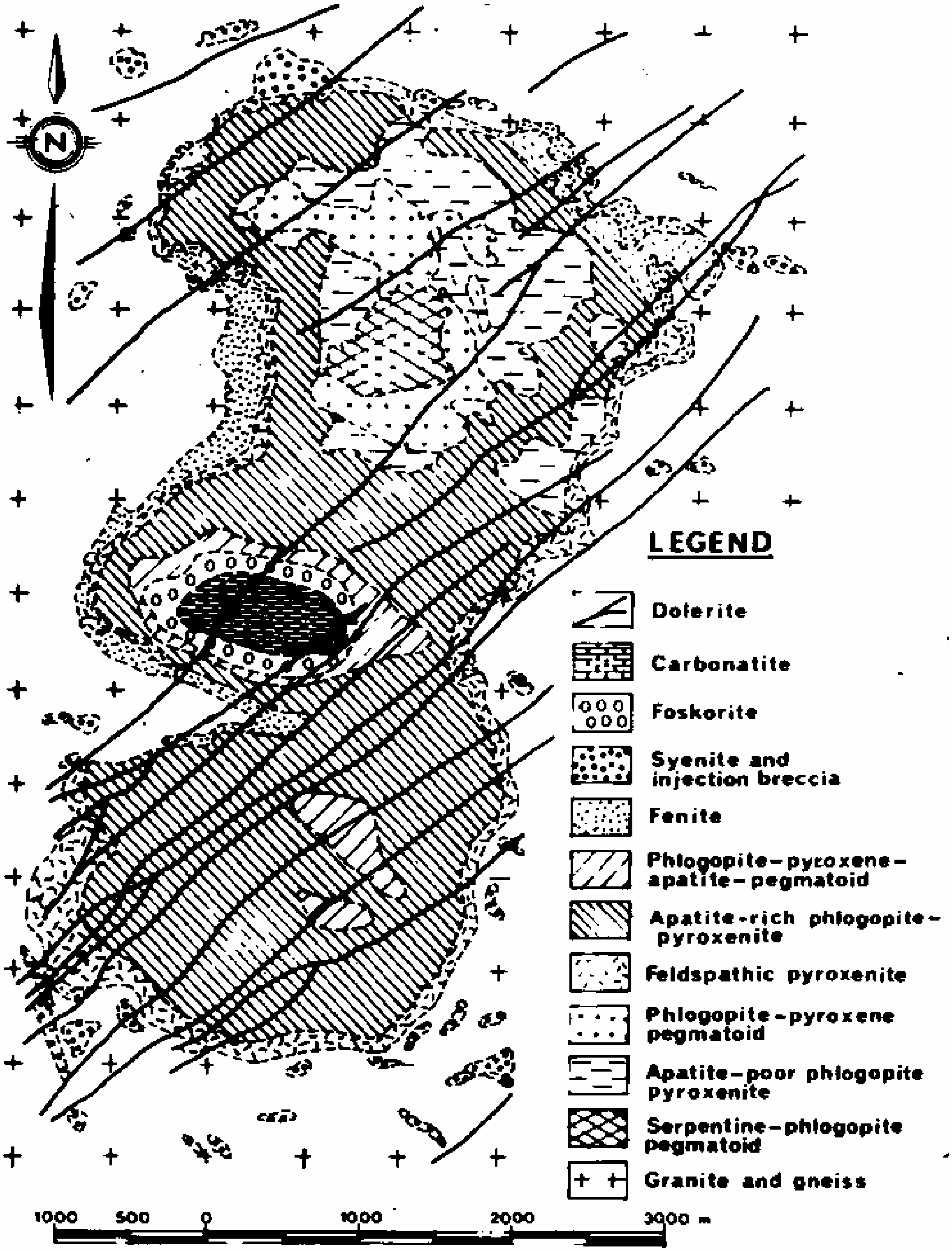
The Palabora Igneous Complex was intruded into the Archean granite-gneiss basement about 2 x 10^9 years ago (Savage, 1987). The complex consists of three lobes of pyroxenite, which form a kidney-shaped body elongated in a north-south direction and covering about 20 km^2 (Figure South Africa 2). The middle intrusion, originally called Loole Kop, has a carbonatite core surrounded by a foskorite zone (olivine [serpentine]-magnetite-apatite assemblage) and a pegmatoid zone. The foskorite is a very coarse-grained rock, and apatite crystals up to 10 cm in diameter have been observed. Foskorite, which represents about 3% of the complex, may contain 25% apatite, 30% magnetite, baddeleyite, and copper minerals.

Pyroxenite forms about 95% of the complex. Several varieties are present, including an apatite-rich type with an apatite content of approximately 17%. Apatite is more abundant in rocks containing higher amounts of phlogopite (Savage, 1987). The average P_2O_5 content of the massive pyroxenite, which contains less than 10% phlogopite, is about 6%. The P_2O_5 content in glimmerite (>75% phlogopite) may be up to 9%.

The north and south lobes have core areas that are composed mainly of pegmatoid. The north lobe has an arcuate zone of glimmerite to the west of the central pegmatoid body. The Foskor open pit is developed on this glimmerite zone.

The Palabora Deposit was initially worked for phosphate between 1930 and 1934, but activities were suspended. Foskor Limited (Foskor) was formed in 1951, and phosphate mining operations began in 1955. The original open pit was based on the central intrusion at Loole Kop. In 1966 the present mine was developed on the north ore body, and Palabora Mining Company Ltd. (PMC), part of the Rio Tinto Group, began development of the copper deposit. PMC produced about 80,000 tpd of copper ore up until 2002 when the copper mining operation changed from an open pit to an underground operation. At that time the amount of copper ore produced was to be reduced to 30,000 tpd. As a part of the agreement, Foskor has the rights to all the phosphate minerals in the PMC ore and any tailings. Two years after going underground, PMC had not met the production goal of 30,000 tpd. Production in 2004 averaged 23,500 tpd (PMC, 2004).

Foskor Limited was founded as a strategic state corporation to ensure a stable supply of internally produced phosphate rock for the South African fertilizer industry and South African farmers. Until 1997 Foskor focused on mining and beneficiation of phosphate rock for the domestic industry and export. In 1997 the government began privatizing many state-owned companies, and Foskor became the sole shareholder of Indian Ocean Fertilizers (IOF) (Foskor, 2005). In 2001, IOF became formally known as Foskor Richards Bay, and the Foskor Group was formed. Foskor Richards Bay produces phosphoric acid and phosphate fertilizers based on imported elemental sulfur and also sells some sulfuric acid to local markets. Foskor Palabora is the phosphate mine and beneficiation facility. Concentrates of copper are also recovered. Foskor Zirconia, near the mine site, produces fused zirconia products.



Source: de Jager (1989).

Figure South Africa 2. Geology of Palabora Igneous Complex

Foskor has received ore from several different sources over the life of operations. This includes pyroxenite ore from PMC pit development, foskorite ore low in copper values from PMC, tailings from the PMC copper operations if they are of suitable grade, and ore from the Foskor open pit. With the closing of the PMC open pit and reduction of copper ore output, the ore mix has changed and production from the Foskor open pit has been increased.

Mining is by conventional methods. Ore is broken by drilling and blasting. Large electric trucks are loaded using electric shovels and front-end loaders. The sides of the pit are sloped at 45° and originally benched at 12-m-high intervals. Run-of-mine ore from various sources is stockpiled near the beneficiation plant. A mobile crusher is used to reclaim stockpiles.

The several ore types available require different processing steps. Run-of-mine ores require several stages of crushing, followed by rod mill grinding. PMC tailings do not require this treatment. Several stages of flotation are required for effective separation and cleaning. Magnetite separation is part of the process. Byproducts include magnetite, baddeleyite, and a copper concentrate, which is sent to PMC. Phosphate concentrates are partly dewatered using thickeners and disk filters and conveyed to stockpiles. Concentrates from the stockpiles are dried in fluid bed and rotary dryers.

Originally a 30% P_2O_5 concentrate was produced (Savage, 1987). Numerous improvements to the process have been made over the years. Table South Africa 1 shows the chemical analyses of raw ore and concentrates PALPHOS 80M and PALPHOS 86S, the two primary phosphate rock products.

The PALPHOS 86S product is almost pure apatite. The main impurity in PALPHOS 80M is calcite, hence the high CO_2 content (4.2%). The apatite is an igneous hydroxylfluorapatite variety. Low NAC P_2O_5 values indicate it is not very soluble and has low potential for direct application.

Resources were indicated by Savage (1987) to be 3.0 x 10^{10} tons to a depth of 1,500 m. To a depth of 600 m, de Jager (1989) indicates in situ resources of 1.3 x 10^{10} tons at a grade of approximately 6.8% P_2O_5. Proven copper ore reserves in PMC's underground mine were 1.85 x 10^{10} tons (PMC, 2004). PMC mined and treated about 8.5 million tons of ore in 2004, The underground operation appears to be a significant source of feed to the beneficiation operation for the future although the amount of feed will be much less than when the open pit was in operation.

Table South Africa 1. IFDC Chemical Analyses of Palabora Ore and Concentrates

Chemical Analyses	Ore	Concentrate PALPHOS 86S	Concentrate PALPHOS 80M
P_2O_5	7.8	41.5	36.5
CaO	15.70	54.5	52.0
F	1.0	2.7	2.1
Na_2O	0.1	0.05	0.04
MgO	22.3	0.35	2.4
SiO_2	20.90	0.38	1.2
Al_2O_3	0.10	0.31	0.11
Fe_2O_3	18.60	0.28	0.54
K_2O	0.05	0.01	0.04
CO_2	NA[a]	0.40	4.20
Cl^- (ppm)	NA	300	300
Cd (ppm)	NA	1	NA
NAC P_2O_5[b]	NA	1.5	0.4
Free H_2O[c]	NA	NA	0.27
LOI[d]	NA	0.26	4.63

a. Not analyzed.

b. Neutral ammonium citrate soluble P_2O_5 (AOAC method).

c. Free H_2O = weight loss, 105°C, 1 h.

d. Loss on ignition = weight loss, 1000°C, 1 h.

Phosphate rock production in 2001 was 2,901,000 tons (Foskor, 2005). In 2002 production was 2,885,000 tons. Production dropped to 2,773,000 tons in 2003 and further dropped to 2,642,000 tons in 2004. Some recovery was made in 2005 as 2,791,000 tons was produced.

Foskor Richards Bay sold 437,000 tons of P_2O_5 as phosphoric acid in 2005 and 174,000 tons of granular fertilizer. About 200,000 tons of phosphate rock was exported.

Other Igneous Deposits—A volcanic vent outcrops on the farms of Kruidfontein, Boschkop, and Elandsfontein about 40 km east of Pilansberg, Rustenburg District, Western Transvaal. A dolomite carbonatite is found within one of the outer rings and is said to contain a fair amount of magnetite and apatite at its northern end (Savage, 1987).

On the farms of Spitzkop, Eenzam, and Rietfontein west of Lydenburg in Eastern Transvaal, a dolomitic carbonate is intruded into the Bushveld granites. Apatite forms from 4% to 25% of various rock types. Apatite is also reported in a lamprophyre that is part of a carbonatite intrusion at Magnet Heights, about 22 km from Spitzkop. Wilson (1998, as quoted in van Straaten, 2002) indicated that the apatite is finely intergrown with non-oxides and attempts to produce a concentrate with more than 20% P_2O_5 proved difficult. About 70 km east of Louis Trichard, apatite crystals occur in pyroxenite and phoscorite associated with a carbonatite in the Schiel Complex. Reserves are estimated to be 36 million tons at 5.1% P_2O_5 (Savage, 1987).

Apatite occurs irregularly and sporadically in veins, lenses, and pockets about 15 km east-northeast of Bandolier Kop in the Soutpansberg District of Limpopo Province (Northern Transvaal). The South African Phosphate Exploration Syndicate Ltd., claimed to have outlined 100,000 tons of rock with 10% to 26% P_2O_5. The company moved on to the more promising Palabora Deposit (Savage, 1987).

Sedimentary Phosphate Deposits—Sedimentary deposits in South Africa occur in rocks ranging from Karroo to recent ages.

Cape Coast Deposits—Late Tertiary sedimentary phosphate deposits occur along the coast between Cape Town and Hondeklip Bay to the north. In the Varswater Formation, up to 20 m of phosphatic medium-grained sand with up to 20% P_2O_5 occurs. Secondary cementation produces lithified bodies within the formation. The entire sequence is overlain by sterile aeolian sands in many areas. Secondary cementation also occurs in underlying rocks including granites and other rock types.

The Varswater Deposit was owned by SA Manganese Simor Ltd. (Samandor) and worked by Chemfos Ltd., a subsidiary. In 1943 a 16% P_2O_5 ore was mined by surface methods and treated at a plant in Bellville. Exhaustion of the reserves resulted in the opening of another area in the 1960s. In 1965, a beneficiation plant was built at Langebaan Road and the original Bellville plant was closed.

The deposit had an average thickness of 10 m over an area of 5 km^2. There were two phosphate beds. Rippers loosened and bulldozed the overburden, and it was removed by scrapers and hauled to the mine dump. Limestone overburden was blasted at times. The deposit was worked on two benches by a power shovel and a dragline. Regular sampling and pit control were used to provide a consistent plant feed in that the ore beds had varying grades.

Ore boulders were stockpiled and crushed. A minor fraction (3%) of the ore required primary crushing. The ore was slurried and deslimed using hydrocones. The slurry was fed to conditioning tanks at 60% solids, and flotation reagents were added. Direct phosphate flotation produced a 29% to 30% P_2O_5 concentrate. The concentrate was filtered and dried using two oil-fired rotary dryers. The concentrate was sometimes mixed with ore to produce a direct-application product called Langfos. After 1969 Langfos Premium with 29% P_2O_5 was produced and sold (Table South Africa 2). In 1977 the capacity was 250,000 tpy; however, the mine was put on care and maintenance until market conditions improved. The deposit produced about 24 million tons before it was closed in 1992 (van Straaten, 2002). Some 25 million tons of ore at 8.5% P_2O_5 remain as proven reserves.

Table South Africa 2. Chemical Analysis of Varswater Phosphate[a]

	%
P_2O_5	29.2
CaO	42.2
Fe_2O_3	1.7
Al_2O_3	1.9
CO_2	2.4
F	2.9
Ti	0.5
SiO_2	14.0
Mg, Na, K	Traces

a. Described by Hendey and Dingle (1989) as phosphorite from the Varswater orebody. However, this is believed to be the beneficiated product at 29% P_2O_5.

There are several other phosphate occurrences in the area. North and east of Varswater, sheet-like beds of hard ferruginous phosphatic material occur; they are 0.6-1.8 m thick, and the average P_2O_5 content is 9%. Chemical analyses of the material indicate it contains iron-aluminum phosphates. Resources of these ferruginous phosphorite reserves are estimated at 6 million tons.

Concretionary lumps and nodules of phosphate were mined from an area west of Langebaan Road Station. The material averaged 22.80% P_2O_5. Small reserves of lower grade material still exist in the area.

The Saldanha Bay Aluminum Company worked small deposits of iron-aluminum phosphates on Constable Hill near Saldanha Bay. The material averaged 22.30% P_2O_5, a trace of CaO, and 19.40% Al_2O_3. Reserves may be on the order of 270,000 tons at 27.5% P_2O_5 (Savage, 1987).

Lenticular deposits of phosphatized calcareous sandstone occur near Mamre Mission Station, about 65 km north of Cape Town in the Darling Division (Savage, 1987). There are two horizons separated by 3 to 3.5 m of clay. The upper horizon contains 21% to 27% P_2O_5 and is about 7 m thick. The resource estimate for the deposit was 50,000 tons.

Hendey and Dingle (1989) provided the following resource estimates for other deposits in the southwestern Cape area.

Board's Quarry–to north (mined out)	907,000 tons @ 12.8% P_2O_5
Old Varswater Quarry (mined out)	5 x 10^6 tons @ 8.0% P_2O_5
Sandheuwel Area (north of Saldanha)	
Sandheuwel	23.6 x 10^6 tons @ 6% P_2O_5
Langloagte	2.7 x 10^6 tons @ 4% P_2O_5
Witteklip	3.9 x 10^6 tons @ 5% P_2O_5
Paternoster Area	
Pelgrimsrust	10 x 10^6 tons @ 5% P_2O_5
Noodhulp	2 x 10^6 tons @ 4% P_2O_5
Duyker Eiland (west of St. Helena Bay)	3.55 x 10^6 tons @ 9.5%-10% P_2O_5

Karroo Deposits—Phosphate nodules and lenses occur in ferruginous sandy shales over a 320-km-long zone between Matjesfontein and the Sundays River (Savage, 1987). There are two zones in the shale. The lenses are difficult to separate from the upper zone. Large concretions (up to 6 m in diameter and 30 cm thick) weather freely from the lower zone. It was estimated in 1940 that 22,000 tons could be recovered relatively easily, but the material is not chemically suitable for fertilizers or animal feeds.

Weenan—Phosphate concretions occur in the Upper Ecca shales on the Lommonage Farm, and on several adjoining farms at Weenan, Natal (Savage, 1987). The nodules occur in lenses that may be up to 0.5 m thick and 45 m long. Individual nodules assay <23% P_2O_5. The average P_2O_5 content of a reef may be about 4%.

A bed of nodular phosphate in Miocene age beds in the Uloa area along the Umfolosi River in coastal northern KwaZulu-Natal was described by Frankel (1966). The refractive index reported (1.622) indicates the material is a carbonate-substituted francolite. No further details are available on this occurrence.

Replacement Deposits—An aluminum phosphate deposit occurs on the Zoetendalesvlei Farm near the Magalkwen River 112 km northwest of Potgietersrus. Dolerite dikes and sills that were intruded into the Waterberg sandstone have been phosphatized by guano from birds nesting in the cliffs above (Savage, 1987). In 1959, reserves were estimated as 40,000 tons at about 24% P_2O_5. The deposit was exploited at one time by the Pretoria North Development Co. (Pty.) Ltd.

A similar occurrence of iron-aluminum phosphate containing 30% P_2O_5 occurs in a diabase sill at the base of a cliff at Kluitjiesfontein, Transvaal. Savage (1987) indicates the occurrence has no economic significance.

Offshore Deposits—The first phosphate samples to be recovered from the sea floor were dredged from the Agulhas Bank south of Cape Town by the HMS Challenger in 1873 (Savage, 1987). Phosphorites are exposed in extensive areas on the Agulhas Bank and off the western margin of South Africa. Age dates on areanceous material are as old as early Oligocene to Mid-Eocene while age dating of the diagenitic material ranges from Early-Eocene to the Pleistocene (Birch, 1990).

Samples of phosphorites from the Agulhas Bank generally show P_2O_5 contents between 10% and 25%. Erosion of outcropping Tertiary beds is considered to be the source of unconsolidated sands and gravels of Tertiary to Pleistocene ages that occur offshore. These sediments generally contain up to 10% P_2O_5. Assuming an average P_2O_5 content of 16% and thickness of 0.5 m, the Agulhas Bank deposit contains 5,500 x 10^6 tons P_2O_5 and the western margin offshore deposit contains 3,500 x 10^6 tons P_2O_5 (Birch, 1990).

Experiments by Foskor indicated that powdered Agulhas Bank material compares with superphosphate in terms of phosphate availability (Savage, 1987). Relatively young phosphorites that have not been exposed to weathering generally contain some of the most highly carbonate substituted francolites (McClellan and Van Kauwenbergh, 1991). Consequently, such francolites are highly reactive, and phosphate rocks containing these highly substituted francolites are among the most desirable for direct application, under suitable agroclimatic conditions.

Guano—Several small islands north of Cape Town were mined for guano at the beginning of the 20th century (Hutchinson, 1950). Tonnages mined from the islands were relatively small.

Sulfur Resources

Sulfur (S) and sulfuric acid are produced in South Africa from pyrite byproduct, which results from beneficiation and washing in the metals and coal mining industry, from smelting off-gases, and from petroleum refining and the production of synthetic fuels. The United States Geological Survey (USGS) lists the following production of sulfur for South Africa for 2003 (USGS, 2005):

Sulfur	2003
	(tons)
Pyrite, 53.75% S	175,000
Byproduct	
Metallurgy	316,000
Petroleum	123,000
Total	**614,000**

PMC, the only South African copper smelter, produced 104,259 tons of 100% sulfuric acid in 2004 (PMC, 2004).

South African coal contains about 1.2% sulfur (EIA, 2004). Pyrites from South African gold deposits in greenstones are generally unsuitable for sulfuric acid production because they have high arsenic levels. While significant tonnages of sulfuric acid are produced in South Africa, Foskor Richards Bay imports elemental S for phosphate fertilizer production.

Gypsum deposits are found in Northern Cape Province. The gypsum layer is approximately 3 m thick, and reserves are in excess of 30 million tons (Oosterhuis, 1998). Byproduct gypsum is produced from phosphoric acid manufacturing by Foskor Richards Bay. Production of crude gypsum in South Africa was 394,069 tons in 2003 (USGS, 2005).

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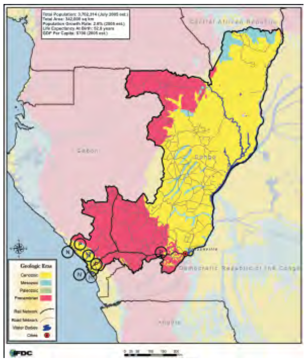
REPUBLIC OF THE CONGO



The Republic of the Congo (Figure Republic of the Congo 1) is bordered to the north by Cameroon and the Central African Republic; the east and south by the Democratic Republic of the Congo; the south by the enclave of Cabinda (Angola); and to the west by Gabon and the Atlantic Ocean. Total area is 342,000 km^2 and 1.45% of the land is arable. The population was estimated as 3.7 million inhabitants in mid-2005 (World Factbook, 2006).

The transportation network comprises 1,242 km of paved roads, 11,588 km of unpaved roads, and 894 km of 1.067-m-gauge railway. There are 4 airports with paved runways and 28 airports with unpaved runways. Including the coast on the Atlantic Ocean and the Congo and Oubangui River, there is 4,385 km of waterways. Brazzaville is the main port on the Congo River, and Pointe Noire is the main port on the Atlantic Ocean. There is a 53-km gas pipeline and a 646-km oil pipeline within the country.

Precambrian rocks are found in the area between the Gabon-Cabinda Basin and the Congo Basin, and in the northwest of the country. Lower Proterozoic gneisses, migmatites, and granites followed by overlying quartzites, mica schists, amphibolites, and porphyritic lavas form the core of the southern Precambrian area. The Mayombe Range forms the eastern border of the southern Precambrian area and the western border of the Congo Basin. The Mayombe System, which is probably Middle Proterozoic in age (Boss et al., 1996), is composed of conglomerates, arkoses, chlorite schists, quartzites, and volcanics. The West Congo System of Upper Proterozoic age consists of sandstones and argillite at the base with limestones, dolomites, and marls in the section above. Granitized Precambrian rocks occur in the Chailu Massif in the northwest of the country.

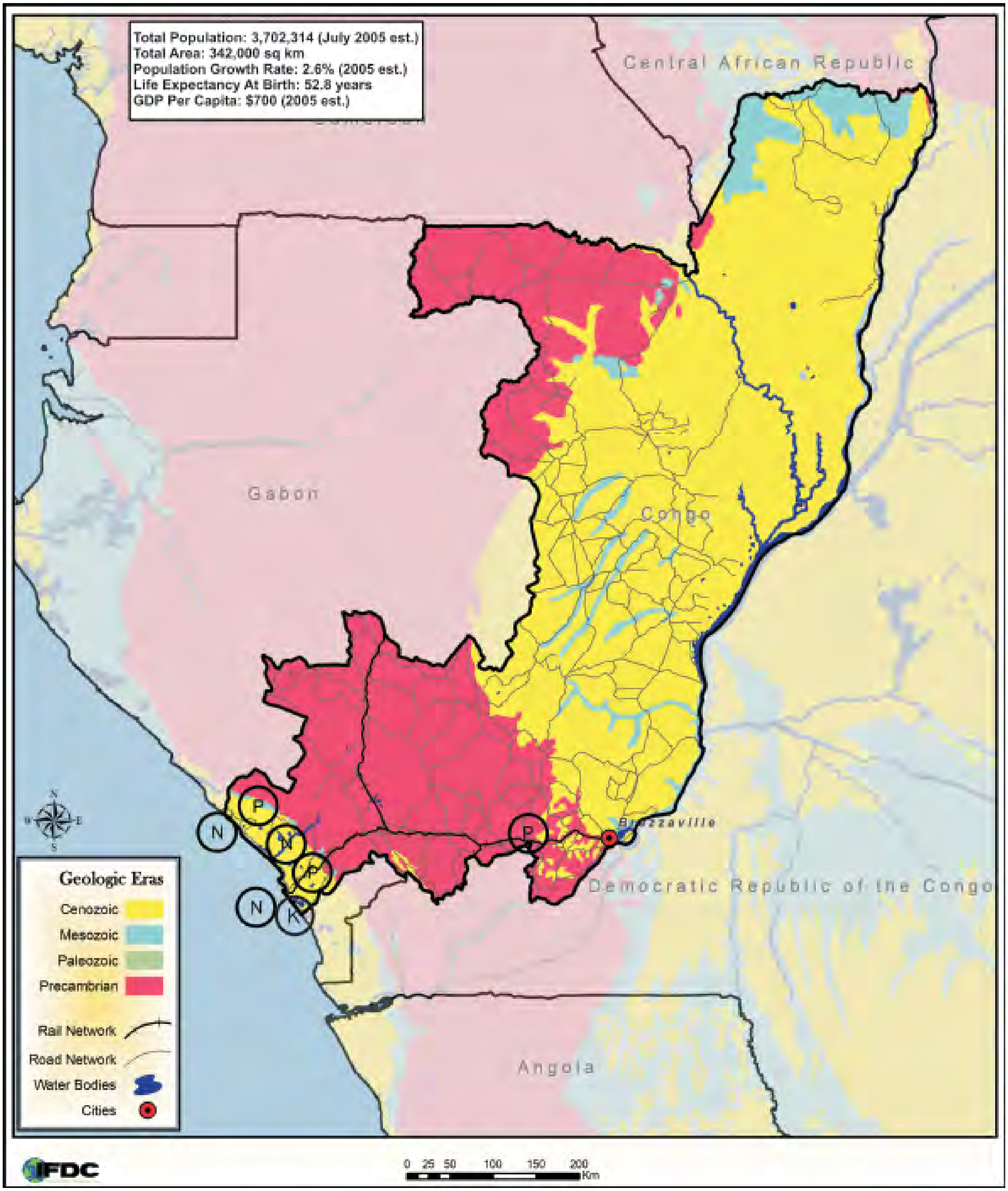
Cretaceous age rocks (conglomerates, sandstones) underlie younger sediments both of the Congo and Gabon-Cabinda Basin. In the interior these sediments, and the following Tertiary sediments, are of continental origin. The overlying Tertiary and Quaternary sediments of the Gabon-Cabinda Basin are primarily of marine origin.

Nitrogen Resources

Oil production from the Republic of the Congo increased from 65,000 barrels per day (bpd) in 1980 to an average of 280,000 bpd in 2000, the peak year of production. Production has steadily declined since then (235,500 bpd in 2004) but is expected to rebound when new fields come online and offset declining production from older fields (EIA, 2005). The Republic of the Congo is the fifth largest oil producer in sub-Saharan Africa after Nigeria, Angola, Gabon, and Equatorial Guinea. In 2000 it was the fourth largest producer.

The Société Nationale des Pétroles du Congo (SNPC) regulates many of the operations in the oil industry. Production-sharing agreements (PSAs) have been used primarily since 1994. In the Congo, PSA partners carry out exploration and development for an agreed period, financing all investment costs and recovering costs when production begins. Approximately one-third of the oil produced goes directly to the government, and SNPC markets it on behalf of the government. The main export blend is Djeno, which has a 27.6º API gravity and a 0.23% sulfur (S) content (EIA, 2005). The oil is classified as medium gravity and sweet.

Through its local subsidiary, Elf-Congo, Total S.A. (France) is the leading oil producer with about two-thirds of all the Congo's output. Total S.A.



Total Population: 3,702,314 (July 2005 est.)
Total Area: 342,000 sq km
Population Growth Rate: 2.6% (2005 est.)
Life Expectancy At Birth: 52.8 years
GDP Per Capita: $700 (2005 est.)

Figure Republic of the Congo 1. Geology, Major Cities, and Transportation Network

operates the largest field (N'Kossa) and hopes to increase output when new fields come onstream. Agip (Italy) is the second largest producer in the Republic of the Congo and produces approximately 25% of the Congo's output.

Fields under development or recently brought onstream include Bilondo, Libondi, Litanzi, Moho Nord, Moho Sud, Nikoso Sud, N'Soko, and Yanga Sud oil fields and the offshore K/A-IMI Unit, which is jointly administered by the Republic of the Congo and Angola (Mobbs, 2004). Exploration wells are currently being drilled on deep-water prospects, and offshore exploration is expected to increase further offshore, similar to what has occurred off Cabinda and Angola.

Although the majority of the Republic of the Congo's natural gas reserves are associated with oil, the country contains some major nonassociated gas fields including the offshore Banga Marine and Litchendjili Marine fields. Most of the Republic of the Congo's associated gas is vented or flared because of a lack of markets and infrastructure. About 3 million m^3/day was being flared in 2003 (Mobbs, 2004).

Agip and ChevronTexaco's 25-MW natural gas-fired power plant in Djeno near Pointe Noire was completed in December 2002 at a cost of US $32 million (Mobbs, 2004). The plant is fueled by associated natural gas from the Kitina, Djambula, and Fonkauda offshore fields, which is separated at the Djeno oil terminal and piped to the plant. The government hopes to use natural gas to fuel power plants in the future.

Estimated proven reserves of oil are 1.5×10^9 barrels (EIA, 2005). Estimated natural gas reserves are 90.6×10^9 m^3 (EIA, 2005; World Factbook, 2006).

The nameplate capacity of the Republic of the Congo's refinery is 21,000 bpd (EIA, 2005). The refinery only supplies the domestic market and often operates at less than half capacity. The Congo government has expressed an interest in privatizing the operation. Mobbs (2004) does not list any production of refined petroleum for the Republic of the Congo since 2002.

Phosphate Resources

Much of what is known about the phosphate resources of the Republic of the Congo is summarized in the work of Giresse (1980a), who gave an overview of the previous work concerning exploration in several areas. Giresse also reexamined outcrops and drill cores (or cuttings) from previous programs. Phosphate-bearing layers were discovered in the Republic of the Congo during oil exploration activities, and a phosphate horizon was discovered in the Sintou-Kola area. After World War II, deposits were discovered in the Holle area, mainly in the Koubambi and Tchivoula Valleys.

The Holle area deposits were investigated between 1955 and 1957 by the Syndicate de Recherches de Phosphate au Moyen–Congo when the feasibility of exploiting the deposits was under consideration for elemental phosphorus production with power supplied by the Kouilou Dam project (Savage, 1987). Several discoveries were made to the south of Holle (Djeba, Loufica, Tchioupi, Zonde) towards the Cabinda border. The presence of aluminum phosphates at the top of the section had the interest of the Society Pechiney of France for some time (Giresse, 1980a). Elevated uranium contents led to exploration by Commissariat à l'Energie Atomique (CEA) of France. The occurrences were reevaluated with Soviet and Bulgarian assistance. Giresse (1980a) indicates that this work studied known occurrences and did not provide much new information.

Early Cretaceous sediments overlie the Mayombe Series Precambrian basement rocks. Early Cretaceous sediments are represented by conglomerates, sandstones, unfossiliferous marls, and limestones. These strata pass locally into an evaporate sequence to the west. The late Cretaceous rocks along the coast are generally covered by Plio-Pleistocene Terminal Continental deposits.

The Senonian transgression reached its maximum during the Santonian stage. Phosphates were deposited after this transgression. The phosphate-bearing Holle Series is Maastrichtian in age. Giresse (1980a) indicates that the phosphate layers show a marked littoral, even lagoonal character. The phosphate occurrences are in very narrow belts along strike, no more than 750 m in width, which continue over considerable distances within small valleys in the Holle area.

The exposures occur on subsided blocks, which Giresse (1980a) indicates may have preserved the beds from subsequent erosion. The top of the Holle Series, which is frequently altered to aluminum phosphates, is probably of Paleocene age.

Holle Deposits—The Holle Series is composed of pebble, sand, clay, and sandy clay lenses that are all more or less phosphatized. The thickness generally does not exceed 10 m, but is variable. There are two facies. The coprolitic–quartzose facies is composed of a conglomerate of quartz pebbles, shark teeth, coprolites, and fish bones. The phosphate-siliceous facies is a finer grained detrital facies with a phosphatic or a quartzose cement.

Phosphatic lenses in the area of Loéme are 1,500 m long, 200 m wide, 15-20 m thick, and contain phosphate reserves of nearly 1,850,000 tons (Giresse, 1980a). Further north and south, drilling penetrated irregular lenticular phospho-siliceous layers with a maximum thickness of 2-3 m. The highest phosphate contents were formed in the coarsest layers.

In the Koubambi River Valley, silicified phosphate nodules were found containing up to 38% P_2O_5. The phosphate beds in this area were apparently quite erratic, and there are no resource estimates for this area.

In the area of the Tchivoula and Akossali Rivers, four lenses were located that contain 3,200,000 tons of resources. The coprolitic-quartzose facies makes up almost the entire section, and it is up to 10 m thick.

Toward Cabinda, phosphate layers have been observed at Djeba, Djenguessé, Kintanzi, Tchioupi, and Zonde. Giresse (1980a) indicated that in the direction of Cabinda several factors appear to be favorable: the cover is preserved, mechanical erosion and alteration are limited, and the deposits are homogeneous. Giresse (1980a) indicated further exploration should be directed to this area.

The Giresse analysis (1980a) included estimations of the composition of the Congo apatite by several methods. The analysis indicated the apatites could be equally well classified as fluor-apatites or carbonate apatites. At this time it was not known that the composition of apatites can vary within deposits and the composition may be related to weathering and or reworking (McClellan and Van Kauwenbergh, 1991; Van Kauwenbergh and McClellan, 1990). Examination of apatite unit cell data in Giresse (1980a) indicates that the apatites are francolites. Apatites from the coprolitic-quartzose facies, the facies that appears to have been significantly reworked, have higher unit cell a-values than apatite samples from the phosphate-siliceous beds. This indicates the apatite in the reworked beds has a lower CO_2 content and may have been altered from an original composition with a higher carbonate content.

Samples from mining studies have P_2O_5 contents in the range of 11.5% to 25%, and the indurated nodules found at N'Tete may have 32% to 37% P_2O_5. The contents of Fe_2O_3 (0.5%–3%) and Al_2O_3 (1.5%–4.5%) vary significantly. Aluminum phosphate found at the top of the phosphate section contains an average of 16.3% P_2O_5, 14% Al_2O_3, and 46.8% SiO_2. The reserve estimate total of 5 million tons is based on phosphate rock layers that contain a minimum of 22% P_2O_5 (Giresse, 1980a).

McClellan and Notholt (1986) indicate that an approximate 34% P_2O_5 product could be obtained from these deposits by heavy-media separation or flotation. An approximate 30% P_2O_5 material could be obtained by mechanical sorting and particle size separation with a recovery rate of 40% to 50%.

Kola Deposits—The Kola area is found in the northwest of the country mainly to the east of the Noumbi River Valley. Phosphate rock outcrops of the Holle Series in this area are restricted to the bottoms of the Celo, Tchessa, M'Bandza, and Missiéssi Valleys. The phosphates are related to an anticlinal structure terminated to the north by a fault and plunging to the south under the swamps of the Kouilou area. All measured dips were less than 10%.

The phosphate rock strata consist of very lenticular soft phosphatic sandstones and marls. The phosphate particles include grains, teeth, scales, and vertebra. The beds average about 2 m in thickness and contain an average of 21% P_2O_5. The tonnage in the area was estimated at less than 300,000 tons (Giresse, 1980a).

The description found in Savage (1987) indicates that the deposits are an extension of the deposits at Holle. To the west the deposits can probably be correlated with phosphate occurrences in neighboring Gabon.

Offshore Congo—Discovery of phosphate sediments offshore of the Republic of the Congo resulted from work undertaken by the Office de la Recherche Scientifique et Technique d'Outre-Mer (ORSTOM) and by the Département de Géologie de l'University Marien Ngouabi in Brazzaville (Giresse, 1980b; Giresse et al., 1981; Barusseau et al., 1988; Sustrac et al., 1990). Between 1970 and 1978, eight offshore programs were completed representing 450 dredgings, 150 cored holes in rock, and 50 Kullenberg cores of sediments. The work identified an area of interest off Pointe Noire. Further investigations began in Gabon under a program called PHOSCAP jointly conducted by CNEXO (changed to the Institut Français pour la Recherche en Mer [IFREMER]), the Bureau de Recherches Géologiques et Minières (BRGM), and other companies, and with the assistance of the oceanographic research ship Capricorn. Work covered an area 150 km long and 35 km wide inshore of the 100-110 m isobath. The study collected 400 surface samples, 82 vibracores (3 m), and 65 dredging samples. Seismic profiles 5-10 km apart were run in this area.

The phosphate concentration discovered south of Pointe Noire was subsequently prospected through the United Nations Revolving Fund for Natural Resource Exploration (UNRFNRE). Through contractors, UNRFNRE conducted seismic profiling and sampling in an area of about 81 km^2. Probable reserves were reported as 7 million tons of phosphorite (van Straaten, 2002).

As a part of these studies, IFDC analyzed eight samples for the Mississippi Mineral Resources Institute at the University of Mississippi (U.S.A.). The chemical analyses of two selected samples are given in Table Republic of the Congo 1. The P_2O_5 contents of the eight samples ranged from 0.49% to 33.4%. The unit cell a-values of the apatite of four of the samples averaged 9.323 Å indicating a francolite with 6.2 wt % CO_2 substitution. The neutral ammonium citrate (NAC)-soluble P_2O_5 of Dredge Sample 31, which contained very little free carbonate, was 7.7%. This value is near the top of the range for carbonate substitution of francolites, and such a phosphate rock would be a very good candidate for direct application under suitable agroclimatic conditions.

Table Republic of the Congo 1. Chemical Analyses, Selected Congo Offshore Samples

Chemical Analysis	Sample No.	
	Dredge 31	Rock Fragment 31
	wt %	
P_2O_5	30.7	14.0
CaO	50.2	48.7
F	3.5	2.2
SiO_2	0.66	4.3
Fe_2O_3	5.6	6.1
Al_2O_3	3.5	1.2
Na_2O	1.2	0.74
MgO	0.63	2.40
K_2O	0.02	0.22
CO_2	5.8	22.10
NAC P_2O_5[a]	7.7	1.5

a. Neutral ammonium citrate-soluble P_2O_5 (AOAC Method).

Comba Deposit—Late Precambrian strata of the Serie Schisto-Calcaire contain phosphate nodules with 28% to 35% P_2O_5. The nodules are found in the middle Niari Valley near Comba, 110 km west of Brazzaville (McClellan and Notholt, 1986). Little is known of this occurrence.

Potassium Resources

The Congo potash deposits are a part of an extensive evaporite basin that extended along the western continental margin of Africa from Angola to Gabon prior to and during the opening of the Atlantic Ocean. The Sergipe Deposit in Brazil, on the other side of the rift, is very similar mineralogically and was formed at approximately the same time.

The Congo potash deposit contains medium-to-small sylvite-bearing sylvinite formations with unusual mineral assemblages. There are commercial quantities of sylvinite, considerably more carnallite, significant amounts of tachyhydrite, and smaller quantities of bischofite ($MgCl_2•6H_2O$) in the deposit. The deposit essentially contains no carbonates (calcite or dolomite) or gypsum (or anhydrite), except at the top of the formation. The lower sections of the basin are filled with land-derived sediments, and the halite rests directly on these sediments. Potash occurs at the edge of the basin, instead of in the more common structure of halite and/or anhydrite and dolomite surrounding the potash and covering a much wider area.

Garrett (1996) indicates that the Congo and Sergipe deposits in Brazil may be of continental and not of marine origin. The potash source could have been geothermal brine with a high calcium (Ca) content similar to the brines emitted from the rift zones of the Red Sea or Salton Sea. The Congo and Brazil deposits are of identical age (Lower Cretaceous, Aptian). Wardlaw and Nicholls (1972) have shown that the Congo and Brazil deposits contain very similar concentrations of 10 trace elements, and a number of the concentrations of these elements are quite different from those found in other potash deposits. Only very hot Ca-rich brines (such as now occur at Lake Magadi, Kenya, depositing soda ash) could crystallize such massive deposits of extremely hygroscopic tachyhydrite and bischofite. Potash occurs primarily around the edges of carnallite zones in these deposits, having been formed by water intruding into the carnallite, which was then converted to sylvinite. The Congo deposit (Holle) contains less sylvinite, about the same amount of carnallite (estimated at 15% of the total salts), and more bischofite than the Sergipe Deposit in Brazil. A "normal" depositional sequence of thin black shales is followed by halite and then carnallite, with some zones converted to sylvinite. In most areas the uppermost mineralized zones contain tachyhydrite or bischofite.

A commercial potash operation was initiated in 1969 but encountered many mining problems leading to poor productivity. The sylvinite beds were more irregularly developed and unpredictable than foreseen. The mine was run continually at a loss, and only in one year were the operating costs recovered (DeRuiter, 1979). The sylvinite beds were often thin and not very continuous; they were irregular in dip and variable in composition, and they occurred within an oddly shaped area (a large U). At Holle, sylvinite was found primarily in the second highest salt (ninth evaporate) cycle in four separate beds. Two layers, beds 3 and 7/8, were mined. In the mining area, the upper bed (7/8) occurred at a depth of 288-380 m over an area of 28 km^2 and averaged 18% K_2O. Bed 3, which was 10-20 m below bed 7/8, had an average thickness of 3 m with an ore grade up to 38% K_2O and only 0.1% insolubles.

After extensive studies, an economically viable project to produce 1,000,000 tons of potassium chloride (KCl) per year from carnallite was envisioned (DeRuiter, 1979). The great thickness and continuity of the carnallite layers and use of the existing infrastructure of the sylvinite mine would offset the additional costs of processing carnallite to produce KCl. During the boring of the carnallite trial galleries on June 20, 1977, water began to seep through the roof. The high solubility of the carnallite led to a rapid increase of water influx, and within 36 hours the entire mine was flooded. Most of the equipment was lost, and the mine was abandoned. In recent years there have been several proposals to reopen the mine as a carnallite mine because of the thickness and uniformity of the carnallite beds.

MagIndustries Corp. indicated on March 30, 2006, that its wholly owned minerals division, MagMinerals, had received the results of a Phase I feasibility report for the development of its Kouilou Potash Project, located near the Atlantic port city of Pointe Noire in the Republic of the Congo (*Green Markets*, 2006). Genivar Consulting Group of Montreal prepared the study based on using solution mining technologies to produce potash from the company's 100%-owned carnallite deposits, which underlie the majority of the 2,200-km^2 Makola License. This is the license area that supported the commercial underground potash production in the 1970s. MagMinerals is currently continuing with a program of drilling, including the installation of commercial-scale wells. Solution mining would produce potash-rich brine that would be treated in a crystallization plant to produce granular and standard-grade potash fertilizers for export. The potash plant would utilize commercially available technologies. One of the primary inputs for this crystallization process is heat that could be produced from natural gas, which is available locally.

The report identifies two potential scales of potash production. At a production rate of 600,000 tpy, the project has a capital cost of US $412 million with an internal rate of return (IRR) of 23% and a net present value (NPV) of US $193 million. At a production rate of 1,200,000 tpy, the project has a capital cost of US $665 million with an IRR of 28% and an NPV of US $493 million. MagIndustries began a series of meetings in early 2006 with equity and debt investors prior to the completion of Phase II of the study. This project is also a part of an integrated project to produce magnesium metal.

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SENEGAL

Senegal is bordered by the Atlantic Ocean to the west, Mauritania to the north, Mali to the east, and Guinea and Guinea-Bissau to the south. Total area is 196,190 km^2; 12.8% of the land is arable. The total population was estimated as 11.1 million inhabitants in mid-2005 (World Factbook, 2006). Annual population growth is 2.5%. Approximately 77% of the labor force is occupied by agriculture.

The transportation network (Figure Senegal 1) consists of 4,271 km of paved roads and 10,305 km of unpaved roads. There is approximately 1,000 km of navigable waterways, primarily on the Senegal, Saloum, and Casamance Rivers. There are nine airports with paved runways.

The geology of Senegal is dominated by two features (Figure Senegal 1). Folded Precambrian to Paleozoic rocks associated with the Mauritanides Belt are located in the far east of the country. The Precambrian is subdivided into the Birimian Volcano-Sedimentary Sequence, the Madina-Kouta Basin Series, and two folded Neoproterozoic/Cambrian Panafrican mountain ranges: the Bassaride Branch and the Koulonton Branch. The Lower Cambrian, composed of tillites, cherts, and limestones, is found in the Faleme Basin. A basin between the Panafrican sequences is filled with Cambro-Ordovician conglomerates, mudstones, and sandstones.

The Senegal Basin is the largest of the coastal basins of West Africa. Total thickness of the sediments may be up to 10 km. Deposition began in the Jurassic. North-south tending growth faults occur in about the area of the present coast. The faults may have been pathways for magmas which intrude the sediments. Salt domes, originating from Jurassic evaporites, lie offshore and intrude Cretaceous and Tertiary sediments. The oldest exposed sediments are from the Cretaceous. The Tertiary sequence is relatively thin; it is no more than 600 m thick.

Nitrogen Resources

Senegal has sporadically produced oil in the past and continues to produce a limited amount of natural gas. The Société des Petroles du Senegal (Petrosen) noted that crude oil production from the Diam Niado Field peaked in 1988 at a little over 18,000 barrels, and condensate production peaked at over 14,000 barrels in 1998 (Petrosen, 2006). Since 2002, oil production has been practically nil. At the present time a pipeline connects a well (or wells) in the Godiaga Gas Field to a storage facility at Kabor. The gas is transmitted through a 6-inch pipeline to a facility run by the Société Nationale d'Eléctricité du Senegal (Senelec) at Cap des Biceps to generate electricity. The well is producing 60,000 m^3/day. All the production is utilized to produce electricity.

More than 140 exploratory wells have been drilled in the Senegal Basin. Most of the wells have been concentrated in the Cape Vert Peninsula and offshore of the Casamance River. The Dome Flore Block on the offshore border with Guinea-Bissau has generated many hydrocarbon shows mainly associated with the Dome Flore and Dome Gea salt domes. Heavy-oil accumulations in the Dome Flore prospect are estimated at 500 million to 1 billion barrels in Oligocene limestone (Petrosen, 2003a). Light-oil accumulations have been encountered in Maastrichtian age sands. Wells drilled on the Dome Gea southwest of Dome Flore indicate heavy oil in Oligocene limestone as well as light oil in lower Miocene sands.

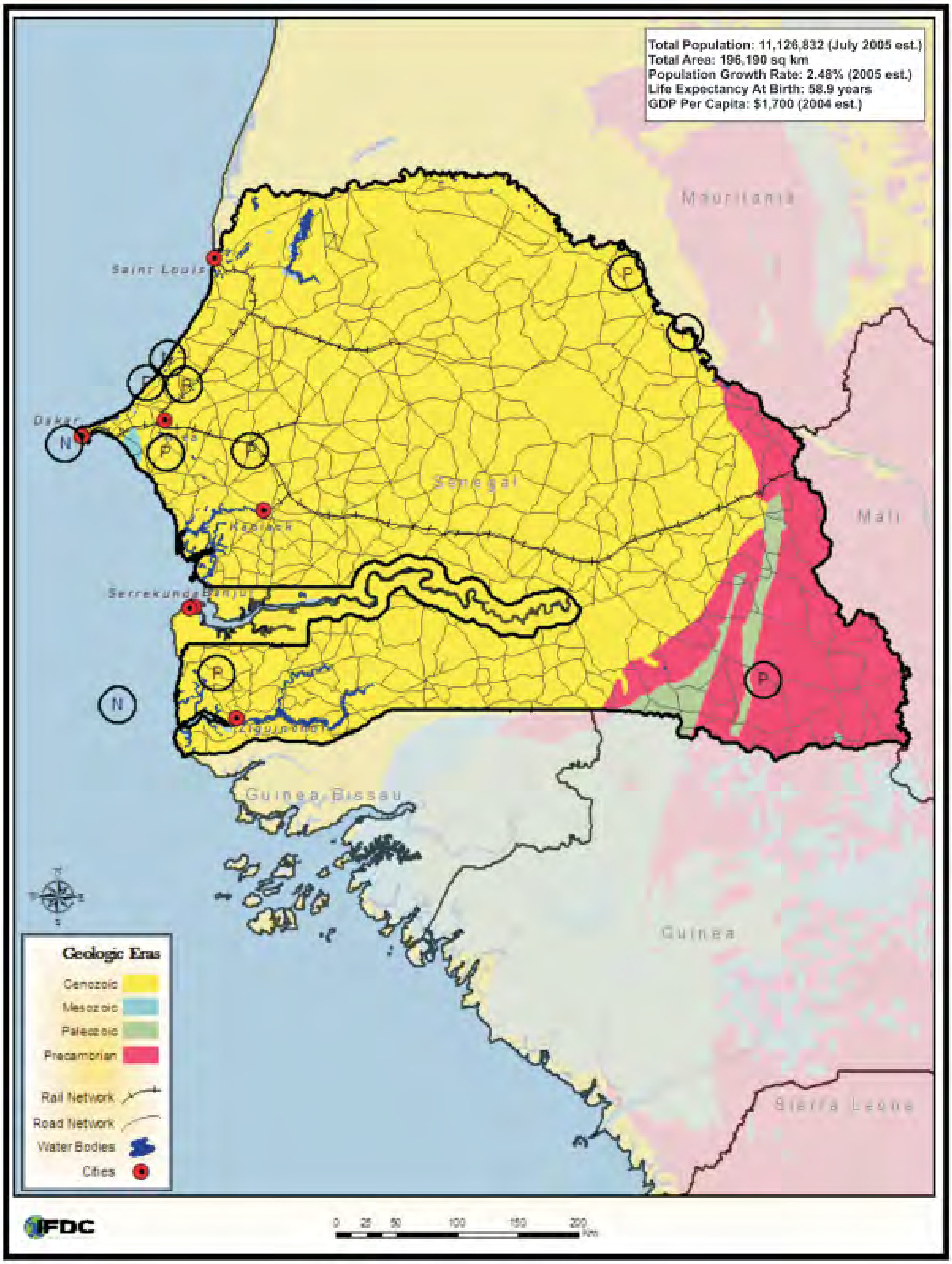


Figure Senegal 1. Geology, Major Cities, and Transportation Network

Exploration continues to the north of these areas both offshore and onshore. The hydrocarbon potential of three sub-basins within the buried onshore Paleozoic Basin of Senegal is also being investigated (Petrosen, 2003b). Brownfield and Charpentier (2003) consider the province underexplored.

The Energy Information Administration (EIA) considers the crude oil reserves of Senegal to be 700 million barrels (EIA, 2003). Proven natural gas reserves are considered to be about 10.99 billion m^3 (EIA, 2006).

Oil is refined at the Société Africaine de Raffinage (SAR) refinery near Dakar. Capacity is 27,000 barrels per day (bpd). The refinery was built by a consortium (Total, Shell, ExxonMobil, and the Government of Senegal) in 1963.

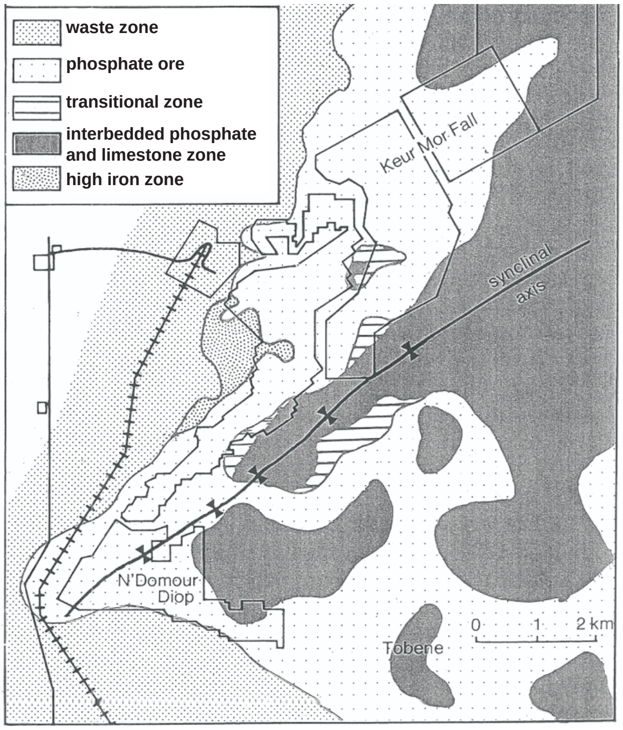
Phosphate Resources

Sedimentary phosphate rock deposits occur at several locations in Senegal. The most extensive and important are the Middle Eocene (Lutetian) deposits, especially those worked on the Thiés Plateau northeast of Dakar. Eocene age phosphates are also found in the Lac de Guires area, along the Senegal River near Matam, to the southeast of Dakar, near Kaolack and at depth near Ziguinchor on the Casamance River. Precambrian phosphates occur in the southeast near Namel.

Taiba—The Taiba Phosphate Deposit was discovered in 1948. The Compagnie Sénégalaise des Phosphates de Taiba (CSPT) was founded in 1957, and the first phosphate rock was produced in 1960 (ICS, 2006).

The Taiba Deposit occurs in the southwestern end of a phosphate-bearing basin approximately 22 km long (Figure Senegal 2). The western margin was most favorable for development, and the initial mine was at N'Domour Diop at a production rate of 600,000 tpy. In 1965 production was increased to 1.6 million tpy. In 1980 production moved to the Keur Mor Fall area.

The phosphate bed averages about 7 m in thickness and is overlain by Quaternary age sands. Overburden is removed with bucket wheel excavators and transferred by conveyor systems to mined-out areas. The ore is mined using draglines directly loading trucks for transport to a scalping-prewash station.



Adapted from Savage (1987).

Figure Senegal 2. Taiba Deposit

The resulting minus 30-mm fraction is transported hydraulically to the beneficiation plant where it is scrubbed, screened, and then deslimed using hydrocones. The deslimed ore is concentrated using flotation. Wet concentrate is stockpiled in an open storage yard to dewater. The concentrate may be dried using rotary dryers.

The phosphate rock mine was refurbished in 2002/2003. Some of the mine equipment was moved from the Keur Mor Fall area to the Tobene area in October 2003. Additional new mining equipment was purchased, including shovels and trucks for ore removal. This development ensured reserves for 20-30 years, and perhaps for over 50 years, at current production rates. The phosphate rock mine capacity is currently approximately 1.8 million tons of product per year. Production figures for 1996-2005 are given in Table Senegal 1. Most of this production is utilized internally to produce phosphoric acid although a small amount may be exported to India.

Table Senegal 1. Production of Phosphate Concentrate, Industries Chimiques du Senegal (ICS) 1996-2005

	Ton x 1,000
1996	1,329
1997	1,481
1998	1,502
1999	1,800
2000	1,738
2001	1,708
2002	1,545
2003	1,472
2004	1,576
2005	1,451

Table Senegal 2. Chemical Analysis of Senegal/Taiba Phosphate Rock

	Sample No. R231.36[a]	Sample 2004[b]
Total P_2O_5, %	36.9	31.5
Citrate soluble P_2O_5, %	5.6	–
SiO_2, %	4.8	–
CaO, %	49.6	44.32
MgO, %	0.03	–
Fe_2O_3, %	0.92	1.03
Al_2O_3, %	0.9	1.55
Total S, %	0.08	–
F, %	4.0	3.13
CO_2, %	2.0	–
Na_2O, %	0.04	–
K_2O, %	0.01	–
H_2O, %	0.32	–
Cl, ppm	67	–
Organic C	0.4	–
LOI[c]	3.1	–
Cd (ppm)	78	74

a. Sample received at IFDC August 1982.
b. Sample collected in early 2004 near end of mining area at Keur Mor Fall.
c. Loss on ignition = weight loss, 1000°C, 1 h.

The composition of the product from the Taiba Mine has changed over the years (Table Senegal 2). A sample of Taiba rock received at IFDC in 1982 had a P_2O_5 content of 36.9% P_2O_5 and a combined Fe_2O_3 + Al_2O_3 (R_2O_3) content of 1.82%. This is very similar to composition given by Savage (1987) for Taiba concentrate. A sample obtained for an IFDC test program (IFDC, 2004) was collected from the Keur Mor Fall area just before the mining equipment was moved (Table Senegal 2). The P_2O_5 content is 31.5% while the R_2O_3 content is 2.58%. Sources in Senegal indicate that, with the move to Tobene, P_2O_5 levels will be at levels experienced 20 years ago and the R_2O_3 contents will be much lower.

Until 1984, almost all phosphate production in Senegal was predominantly through CSPT as sales of phosphate rock. In 1976 the Société des Industries Chimiques du Senegal (ICS) was founded. In 1984, ICS began to export phosphoric acid from the Darou-Khoudoss plant near the phosphate mine, mainly to its partner, Indian Farmers Fertiliser Cooperative Ltd. (IFFCO), in India. At its creation, ICS also acquired the fertilizer granulation plant of the Société Industrielle des Engrais du Senegal at Mbao, located just to the north of Dakar.

In 1990, ICS increased phosphoric acid production from 720 to 1,015 tons P_2O_5 per day under a program financed by Agence Française de Développement (AFD). In 1996, ICS merged with CSPT, thus unifying the entire Senegalese phosphate sector. In 2002/2003, a second phosphoric acid plant was commissioned at Darou-Khoudoss, effectively doubling the phosphoric acid capacity to 660,000 tons P_2O_5 per year.

Less than 100,000 tons of the phosphoric acid production is utilized at the granulation plant at Mbao, and the rest is mainly exported to IFFCO. The capacity of the NPK plant at Mbao is approximately 200,000 tpy. About 40,000-50,000 tons of the NPK products is marketed in Senegal, and the rest is sold mainly in West Africa.

Sulfur to produce sulfuric acid for the Darou plants is purchased from a variety of sources on the world market. The sulfur is brought to Darou from the port of Dakar by special bottom-dump rail cars. The sulfuric acid plant associated with the Darou 1 phosphoric acid plant is a single absorption plant.

The sulfuric acid plant associated with Darou 2 is a double contact-double absorption Monsanto sulfuric acid plant. Each sulfuric acid plant can produce over 3,000 tpd of 100% sulfuric acid. There is 20,000 tons of sulfuric acid storage capacity. Total electrical generation capacity for the two sulfuric acid plants is 43 MW. The phosphoric acid plant complex requires 25 MW of power. The remaining power may be utilized by the mine; the main source of power for the mine is the national electric company, Senelec.

Both the phosphoric acid plants at Darou utilize a dihydrate process. Darou 1, the older plant, utilizes a slurried phosphate rock feed. Darou 2, the new plant, utilizes a dry rock feed. Both plants utilize flat rotating pan filters. Darou 1 has two Ucego filters; the two filters have a combined surface area of 195 m^2. The Darou 2 plant filter has an area of 240 m^2 and is said to be the largest filter of its type in the world. The Darou 2 plant also incorporates a 30-m^2 belt filter, which is utilized to process clarification solids from a large clarifier tank in the concentration section. The Darou 1 plant typically produces filter-grade acid at 26%-27% P_2O_5, and the Darou 2 plant typically produces 28%-29% P_2O_5 filter-grade acid.

From the filters, the acid is concentrated to 52% P_2O_5 by typical vacuum loop concentrators. There are three concentrators associated with Darou 1 and two concentrators associated with Darou 2. The Darou 2 concentration system also includes a large clarification tank. Phosphoric acid typically exits the concentration systems at 80°-85°C.

From the evaporation sections, the concentrated phosphoric acid is pumped to rubber-lined open-air pools. There are five pools of 3,000-ton P_2O_5 capacity each at Darou. The phosphoric acid can be stored in open pools because the average yearly rainfall is only about 500 mm at the site. During the rainy season the acid is only diluted about 1% P_2O_5 during the worst of conditions. The residence time in the pools is relatively short at Darou before the phosphoric acid is loaded. If all the pools are in service, the acid storage time is about 7 days, and typically some of the pools may be under repair or otherwise out of service.

From Darou, the phosphoric acid is shipped to Mbao by rail in special dedicated cars. There are seven rubber-lined phosphoric acid pools at Mbao with capacities between 6,000 and 9,000 tons P_2O_5. From these pools the phosphoric acid can be pumped to the NPK granulation plant or to oceangoing vessels. The offshore loading facility is about 2 km away.

A major issue with the use of the Taiba phosphate rock is a cadmium content of over 70 ppm (Table Senegal 2). Intermediates and products produced using Taiba phosphate rock have relatively high cadmium contents (Table Senegal 3). The cadmium content of such products is particularly an

Table Senegal 3. Chemical Analysis of Senegal/Taiba Phosphate Rock (R231.36), Phosphogypsum, Filter-Grade and Concentrated Acids, and Fertilizer Products Showing the Fate of P_2O_5 and Some Heavy Metals

	Senegal Rock	Gypsum Cake	Filter Acid	Concentrated Acids		Fertilizer Products		
						DAP	TSP	SSP
Total P_2O_5 (wt %)	36.9	0.59	29.8	42.8	57.4	46.5	49.8	22.3
Cd (ppm)	78	13	47	70	87	84	98	36
AS (ppm)	6	2	2	6	7	5	7	4
U (ppm)	105	5	78	114	144	120	146	66
V (ppm)	219	2	172	259	325	296	337	149
Cr (ppm)	131	1	123	396	432	523	399	477
Hg (ppm)	0.209	0.142	0.019	0.007	NA	0.021	NA	NA
Pb (ppm)	4	NA	NA	NA	NA	NA	NA	NA
Se (ppm)	2	NA	NA	NA	NA	NA	NA	NA

NA = Not analyzed.

issue in Europe and over the years has certainly resulted in limiting the markets available to Taiba phosphate rock or fertilizers produced from Taiba phosphate rock (Van Kauwenbergh, 2004).

IFDC has performed a series of studies for ICS in order to evaluate removing cadmium from either the rock or phosphoric acid (IFDC, 2003a; 2003b; 2004). Merchant-grade phosphoric acid (52%-54% P_2O_5) was produced with as little as 10 ppm cadmium.

Pallo Mine (Thiés Area)—The Pallo Mine is located about 80 km from Dakar near Pallo. The rock is treated at Lam Lam Village, which is connected to the main rail line to Dakar by a 3-km spur route.

Deposits of calcium aluminum phosphate have been created by the lateritic weathering of the Lutetian age phosphates. At Pallo the laterized bed has an average thickness of 17 m beneath 2-3 m of overburden. Reserves have been estimated at 100 million tons at 28.0%-29.5% P_2O_5 (Savage, 1987). There is also about 2 million tons of apatitic phosphate ore in the area. The deposit was controlled and operated by Société Senegalaise de Phosphates de Thiés, which was owned 50% by the Senegalese government and the Rhône-Poulenc Group.

The ore was mined in an open pit utilizing bulldozers and transported to Lam Lam for processing. At Lam Lam the material was crushed and screened. The product was the 4-mm sized material. Production capacity was 600,000 tpy. A portion of the ore was calcined in rotary kilns which utilized oil for fuel. The capacity of the kilns was 350,000 tpy. This clinker was ground at Lam Lam or transported elsewhere for grinding. The calcination was only at approximately 600°C. This temperature is sufficient to destroy the crystal structure of the alumino-phosphate minerals by driving off the structural water. The product contained about 34% P_2O_5 with 26%-27% P_2O_5 soluble in ammonium nitrate solution (Joulie Test) (Savage, 1987). The ground product was marketed under the name PHOSPHAL. The product was used domestically and was also exported to France.

Total production from the Pallo Mine from 1970 to 1985 ranged from 130,000 to 482,000 tpy (Savage, 1987). In 2001 aluminum phosphate production was 405,400 tons (Thomson, 2006).

Matam (Ouali Diala)—The Matam deposits occur on the south bank of the Senegal River on the border with Mauritania. The phosphate layers are 4-16 m thick. Pascal and Faye (1989) describe the deposits in some detail. The deposits are associated with the Bofal and Loubboira Deposit to the west and north in Mauritania. Three main sedimentary facies have been established. Seven sub-deposits occur over about 100 km along the river. The N'Diendouri and Ouali Diala deposits contain over 10 million tons each. McClellan and Notholt (1986) indicate a total of 40 million tons averaging 28.7% P_2O_5 for the area.

A sample of Matam phosphate rock was studied by IFDC (1983) (Table Senegal 4). The sample was composed of apatite (80%-85%), quartz (SiO_2, 10%-15%), goethite (FeO(OH), 2%-3%), and clays (5%-8%). The apatite was a carbonate-containing francolite. The combined Fe_2O_3 + Al_2O_3 content of the ore (3.8%) was considered somewhat high.

The IFDC study concluded that the Matam phosphate rock, due to its high NAC solubility (4.5% P_2O_5), was more suitable for direct application than

Table Senegal 4. Chemical Analysis of Phosphate Rock From Matam, Senegal

Component	%
Total P_2O_5	28.7
NAC soluble P_2O_5[a]	4.5
CaO	46.3
SiO_2	14.0
F	1.7
Al_2O_3	1.8
Fe_2O_3	2.0
Na_2O	0.32
MgO	1.1
K_2O	0.09
S	0.2
Cl	0.005
CO_2	2.9
H_2O	2.3
C	0.19
Loss on ignition[b]	6.8

a. Neutral ammonium citrate-soluble P_2O_5, AOAC method.
b. Loss on ignition heated l h at 1000°C.

were other sources in Senegal. Also, the rock could be beneficiated by desliming to remove clays and flotation to remove silica.

The Government of Senegal considers the development of the Matam Deposit to have a high priority.

Other Eocene Deposits—Eocene phosphate beds with P_2O_5 contents up to 39.0% have been encountered in boreholes beneath 40 to 56 m of overburden in the Kaolack area along the Dakar-Bamako railway (Savage, 1987).

At Pire Gouvyere, east of Taiba, 25 million tons of marketable product at 34% P_2O_5 is estimated to be available (McClellan and Notholt, 1986). The phosphate beds exceed 6 m in thickness with 25 m of overburden.

Lutetian phosphatic marls were discovered during oil exploration in a borehole drilled by Société Française des Petroles near Ziguinchor on the Casamance River (Gorodiski, 1958), and samples analyzed by the Service de Géologie et de Prospection Minière had up to 10.2% P_2O_5. McClellan and Notholt (1986) indicated that subsequent work by Bureau de Recherches Géologiques et Minières (BRGM) revealed the presence of 10 m of phosphatic marls averaging 15.7% P_2O_5.

An area in the Louga-Lac de Guires region was investigated for phosphate potential by the Syndicat du Lac de Guires (Savage, 1987). Boujo et al. (1980) outlined the results of studies in this area. No significant accumulations were delineated.

Infracambrian Phosphates—Phosphate rock of Infracambrian age was discovered in southeastern Senegal during a scintillometer survey in the mid-1970s (McClellan and Notholt, 1986). Field studies indicated a sequence near Namel was 3-12 m thick and was exposed for about 1 km. Samples analyzed at IFDC (McClellan and Saavedra, 1986) contained 24.2% and 19.0% P_2O_5. Samples obtained from the surface were siliceous while samples obtained from 8 m below the surface contained significant calcite.

Sulfur Resources

Sixteen exploratory oil wells offshore of the Casamance River were drilled for sulfur prospecting (Bermúdez-Lugo, 2003). The wells were drilled on the flanks and the top of two salt diapirs (Dome Flore and Dome Gea). If the heavy-petroleum resources of these domes are developed, sulfur may be available from the refining of the crude oil. The heavy oil is associated with Oligocene carbonate beds. Oil produced from carbonates generally contains significant sulfur.

Phosphogypsum resources exist at the ICS plant at Darou. For each ton of P_2O_5 produced, approximately 5 tons of gypsum is produced. Millions of tons of gypsum is available at Darou.

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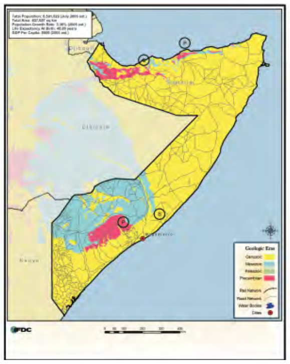
Somalia



Somalia (Figure Somalia 1) is bordered to the west by Djibouti, Ethiopia, and Kenya; to the north by the Gulf of Aden; and to the east by the Indian Ocean. Formerly known as the Somali Republic and the Somali Democratic Republic, it has no permanent national government. There is a Transitional Federal Government, which controls a limited amount of the country. The total area is 637,657 km^2 and approximately 1.7% of the land is arable. The population was estimated in mid-2005 as 8.6 million inhabitants. Annual population growth was estimated at 3.38% (World Factbook, 2006). Pastoral nomadism occupies 71% of the labor force.

The transportation network (Figure Somalia 1) comprises 2,608 km of paved roadways and 19,492 km of unpaved roads. There are 6 airports with paved runways and 58 airports with unpaved runways. The main ports are Boosaaso, Berbera, Chisimayu (Kismaayo), Merca, and Mogadishu (Mogadiscio).

Precambrian rocks are exposed to the west of Mogadishu and in the north paralleling the Gulf of Aden. The Bur Masif to the west of Mogadishu consists of marbles, quartzites, amphiboles, and gneisses, which are intruded by granites. The northern Precambrian areas include an alkaline complex (Darkainle) and are associated with an Early Paleozoic fold belt.

Paleozoic sediments outcrop in a limited area north of Mogadishu. Jurassic age sediments overlie the Precambrian and Paleozoic sediments. Cretaceous age sediments to the north and west of Mogadishu form a part of the Somali-Ogaden embayment. Cenozoic marine sediments cover most of Somalia. Volcanics are found near the Djibouti border, along the Gulf of Aden, and in an area near the junction of the borders of Somalia, Ethiopia, and Kenya.

Nitrogen Resources

Somalia has no hydrocarbon production. Oil seeps were identified during the colonial era by British and Italian geologists. Several oil companies including Agip, Amoco, Chevron, Conoco, and Phillips held concessions in the country or in territorial waters, mainly in the north of the country. All the oil companies declared force majeure following the collapse of the central government in 1991.

Many experts indicate Somalia has high potential to produce oil and gas (Fineman, 1993; Salad and Hilowle, 2000; Kielmas, 1991). The main target area is northern Somalia where stratigraphic sequences may exist similar to sequences found across the Gulf of Aden in oil-rich Saudi Arabia and Yemen.

Several sources indicate that Somalia has natural gas reserves. The Energy Information Administration (2003) indicates that there are 200 billion ft^3 of proven natural gas reserves. The Index Mundi (2006) indicates 2,832 million m^3 of verified reserves. Yager (2000) indicates estimated resources of 6 billion m^3 of natural gas. None of the sources that quoted reserve/resource figures indicated the field or area from which the figures were developed.

Phosphate Resources

Metamorphosed sedimentary phosphate rock occurs in the Bur area at Modu-Mode 25 km from Buurhakaba on the road to Baidoa. Foster and Harrison (2000) indicate that the deposit contains an average of 24% P_2O_5. The extent of the deposit is not known (van Straaten, 2002).

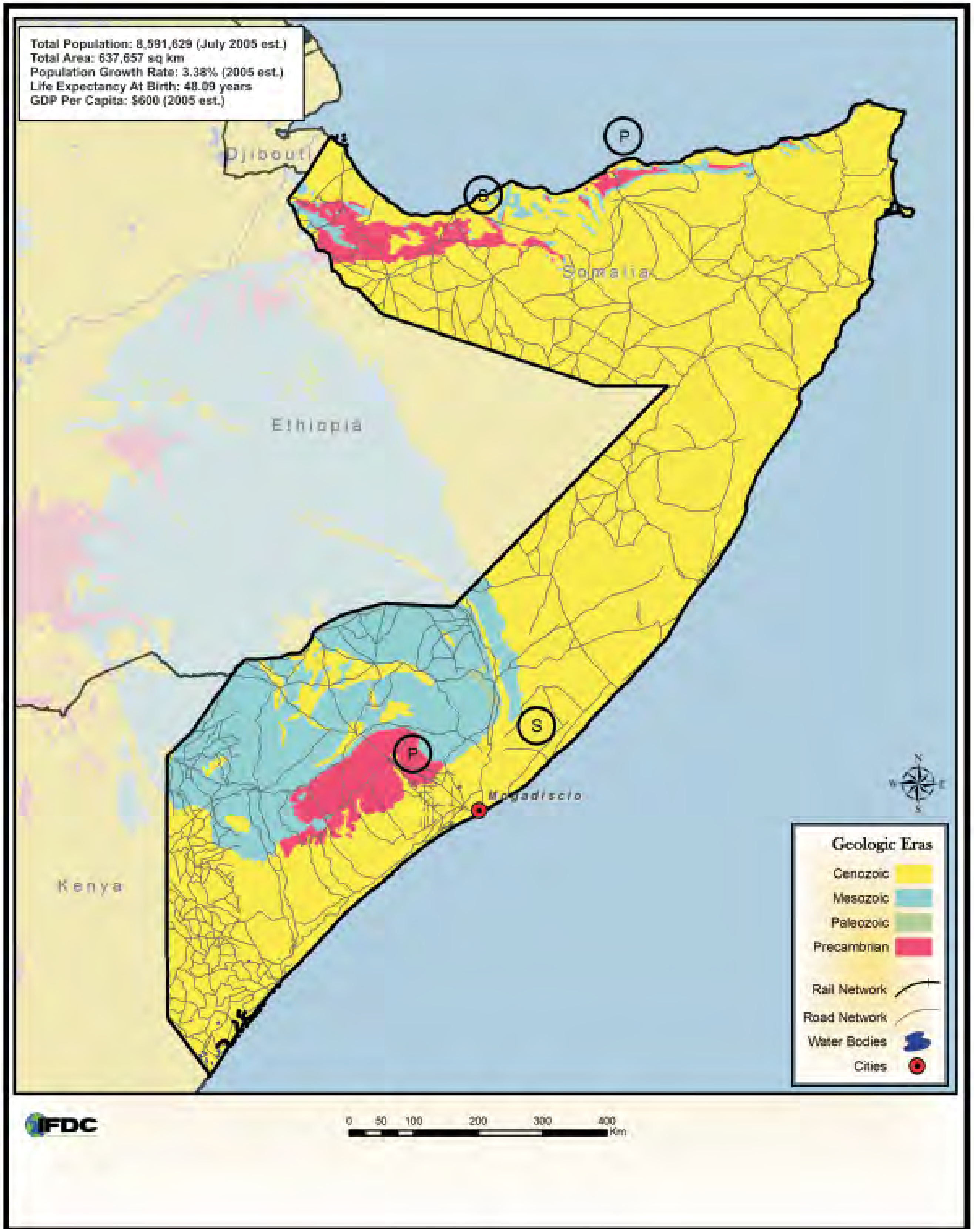


Figure Somalia 1. Geology, Major Cities, and Transportation Network

Deposits associated with bird guano on Mait Island, 60 km northeast of the port of Heis (or Xiis) were worked intermittently for many years (Farquharson, 1924; McClellan and Notholt, 1986). Partial chemical analyses of material collected in the 1930s by the Mineral Resources Division, British Geological Survey indicated a range of 10% to 28% P_2O_5. McClellan and Notholt (1986) indicated that reserves are negligible.

Sulfur Resources

Gypsum deposits occur at Suria Malableb, which has an estimated resource of 5 million tons of 80% pure gypsum and 2.5 million tons of 90% pure anhydrite (Yager, 2000). The material has been calcined to make chalk and medicinal plaster. The material was utilized in the cement plant at Berbera. At one time, over 1,600 tpy was utilized at the cement plant (Yohannes, 1994).

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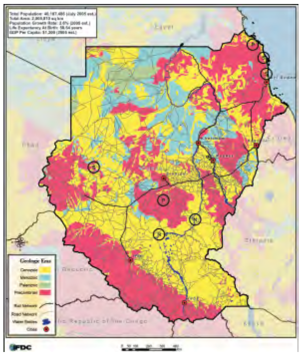
SUDAN



The Republic of Sudan (Figure Sudan 1) is bordered by the Democratic Republic of the Congo, Uganda, and Kenya to the south; the Central African Republic, Chad, and Libya to the west; Ethiopia and the Red Sea to the east; and Egypt to the north. Sudan is the largest country in Africa. Total area is 2,505,810 million km^2 and approximately 6.8% of the land is arable. The population was estimated at 40.2 million inhabitants in mid-2005 (World Factbook, 2006). Annual population growth was estimated at 2.6%. Eighty percent of the labor force is occupied by agriculture.

The transportation network consists of 4,320 km of paved roads, 7,580 km of unpaved roads, and 5,995 km of railway, of which 4,595 km is 1.067-m gauge and 1,400 km is 0.600-m gauge (for cotton plantations). There are 14 airports with paved runways and 72 airports with unpaved runways. There is 4,068 km of waterways, and 1,723 km is open year round on the White and Blue Nile Rivers. Port Sudan is the main port. There is 156 km of gas pipeline, 810 km of pipeline for refined products, and 2,368 km of oil pipeline.

The Precambrian Basement Complex of Sudan consists of igneous, metamorphic, and sedimentary rocks and occupies more than 49% of the surface area of the country (Whiteman, 1971). Sudan is structurally complex and is crossed by major fault systems and shear zones. Several large rift systems have been identified in Sudan including the Southern Sudan Rift, the White Nile Rift, the Blue Nile Rift, and the Atbara Rift. The basement rock formations occur in five uplifted blocks separated by rift zones and grabens. The inter-block depressions (grabens) are filled with sediments that range from Paleozoic to Recent in age. The sediments in some of these basins are more than 3.5 km thick (van Straaten, 2002). Oil exploration has focused on these basins.

Paleozoic age rocks occur in the northwest of the country. Extensive areas of the basement complex are covered by the Late Cretaceous Nubian Sandstone. Much of the southern part of the country is covered by Tertiary-Quaternary rocks of the Umm Ruwaba Formation.

Mesozoic to Tertiary volcanics occur in southern Sudan near the Kenya border, in western Sudan near El Flasher, in eastern Sudan near the Ethiopian border south of Kassala, and scattered as small discrete bodies all across northern Sudan. Approximately 100 alkaline ring complexes have been identified in Sudan (Vail, 1985).

Nitrogen Resources

Much of the information for the following discussion of oil in Sudan was obtained on the website of Human Rights Worldwide (2006). Chevron was granted an oil concession in Sudan in 1976. Chevron discovered oil in southern Sudan in 1978 and was developing the Unity and Heglig oil fields when civil war broke out. Three Chevron employees were killed in 1984 and Chevron suspended operations. The French firm Total, which also had initially acquired concessions, likewise suspended operations. Chevron sold out its rights to the entire Sudan concession in 1992.

The government subdivided the Chevron concession into smaller blocks. A Canadian independent, Arakis Energy, acquired Chevron Blocks 1, 2, and 4. In 1966 Arakis brought eight wells onstream, trucking oil to a small refinery at El Obeid in Northern Kordorfan where it was processed for domestic consumption.

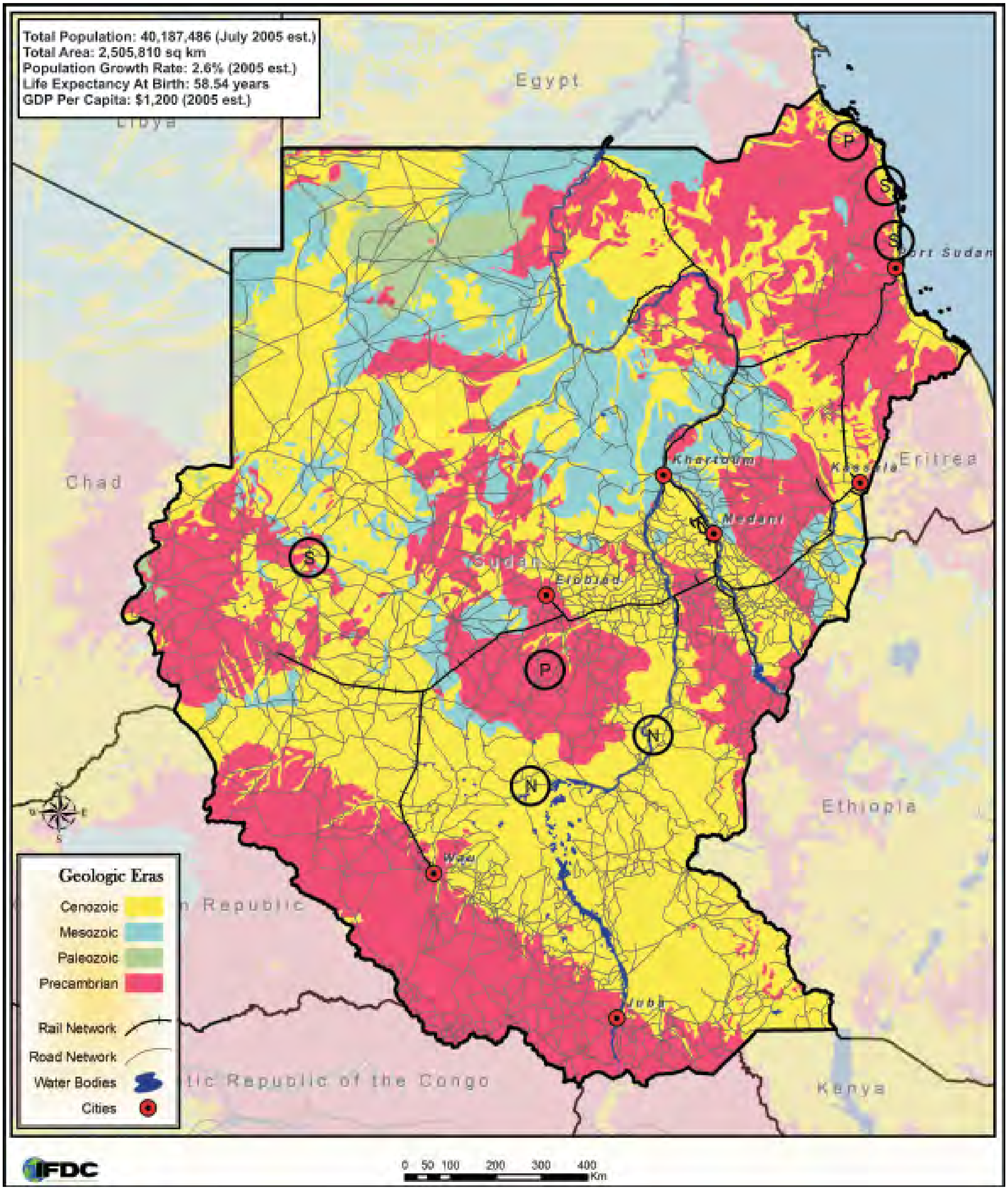


Figure Sudan 1. Geology, Major Cities, and Transportation Network

In late 1996, Arakis sold 75% of its interest to a consortium called the Greater Nile Petroleum Operating Corporation composed of three state-owned companies (China National Petroleum Company [CNPC], Petronas Carigolli Overseas Sudan Berhad [Malaysia], and Sudapet Limited [Sudan]). CNPC and Petronas provided project funding initially. In October 1998, Talisman Energy of Canada acquired Arakis. Under Talisman Energy influence, the Heglig and Unity fields were further developed. A 1,540-km pipeline was built, a new terminal was built at Port Sudan for supertankers, and the first crude oil was exported from Sudan. In 2002, under pressure from human rights groups and adverse publicity, which apparently resulted in discounting of share value, Talisman Energy sold its Sudan interests to ONGC Videsh Limited, a subsidiary of Oil and Natural Gas Corporation Limited, India's National Oil Company.

In 1997 International Petroleum, a subsidiary of Lundin Oil AB, signed an agreement for rights to Block 5A, adjacent to Block 1. Petronas subsequently purchased International Petroleum's share. Activities have been intermittent in this block due to security concerns.

In 2004 a consortium including CNPC, Petronas, Sudapet, Gulf Oil Petroleum and Al-Thori Corporation began development of Blocks 3 and 7, mainly in White Nile and Upper Nile Provinces (EIA, 2005). Discoveries included the Adar/Yale and Tale fields, scheduled to come online in 2005; capacity of the fields was to increase to 300,000 barrels per day (bpd) in late 2006. An 870-km pipeline was to be constructed to a new export terminal near Port Sudan.

Exploration activity continues in several regions of Sudan. In recent years proven reserves have increased considerably on a yearly basis. Proven oil reserves in Sudan are considered as 1.6 billion barrels (2005 estimate) (World Factbook, 2006). Proven gas reserves are considered as 99.11 billion m^3 (2005 estimate) (World Factbook, 2006).

Production of crude oil was 77.76 million barrels in 200l, 87.76 million barrels in 2002, and 110 million barrels in 2003 (Yager, 2003). Production in 2004 was approximately 125 million barrels (EIA, 2005). Oil output was scheduled to double by the end of 2006 (*Sudan Tribune*, 2006).

There are several oil refineries in Sudan—the Khartoum refinery opened in June 2000 and initial capacity was 50,000 bpd. Plans were to increase capacity of the Khartoum refinery and the Port Sudan refinery to 100,000 bpd each (EIA, 2005). In addition to the Khartoum and Port Sudan refineries, there are refineries at El Gily (50,000 bpd) and El Obeid (10,000 bpd).

There is no information in any of the literature available concerning the use of associated gas or byproducts from refining. It is assumed significant gas flaring is probably occurring in Sudan.

Phosphate Resources

Halaib District—Phosphorite is indicated to occur in the Halaib District north of Port Sudan (Whiteman, 1971). No other details are available.

Nuba Mountains—Two occurrences of phosphate breccias (Uro and Kurum) were discovered in the Nuba Mountains in 1983 (Mageed, 1998, as quoted in van Straaten, 2002). The deposits were located on the basis of radioactive anomalies at Uro. Wavellite and crandallite were detected. No apatite mineralization was mentioned. At Kurum, secondary aluminum-phosphates (crandallite, woodhouseite, and wavellite), as well as varisite, were detected in zones over breccia containing apatite. The mean P_2O_5 content was 20.06% P_2O_5. A preliminary resource estimate indicates 1.68 million tons of phosphate ore grading 20% P_2O_5.

Other Occurrences—Apatite occurs in small quantities at Shereik, Northern Province, in metamorphosed sediments (Whiteman, 1971; McClellan and Notholt, 1986). Van Straaten (2002) indicates that the occurrences of apatite in pegmatites in the Baiguda Desert, 130 km north-northwest of Atbarah, are of no practical and economic importance.

Sulfur Resources

Thick sequences of gypsum occur in the Middle Miocene Dungunal Formation and the Middle or Lower Miocene Majhersum Formation along the Red Sea Coast (Whiteman, 1971). Oil exploration wells have penetrated over 600 m of calcium sulfate-bearing beds. These beds outcrop at various localities near the Red Sea coast. Chemical analyses of outcrop samples indicate more than 90% gypsum for some of the beds. Limited amounts of gypsum are mined for use in the cement industry. In 2002 Sudan produced 4,540 tons of gypsum (Yager, 2003).

Copper sulfides are known to exist in many localities in Sudan. Hofeat en Nabas (literally Hole of Copper) was worked in ancient times and in the 20th Century (Whiteman, 1971). Lead and zinc sulfides are also known from several localities.

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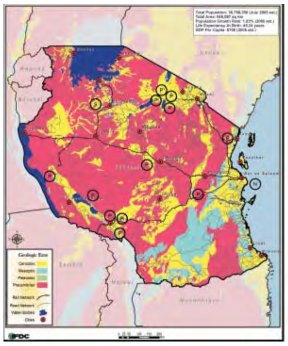
TANZANIA



The United Republic of Tanzania (Figure Tanzania 1) is bordered by Rwanda, Burundi, the Democratic Republic of the Congo, Zambia, and Malawi to the west; Uganda and Kenya to the north; the Indian Ocean to the east; and Mozambique to the south. The total area is 945,087 km^2 and approximately 4.52% of the land is arable. The population was estimated in mid-2005 as approximately 36.7 million inhabitants. Annual population growth was estimated at 1.8% (World Factbook, 2006). Agriculture occupies 80% of the labor force.

The transportation network is composed of 3,704 km of paved roadways, 84,496 km of unpaved roadways, and 3,690 km of railways of two gauges. There are 123 airports, of which 11 have paved runways. There is a 29-km gas pipeline and an 866-km oil pipeline. Dar es Salaam is the main port.

Archean Precambrian granites and gneiss form the central Tanzanian Craton within the country (Figure Tanzania 1). Archean rocks of mainly sedimentary origin form a band running east-west turning to the northwest over the southern part of the Tanzanian Craton. Archean greenstone belts containing mafic volcanics, some felsic volcanics, banded iron formation, and fine-grained clastic sediments are found in the central craton near Lake Victoria.

Weakly metamorphosed schists, phyllites, argillites, and quartzites of the Karagwe-Ankolean System are largely confined to western Tanzania. Precambrian rocks of the Ubendian and Usagaran Systems border the Tanzanian Craton to the west, east, and south. The rocks of these systems are typically highly metamorphosed gneisses with some marbles.

Paleozoic weakly metamorphosed schists, phyllites, argillites, and quartzites of the Bukoban System are largely confined to western Tanzania. Karroo (Karoo) System clastic sedimentary rocks, which are late Permian to Jurassic in age, are found along the coast, the Selous Basin, and several other minor interior basins. Jurassic and Cretaceous shales, sandstones, carbonates, and evaporites of the coastal basins overlie Karroo and Precambrian basement rocks. Cenozoic marine and continental rocks overlie older sediments of the coastal and inland basin. Mesozoic-Cenozoic alkaline intrusives (carbonatites, kimberlites, and related rocks) occur as small bodies across Tanzania.

Cenozoic volcanics (Miocene to Recent) are related to rifting. These volcanics are found at the north end of Lake Nyasa. The Western Rift runs through Lake Nyasa into Lake Tanganyika and northwards. Another group of volcanics, found in north-central Tanzania, are related to the Eastern Rift. The Eastern Rift begins in central Tanzania and extends through Kenya and Ethiopia.

Nitrogen Resources

Petroleum—Oil and gas exploration began in Tanzania when British Petroleum and Shell were awarded a concession in 1952 covering the onshore coastal basin and Zanzibar, Pemba, and Mafia Islands (MBendi, 2006). Four wildcat wells were drilled, one on each island and one in the Mandwa Basin. Because none of the wells resulted in commercial discoveries, the concession was relinquished in 1969.

The Tanzania Petroleum Development Corporation (TPDC) was formed in 1969. Agip was awarded

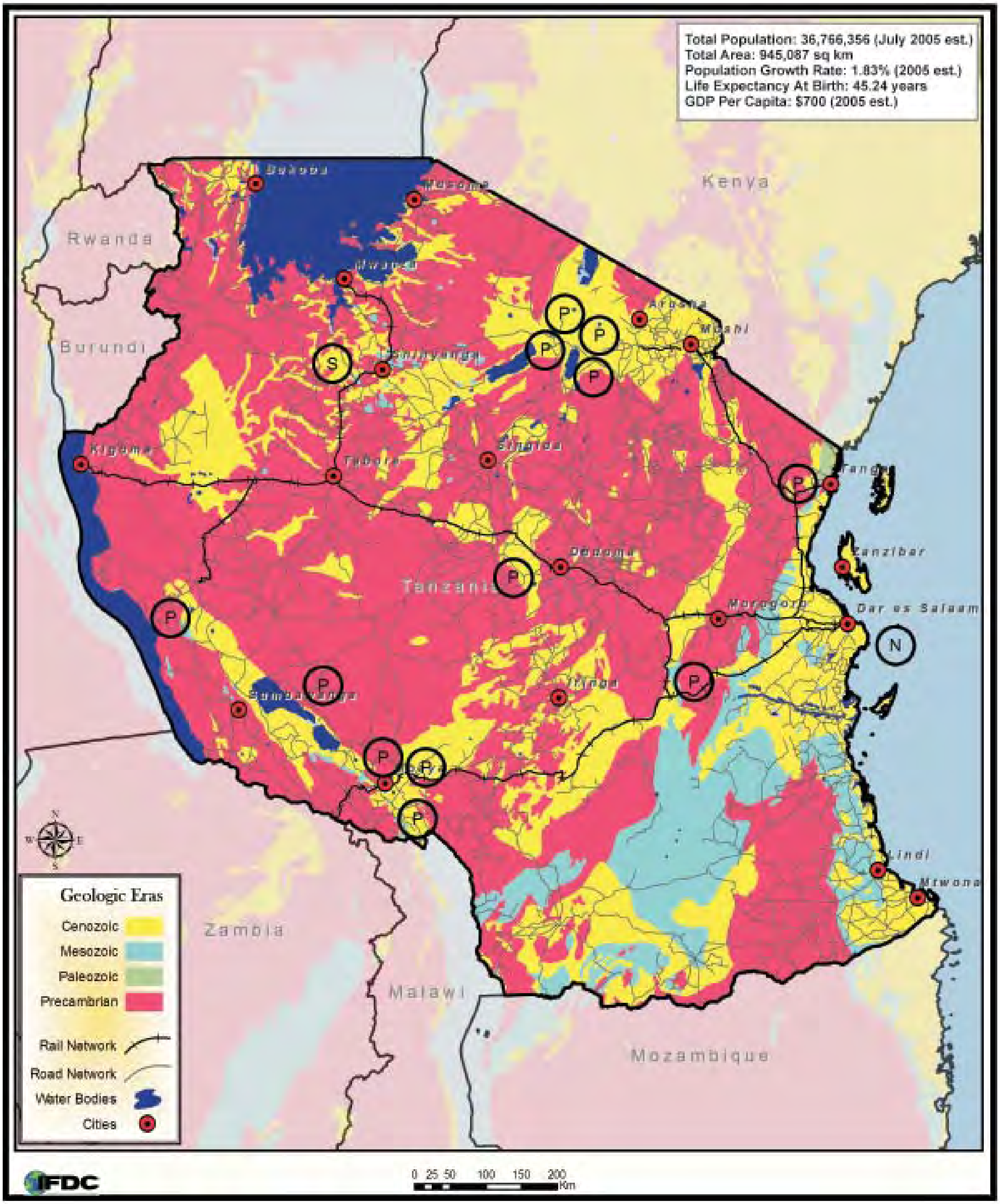


Figure Tanzania 1. Geology, Major Cities, and Transportation Network a concession for the coastal areas and to a water depth of 200 m. From 1973 to 1982, Agip and Amoco drilled three offshore and three onshore wells, resulting in the discovery of the Songo Songo and Mnazi Bay Gas Fields.

During the 1980s Shell and Esso carried out an extensive exploration program in the Selous Basin and Rafiji trough. Three wells were drilled. The Ruva Basin was awarded to the International Energy Development Corporation (IEDC), later joined by BHP and Elf who performed seismic work and drilled two wells. Amoco drilled two shallow wells in the Rukwa Basin in 1983/84.

From the late 1970s TPDC conducted onshore and offshore seismic programs and drilled several wells. TPDC also carried out an appraisal program of the Songo Songo Gas Field, drilling several wells during the 1980s. At the end of the 1980s, Shell held a license for the Mandwa and Mafia Basins, and Texaco held a license for the Ravuma Basin. One well was drilled in each basin.

In the 1990s Dublin Petroleum International Ltd. signed a production-sharing agreement (PSA) for the Mandawa and Rufiji Basins, and two wells were drilled. Antrim Energy Ltd. and Canop Worldwide signed PSAs for the Pemba/Zanzibar and Dar es Salaam/Mafia regions, respectively. Gulf Western Mining signed an agreement covering parts of the Tanga, Ruva, and Kimbiji areas. In 1999 Ndovu Resources, Australia, acquired the rights to explore 31 offshore blocks for 11 years. In February 2002 Ndovu Resources drilled well Nyuni1 to a depth of 3,895 m. The well logged hydrocarbons in Lower Cretaceous and Jurassic formations.

In early 2005 EnerGulf Resources Inc. entered into a memorandum of understanding with JEBCO Seismic Ltd. to explore the Tanga Block. Existing seismic coverage indicates the presence of multiple hydrocarbon traps in the area.

Tanzania currently has no proven oil reserves (Index Mundi, 2006; World Factbook, 2006). Proven natural gas reserve estimates range from a total of 11.33 billion m^3 (World Factbook, 2006) to 17 billion m^3 at Songo Songo (PanOcean Energy Corp. Ltd., 2004) and 2.1 to 6.1 billion m^3 at Mnazi Bay (Yager, 2003).

Coal—Tanzania has 10 identified coalfields. Resource estimates for these coalfields are given in Table Tanzania 1 (Mchihiyo, 1984). The coals are of Permian age and range from low to high volatile bituminous coals with high ash and low sulfur contents. All the deposits are located in the remote southwest of the country. The remoteness of the deposits and lack of transportation facilities have hindered development.

In September 1987, *Mining Magazine* (Anonymous, 1987) reported that the Kiwira Colliery, built with Chinese assistance, was to be online in October 1988. Initial production capacity was to be 150,000 tpy and was expected to increase to 600,000 tpy. Yager (2003) reported that production fell in 2003 to 54,610 tons from 79,210 tons in 2002 because of problems with mining equipment. MBendi (2006) reported that Kiwira Coal Mines is to produce more electricity after the injection of US $6 million by a new investor, Tanpower, which purchased 88% of the shares. The company is expected to boost production from 500,000 tpy to 1.5 million tons annually within 18 months.

Yager (2003) indicated that the state-owned National Development Corporation (NDC) had

Table Tanzania 1. Coal Resources of Tanzania[a]

Coalfield	Resources
	(tons)
Songwe-Kiwira	5.96×10^8
Kiteweka-Mchuchuma	4.95×10^8
Njuga	1.26×10^8
Ngaka	1.12×10^8
Mhukuru	1.9×10^7
Galula	$1.7–5.7 \times 10^7$
Ufipa	5.7×10^7
Liweta	3.4×10^7
Lumecha[b]	
Total	**$1.52\text{-}1.55 \times 10^9$**

a. After Mchihiyo (1984).

b. No estimate of resources.

formed a joint venture with Cinergy Global Power Inc., Grinaker-LTA, and Siemens Ltd. to develop the Mchuchuma Deposit. In the first phase of the project, NDC planned to build a surface mine with a capacity of 1.5 million tpy and a coal-fired power plant; NDC has completed the feasibility study on the mine and power plant (NDC, 2006).

Phosphate Resources

Sedimentary Deposits—

Minjingu—The Minjingu Phosphate Deposit is located on Minjingu Kopje, a small hill in the Arusha Region near the eastern shore of Lake Manyara (Figure Tanzania 2). The Great North Road from Arusha to Minjingu makes the deposit easily accessible.

The deposit was discovered by New Consolidated Gold Fields (NCGF) in 1956 when an airborne geophysical survey revealed a radioactive anomaly. NCGF continued to prospect the Minjingu Deposit and other deposits in the area until 1961 (NCGF, 1958-60). Since 1961, studies have been conducted in the area by GEOMIN of Romania (1970, 1974); RUDIS Engineering (Yugoslavia); the Japan Consulting Institute (JCI, 1968); Klöckner Industries (1970); the Mineral Resource Division of the Tanzanian Ministry of Energy, Water, and Minerals; and the Tanzanian State Mining Corporation (STAMICO). In 1983 the Minjingu Phosphate Company (MIPCO), a division of STAMICO, began production in cooperation with KONE OY of Finland.

Initially the phosphate rock produced at Minjingu was to be shipped by truck and rail to the Tanzania Fertilizer Company (TFC) in Tanga. At Tanga, TFC produced phosphoric acid and triple superphosphate (TSP). TFC was shut down in 1991. Mining and production of phosphate rock at Minjingu were severely affected. New market outlets were sought, including exports to Kenya for single superphosphate (SSP) manufacturing. Efforts were also undertaken to promote the material as a direct-application fertilizer.

Figure Tanzania 2. Minjingu Hill, Tanzania, View From the Southeast

In 2001, MIPCO was liquidated and sold to private investors. A new company, Minjingu Mines and Fertilizer Ltd. (MMFL), was formed. Currently MMFL has revived mining, and production technology has been improved, including lowering the moisture content of the final product. Phosphate rock for domestic direct application is being promoted. The export market for SSP manufacture and direct application in Kenya has been revived. New market outlets for direct application have been developed or are under development in the Republic of South Africa, Zambia, Uganda, and Rwanda.

The deposit is of Pleistocene age, and most sources agree that the phosphate is of a guano origin, formed when Lake Manyara was at a much higher level and Minjingu Hill was an island. Numerous bird bones can be found in the phosphate layers. The highest concentrations of phosphate, as well as the mine, are located on the flats below the northern slope of the hill. Two general types of ore have been differentiated. Type A ore is highly indurated (hard ore) while Type B is the soft ore that is currently mined.

Type A ore consists of siliceous phosphate with quartzite boulders interbedded with clays and chert. The A zone ore (Figure Tanzania 3) is up to 24 m thick and averages about 24% P_2O_5. Hand sorting, crushing, and flotation of Type A ore has produced concentrates containing more than 30% P_2O_5 at recoveries of 65% of the total P_2O_5 (Edwards, 1965). This indurated ore has not been mined.

NCGF data indicate that a bulk sample of Type A from 20 pits on the south side of the hill analyzed 24.3% P_2O_5. Both NCGF and GEOMIN (1974) data indicate that the only way to upgrade the hard rock is by flotation. Depending on the process used, about 50% beneficiation recovery is indicated to produce concentrate grades over 32% P_2O_5. The concentrates produced by NCGF and GEOMIN had Fe_2O_3+Al_2O_3/P_2O_5 ratios from 0.14 to 0.17 (Table Tanzania 2). The Fe_2O_3+Al_2O_3/P_2O_5 ratios of phosphate concentrates used for chemical fertilizer manufacture are generally below 0.10. Possible difficulties to be encountered in the utilization of hard rock concentrates in conventional chemical fertilizer processes include formation of insoluble compounds and sludges and production of sticky products. Processes less critical with respect to impurities, such as partially acidulated phosphate rock, might be used to process the concentrates.

Because the hard rock is indurated, mining of this rock would require additional drilling, blasting, and rock-breaking equipment in addition to the equipment used to mine soft ore. If the hard ore is to be beneficiated by flotation, an entirely new beneficiation plant would be required. Equipment required at the beneficiation plant would include primary and secondary crushers, a grinding mill, attrition scrubbing and desliming units, conditioning tanks, flotation cells, a dryer, and product storage facilities. In addition to capital equipment expenditures, the operation of the plant would require flotation reagents, and NCGF estimated 60 tons of

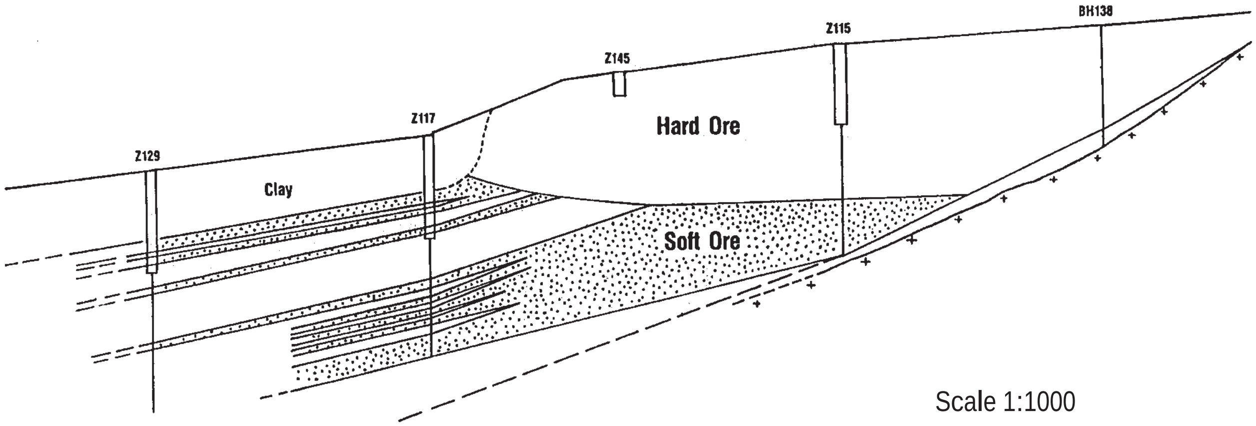


Figure Tanzania 3. Cross Section of Southern Side of Minjingu Hill (Adapted from NCGF Reports)

Table Tanzania 2. Chemical Analyses of Minjingu Hard Ore Concentrates Produced by Flotation

	Concentrate I[a]	Concentrate II[a]	20 Pit[b] Composite
	(wt %)		
P_2O_5	34.1	32.5	33.0
CaO	40.75	40.35	42.80
F	1.93	1.42	1.30
SiO_2	8.7	11.5	10.18
Al_2O_3	3.37	3.86	3.04
Fe_2O_3	1.72	1.67	1.74
MgO	0.60	0.47	Trace
Na_2O	0.90	0.57	0.75
K_2O	1.07	1.16	0.57
SO_3	0.32	0.16	–
CO_2	1.85	1.89	3.28
Cl	0.11	0.11	1.09
LOI	6.63	6.74	–
CaO/P_2O_5	1.19	1.24	1.30
$Fe_2O_3+Al_2O_3/P_2O_5$	0.15	0.17	0.14

a. GEOMIN (1970).
b. NCGF (1958-60).

water would be required to process 100 tons of run-of-mine ore.

Type B ore is a powdery, soft, friable rock. This ore occurs downdip of the A ore zone in three main beds, which dip 4°-6° to the north to a depth of 15-20 m. Phosphate horizons are separated by clay beds that vary in thickness from 2 to 7 m. The average thickness of the first phosphate bed is about 2.5 m with an average P_2O_5 content of 23% (Hangi, 1986); the second bed is 1.5 m thick with an average P_2O_5 content of 24.6%; and the third bed is about 1.2 m thick with an average P_2O_5 content of 24.5%. The three main beds pinch out about 250 m from the base of the hill. Below the main beds, to a depth of 60-75 m, there are a number of discontinuous, lenticular beds that vary from 10% to 23% P_2O_5 (see Figure Tanzania 4 for a cross section). Total resources of Type B ore average approximately 18.5% P_2O_5 (Harris, 1981).

The mine is an open-cast operation employing a bulldozer, hydraulic excavators, front-end loaders, and dump trucks (Figures Tanzania 5 and 6). Stripping and mining are carried out continuously except during March and April, the peak of the rainy season. During these months, the operations are carried out on an intermittent basis.

Beneficiation is a totally dry process. From the open pit, ore is hauled to the feeding station. Friable ore is passed through a grizzly onto a belt feeder, and well-cemented lumps of the Type B ore are fed to an impact crusher (Figure Tanzania 7). The crusher reduces the ore size to minus 50 mm. The crushed ore is then sized on an 8-mm single-deck screen. Phosphate is recovered from the oversized waste by hand picking, and the remaining oversize is sent to a waste pile.

The minus 8-mm material from the screen and the hand-picked plus 8-mm material is then transferred to a 230-m^3 intermediate bin in the main beneficiation plant (Figure Tanzania 8). The ore is then transferred to the rapid dryer. Temperature of the dryer gas ranges from 800° to 1000°C, and the moisture content of the ore is reduced from about 15% to 3%-5%. Drying consumes about 17 L of diesel oil per ton of product. The dried ore is screened, and the oversize goes to waste. The undersize ore is screened, and the fines are cycloned. The product consists of the undersize from the screens and the underflow from the cyclones and is stored in two 320-m^3 product silos. There is also storage capacity in Arusha (Figure Tanzania 9).

The design capacity of the plant is 1×10^5 tons of 28% to 30% P_2O_5 concentrate per year from 1.65×10^5 tons of ore. The *Engineering and Mining Journal* (Anonymous, 1984) indicated that the plant had reached design capacity in its first year of operation. In 1986 the *Mining Journal* (Anonymous, 1986) reported that production was only 21,000 tons. Limited production resulted from a shortage of railcars used to transport the concentrate from Arusha to the port and TFC fertilizer plant at Tanga. In 1987 production was estimated at 25,000 tons, and transportation was still a problem. The mine was operated on a one-shift 5-days/week basis, and the beneficiation plant was operated 2 days/week. When the two 600-ton silos at the plant and the 4,000-ton storage facility at Arusha reached capacity, the

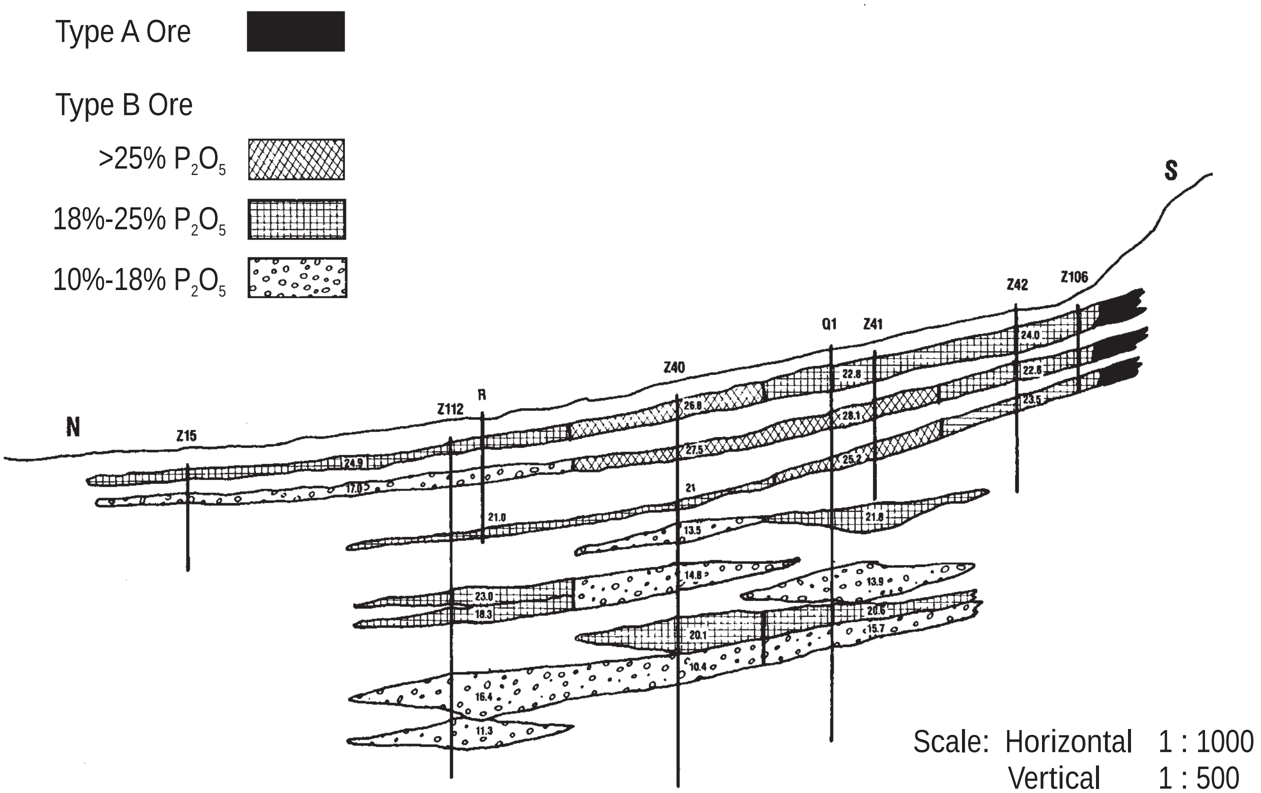


Figure Tanzania 4. North-South Profile of the Minjingu Deposit (Adapted from Brinkmann and Kantor, 1987)

Figure Tanzania 5. The Minjingu Mine, Looking West Toward Lake Manyara

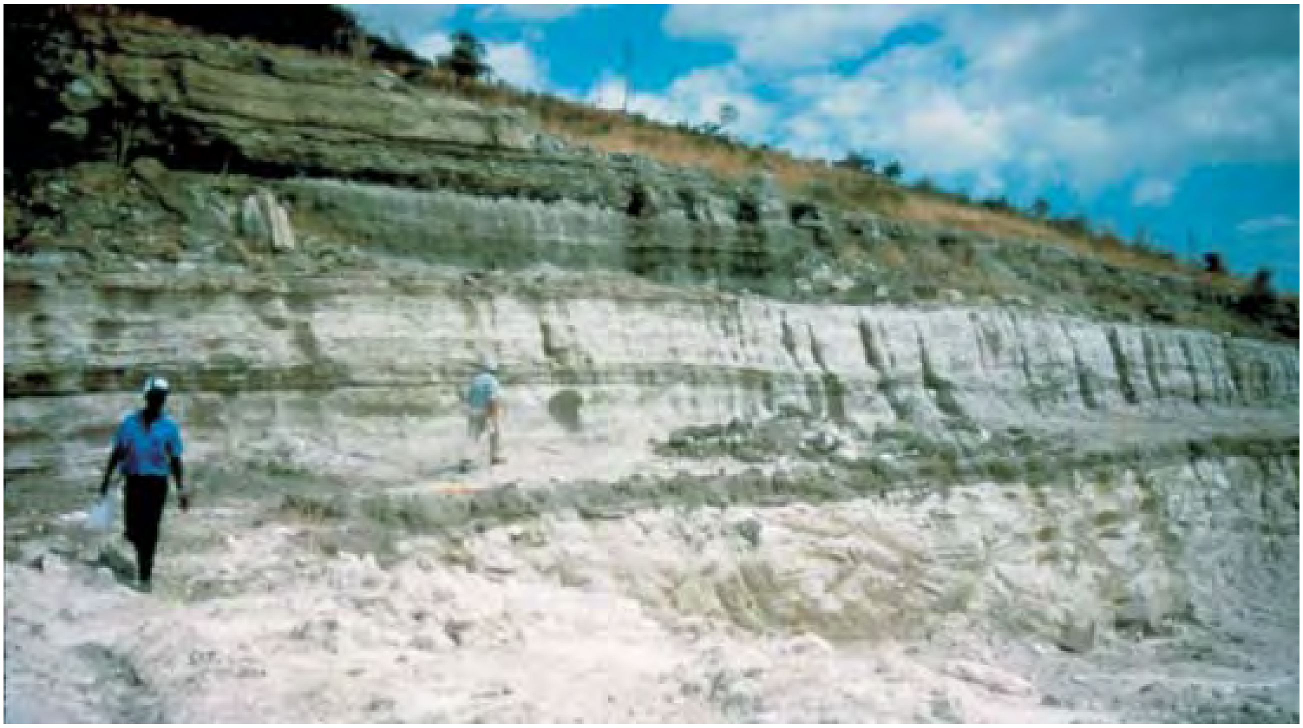


Figure Tanzania 6. Minjingu Mine, First Two Beds of the Soft (Type B) Ore Zones

Figure Tanzania 7. Minjingu Beneficiation Plant, Initial Crushing Station

operation was put on standby until storage space became available.

Samples of Minjingu ore, concentrate, and a bird-bone concentrate have been characterized at IFDC (Van Kauwenbergh, 1985). Chemical analyses (Table Tanzania 3) indicate that the P_2O_5 content of the ore is upgraded about 14% by the dry separation process. Reductions of the SiO_2, Al_2O_3, Fe_2O_3, K_2O, and CO_2 contents occur during beneficiation. Soft phosphate ore, concentrate, and bird bones can be resolved into five identifiable phases (Table Tanzania 4).

Apatite is the major phase with varying amounts of feldspar. Dolomite, calcite, and quartz constitute the gangue minerals. The apatite of the deposit is unusual. The crystallographic properties (unit-cell dimensions) and chemistry (high F^{l-} content) indicate a low-carbonate-substituted carbonate-fluorapatite (francolite). Based on these data, the predicted neutral ammonium citrate (NAC) solubility (P_2O_5), using previously established statistical models for francolite, should be in the range of 2.0% to 2.7% P_2O_5. However, the Minjingu phosphate ore and concentrates have high NAC solubilities ranging from 5.6% to 12.9% P_2O_5. These NAC solubilities

Figure Tanzania 8. Minjingu Mine, Main Beneficiation Plant

Figure Tanzania 9. Minjingu Mine, Storage Facility in Arusha at the Rail Line, 4000-Ton Capacity

Table Tanzania 3. IFDC Chemical Analyses of Minjingu Ore and Concentrates

Chemical Analysis	Soft Ore	Concentrate	Bird-Bone Concentrate
	(wt %)		
P_2O_5	25.0	29.0	32.6
CaO	38.8	41.7	48.5
F	2.6	3.1	3.0
SiO_2	12.5	9.4	1.1
Al_2O_3	2.2	1.2	0.2
Fe_2O_3	1.3	0.89	0.1
Na_2O	1.4	1.3	1.0
MgO	2.6	3.2	2.5
K_2O	1.2	0.78	0.1
CO_2	6.9	3.1	9.1
SrO	1.04	1.4	0.6
BaO	0.25	0.20	0.2
TiO_2	0.18	0.13	
S	0.11	0.09	<0.05
Cl^{1-} (ppm)	145	127	46
Free H_2O[a]	5.8	4.1	1.6
LOI[b]	13.7	10.7	11.9
NAC-soluble P_2O_5[c]	6.1	5.6	12.9

a. Free H_2O = weight loss, 105°C, 1 h.
b. Loss on ignition = weight loss, 1000°C, 1 h.
c. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).

Table Tanzania 4. IFDC Mineralogical Analyses of Minjingu Ore and Concentrates[a]

	Apatite	Feldspar[b]	Dolomite	Quartz	Calcite
Soft ore	68[c]	13	10	5	4
Concentrate	81[c]	7	6	6	–
Bird-bone concentrate	88[d]	11	1	–	

a. All modal analyses normalized.
b. Based on a sanadine composition.
c. Based on a mixture of francolite and high-strontium igneous apatite composition.
d. Determined by subtracting dolomite from bulk analysis.

are equivalent to and above those for the most highly carbonate substituted francolites (Tunisia, North Carolina). The IFDC studies show that the Minjingu phosphate is a complex mixture of apatites. The bird-bone component (citrate-soluble P_2O_5 = 12.9%) may be the dominant factor influencing the NAC solubilities of the concentrate and ore. Minjingu phosphate should be a highly effective direct-application P_2O_5 source when used under suitable agroclimatic conditions.

Various reserve/resource estimates for the Minjingu Deposit are conflicting. Total geological resources are listed as 1 x 10^7 tons by a number of sources (Harris, 1981; NCGF, 1962; Hangi, 1986). Savage (1987) indicated there were total reserves of 1 x 10^7 tons of minable ore averaging 20% P_2O_5 within 60 m of the surface. NCGF (1962) listed the following reserves by ore type:

Type Al = 1 to 2 x 10^5 tons of hard rock.

Type A2 = 3 x 10^6 tons of semihard rock.

Type B3 = 3.5 x 10^6 tons of soft rock capable of
being upgraded by dry separation.

Masao (1986) indicated that the results of investigations by Klöckner Industries showed reserves to be about 4 x 10^6 tons.

CSM Consulting OY and IFDC (1988) reevaluated the reserve estimates based on original documentation and estimates by geologists at the mine (Table Tanzania 5). As estimates evolved over time, reserve estimates were reduced. This study also revised the estimate of concentrate remaining at a measured density of 1.6 tons/m^3 and actual recovery based on mining and beneficiation plant data, indicating that 273,314 tons of concentrate could be produced using identified reserves (Table Tanzania 6). Van Straaten (2002) indicated that figures cited by the mine geologist in 1997 were 3.3 million tons of soft ore reserves and 4.8 million tons of hard ore reserves.

The Pyramids—The Pyramids are two conical hills located about 10 km south of Minjingu. In the course of prospecting the Minjingu area, a total of 82 pits was dug around these hills to depths of 9-15 m (NCGF, 1958–60). Many of the pits had to be abandoned because of the groundwater inflow. While

Table Tanzania 5. Minjingu Phosphate Resource—Reserve Estimates

Study	Soft Rock		Hard Rock		Depth	Comments
	North	South	North	South		
					(m)	
NCGF, 1958-60	4,810,000 tons[a] @ 18.5% P_2O_5		5,010,000 tons @ 21.4% P_2O_5		≅60	Over 150 pits and boreholes, no cutoff grade or bed thickness
JCI, 1968	997,000 tons[b] @ 21.1% P_2O_5				≅20	Upper 2 beds and portion of 3rd bed, NCGF data, and two pits and two trenches
Klöckner, 1970	1,730,060 tons[a] @ 18%-20% P_2O_5	1,326,084 tons @ 18%-20% P_2O_5	188,350 tons @ 18%-20% P_2O_5	1,093,690 tons @ 18%-20% P_2O_5	≅25	NCGF data and resampling of NCGF pits and trenches
Weaver, 1975	3,553,417 tons[a] @ 19.0% P_2O_5 1,385,675 tons @ >23.7% P_2O_5 2,167,742 tons @ <23.7% P_2O_5				≅60	NCGF and JCI data, beds over 0.5 m thick and greater than 7% P_2O_5
Shah, 1976	1,972,963 tons @ >24% P_2O_5	–	–	–	≅23	24 boreholes drilled, NCGF and J. L. Weaver's data, beds over 30 inches thick
Kurvinen, 1983	1,008,969 tons[a] @ 23.6% P_2O_5	–	–	–	≅18-20	J. L. Weaver's data, upper 2 beds
Stage I, Mining Area	737,045 tons @ 24.2% P_2O_5					High-grade portions of the upper 2 beds
Mwambete, 1987	860,946 tons[a,d] @ 23% P_2O_5 688,756 tons[c,d] @ 23% P_2O_5	–	–	–	≅25	Bed 1, bed 2, and a portion of bed 3

a. Bulk density = 2 tons/m^3.
b. Bulk density = 1.76 tons/m^3.
c. Bulk density = 1.6 tons/m^3.
d. Remaining reserves.

Table Tanzania 6. Comparison of Various Minjingu Ore Reserve Estimates

	Original Ore Reserve	Recalculation to 1.6 tons/m^3	Concentrate[a] Available
JCI, 1968	997,000 @ 1.76 tons/m^3	906,364	380,673
Klöckner, 1970	1,730,060 @ 2.0 tons/m^3	1,384,048	581,300
Kurvinen, 1983	737,045 @ 2.0 tons/m^3	589,636	247,647
Mwambete, 1987	1,102,044 @ 2.0 tons/m^3	881,635	370,286
CSM Consulting Ltd. & IFDC, 1988		688,756[b]	273,314

a. Ore reserves at 1.6 tons/m^3 x 42% recovery.
b. 6-30-87.

the radiometric survey that led to the discovery of the Minjingu Deposit did not indicate any anomalies in this area, phosphate layers similar to those at Minjingu were encountered beneath 5-6 m of overburden.

The phosphate layers are most abundant around the northern end of Mwembe Hill, the northernmost of the hills. Two phosphate layers up to 2 m thick with approximately 20% P_2O_5 were encountered in the first line of 45 pits at the base of the hill. A second line of 19 pits was dug about 60 m outside the first, confirming the extent of the phosphatic layers. The resources of the area have not been proven. No boreholes were drilled in the area, and the lateral and vertical extents of the phosphate beds are not known.

In 1975 STAMICO dug a few pits around the hills to confirm the NCGF work (A. Y. Hangi, personal communications). No further work was done to estimate the resources because the Minjingu deposits were the most likely to be developed and seemed adequate. Work to define the Pyramids Deposit may be resumed when the deposit at Minjingu nears exhaustion.

Other Occurrences in the Lake Manyara Basin—South of Lake Manyara, phosphate occurrences have been noted at Besi Hill, Sino Hill, and an unnamed hill 8 km northwest of Besi Hill (Orridge, 1965). Like Minjingu and the Pyramids, these hills may have been islands when Lake Manyara was at a much higher level.

Chali Hills—The Chali Hills deposit is located in the Dodoma District on the southern margin of the Bahi Depression. Thin veneers of apatite containing about 20% P_2O_5 are found on the quartzite bedrock of the hills (Harris, 1981). Drilling around the hills showed a discontinuous horizon a few meters in thickness at less than 5% P_2O_5 (Masao, 1986).

Chamato Hill—This prospect is situated on the main Iringa-Mbeya Road about 54 km east of Mbeya Town. Small patches of phosphate rock occur in a gully cut through tuffs and porcellaneous pyroclastic rock at the foot of the hill. The apatite content of these patches approaches 60% (Masao, 1986).

Lactolil Beds—Pliocene tuffs up to 130 m thick occur in north Tanzania on the Eyasi Plateau and Serengeti Plain. Chemical analyses of altered tuffs indicate a range of 0.64%-4.61% P_2O_5 (Hay, 1978).

Galappo Area—Phosphatic, pisolitic limestones have been noted in the Galappo area east of Babati in the Mbulu District (Oates, 1933). It has been hypothesized that these beds were derived from the weathering of Tertiary age beds in the area that contain 0.4%-0.8% P.

Guano—Guano deposits occur at Sukamawera in the Songwe River area of Mbeya District in a thick travertine formation over Cretaceous sandstone. A total of 3,323 tons of guano was extracted during 1934-57 for direct application (Harris, 1981). The deposit has been examined by the Tanzanian agrogeology team; although the P_2O_5 analyses are relatively high at 27% to 37%, reserves are negligible (Masao, 1986).

Bird guano also is found on Latham Island about 160 km east-southeast of Dar es Salaam. Although the island is quite small (300 m x 150 m), reserves are estimated at 1.9 x 10^5 tons (Harris, 1981). The average P_2O_5 content is 8.5%, and simple particle sizing can upgrade the ore to 12.5% P_2O_5. Small guano deposits are also found at Amboni (Tanga District, Kilwa Region) and in the Njombe District.

Igneous Deposits—

Galappo Carbonatite—Located 16 km east of Babati in the Mbulu District, the Galappo Carbonatite has been explored for pyrochlore (Harris, 1981). Principal accessory minerals are magnetite, vermiculite, and apatite. The prospect is reported to be nearly covered by thick terra rosa although sporadic outcrops occur in a 1.6 x 2.4 km area. While it has been speculated that the occurrence of phosphatic limestones in the area may be related to the weathering of local Tertiary age ash beds, these limestones may be related to the carbonatite. There are no known P_2O_5 analyses of the carbonatite or residual soils.

Hanang Carbonatite—Discovered during an airborne scintillometer survey, this prospect is located on the western flank of the extinct Hanang volcano in the Mbulu District. Principal accessory minerals are pyrochlore, magnetite, and apatite (Harris, 1981).

Mbalizi Carbonatite—First discovered by a group of Soviet geologists in 1972 (Pentel'kov and Voronovskiy, 1979), the Mbalizi Carbonatite is located in the Mbeya District near Mbalizi Township and is crossed at its center by the Tanzania-Zambia Highway. The geologic structure of the deposit is not well known, and it has a thick volcanic cover. The outcrop of the deposit extends approximately 1.2 km north-south and approximately 250 m east-west at its center. Masao (1986) was of the opinion that the deposit may be a ring structure. Coarse- to fine-grained apatite sovites are a common rock type. Mafic banding is common. Mafic minerals include biotite-phlogopite, pyroxenes, amphiboles, and magnetite. Shapiro field tests and X-ray fluorescence (XRF) analyses indicate that the P_2O_5 content ranges from 4.7% to 8.3% P_2O_5 (Masao, 1986).

One sample of unweathered Mbalizi Carbonatite (3.2% P_2O_5) has been analyzed at IFDC (Table Tanzania 7). Mineralogical analysis indicated the sample is composed of calcite, apatite, and dolomite (Table Tanzania 8). The mineralogical characteristics and low grade of this sample indicate that it would be difficult and expensive to upgrade. However, this sample may not be representative of the entire deposit (E. P. Mchihiyo, 1987, Ministry of Energy and Minerals, Personal Communication).

Table Tanzania 7. Chemical Analysis of Unweathered Mbalizi Carbonatite

	Mbalizi Carbonatite
	(wt %)
P_2O_5	3.20
CaO	53.60
F	0.23
SiO_2	0.90
Al_2O_3	<0.1
Fe_2O_3	0.8
Na_2O	0.5
MgO	1.3
K_2O	<0.1
CO_2	39.7
Organic C	0.8
LOI	39.7

Table Tanzania 8. Mineralogical Analysis of Unweathered Mbalizi Carbonatite

	Mbalizi Carbonatite
	(wt %)
Calcite	86
Quartz	–
Dolomite	4
Apatite	7.5
Goethite	–

Mbozi Gabbro-Syenite Complex—The Mbozi Syenite Complex consists of a suite of basic rocks intruded by alkaline rocks of late Precambrian Age. The prospect is located in the Mbozi District, 80 km southwest of Mbeya Town on the Mbeya-Tumduma road. It is an ellipsoidal body (20 x 12 km) with the long axis bearing northwest to southeast. While there is no information on any apatite associated with the structure, the inner part of the ring is composed of nepheline syenite. Apatite is commonly associated with alkaline intrusions.

Musensi-Mbulu Intrusions—This carbonate-containing biotite pyroxenite deposit forms two hills in the Mbozi District about 40 km west of Mbeya Town. Boreholes sunk in the course of prospecting for uranium minerals also showed minor amounts of niobium. No phosphate analyses are available. Feldspathic dikes surround the center of the intrusion, suggesting a ring structure. A massive carbonatite body may be present at depth (Masao, 1986).

Nachendezwaya Carbonatite—The Nachendezwaya Carbonatite, located in the Ilege District, is a sovite dike approximately 900 m long with an average thickness of 24 m. The P_2O_5 content of the rock ranges from 2.1% to 6.1% (Masao, 1986). In 1978 RUDIS experts from Yugoslavia estimated 6.1 x 10^6 tons of phosphate ore resources. They concluded that the identified phosphate resources were too small to be of economic significance. Small-scale exploitation might be possible with concurrent vermiculite and nepheline production.

Ngualla Carbonatite—The Ngualla Carbonatite is a ring-like structure approximately 4.0 km in diameter located about 48 km east of Lake Rukwa in Chunya District. Composition is sovite to dolomite with mafic dikes, lenses, and magnetite. During 1957-61, Western Rift Exploration Company (WRECO) explored the deposit for niobium minerals (Masao, 1986). During 1966-69 Williamson Diamonds Ltd. prospected for diamonds, base metals, and rare earths in the area. Chemical analyses by WRECO indicated <1% to 7.4% P_2O_5 in the rock and 0.52% to 7.4% P_2O_5 in the soils. The Tanzania-Canada agrogeology team hand-picked samples with more than 10% P_2O_5 from the soils. Van Straaten (2002) indicated that the Tanzania-Canada agrogeology team discovered a late-phase magnetite-apatite vein, 15 to 20 m wide and several hundred meters long. Several exploration pits in red residual soils to depths of 5 m or more revealed phosphate concentrations of 12% to 20% P_2O_5. No formal phosphate resource evaluation was performed.

Oldongo Dili Carbonatite—The Oldongo Dili Carbonatite is located within the Eastern Rift of northern Tanzania about 20 km east of Oldeani, Mbulu District. Sovite is intruded into a fenitised Usagaran basement in steeply dipping ring-like and semiarcuate zones (Masao, 1986). The aureole of fenitization measures about 3 x 1.6 km, and the carbonatite body measures about 1 km x 0.6 km. Pyrochlore, magnetite, apatite, augite, alkali amphiboles, and micas are common accessory minerals. Analyzed Nb_2O_5 contents range from 0.3% to 0.4%. Analyzed P_2O_5 contents typically are 1% to 3%. One specimen from Hill 009 analyzed 33% P_2O_5.

Panda Hill (Mbeya) Carbonatite—The Panda Hill Carbonatite is a circular plug (1.2 km x 1.4 km) of sovite and ankeritic carbonatite located 40 km southwest of Mbeya Town, Mbeya District. The carbonatite does not show a well-developed ring structure. Mbeya Exploration Company (MDEXCO) explored the deposit for pyrochlore between 1954 and 1963. During 1978-80, RUDIS experts from Yugoslavia explored the complex and studied the possible production of pyrochlore, apatite, and carbonate. On the basis of these studies, STAMICO was advised to start exploitation (Masao, 1986).

The P_2O_5 content of the hard rock deposit averages about 3.4%. Apatite constitutes about 10% to 12% by volume in the sovite, and minor bodies of phoscorite contain up to 30% apatite (Basu and Mayila, 1986).

Beneficiation tests by the Yugoslavians indicated that a 36% P_2O_5 concentrate could be obtained from a 3.35% P_2O_5 feed with 70% recovery. From a concentration of 0.30% Nb_2O_5, a concentrate of 60.0% Nb_2O_5 with 60% recovery was obtained. Resources of ore from the surface to the 1,300-m level are 3.70 x 10^8 tons (Masao, 1986).

Pitting up to 10 m deep on Panda Hill by the Ministry of Energy and Minerals indicated substantially higher P_2O_5 contents than previous studies (17% to 25% P_2O_5) (E. P. Mchihiyo, 1987, Ministry of Energy and Minerals, Personal Communication). The P_2O_5 contents of the residual soils appear to increase with depth and are enriched at the weathered rock contact. Van Straaten (2002) indicated that the Tanzania-Canada agrogeology team delineated approximately 1 million tons of residual phosphates with an average grade of 10% to 31% P_2O_5 in the Kunja-Mtoni zone of Panda Hill.

Sangu-Ikola Carbonatite Complex—Located in the Mpanda District, 70 km southwest of Mpanda Town, the Sangu-Ikola Carbonatite Complex is most easily accessed by boat from Lake Tanganyika. The complex is composed of three ring structures:

1. Ikamba Carbonatite, 18 x 1.5 km.
2. Ikola Carbonatite, 3 x 1 km.
3. Middle Carbonatite, 1 x 0.2 km.

Host rocks include garnet-amphibolites and quartzites. Although the complex has been mainly investigated for its possible niobium content, interesting apatite contents have been noted (Masao, 1986). Apatite contents of the rock vary from 16% to 35%. Residual soil samples have assayed over 10% P_2O_5.

Songwe Scarp Carbonatite—The Songwe Scarp Carbonatite is situated in the Mbeya District along the road to Utengule. The structure resembles a dike about 19 km long parallel to the present rifting. The body is discontinuous and varies in width from 6 to 80 m. Composition is fine-grained siliceous dolomitic to sideritic carbonate. The carbonatite is generally resistant to weathering, probably because of the high silica content. However, some zones weather to a limonitic material. An XRF analysis of the weathered material (Masao, 1986) indicates a P_2O_5 content of over 17% (Table Tanzania 9). One sample of weathered Songwe Scarp carbonatite has been chemically analyzed at IFDC (Table Tanzania 9). Mineralogical analysis indicates the sample is composed of quartz (80 wt %), apatite (8 wt %), goethite (8 wt %), and calcite (1 wt %). The low phosphate grade and mineralogical characteristics of the sample suggest it would be difficult and expensive to upgrade. The P_2O_5 analyses of fresh carbonatite are reported to be variable (Masao, 1986). Some lenticular bodies averaged 10% P_2O_5 while others averaged 3% P_2O_5.

Zizi Carbonatite—Located in the Morogoro District 50 km south of Kisaki, the Zizi Carbonatite is a steeply dipping band of apatite-sovite approximately 20 m thick and 1.15 km long on strike (Harris, 1981; Masao, 1986). This carbonatite had been first described as an apatite limestone (Stockley, 1946). Samples from the carbonatite range from 4.5% to 10.5% P_2O_5 with an average of 7.28%. Resources are estimated to be 2 x 10^6 tons/100 ft of depth. Concentrates of up to 25% P_2O_5 have been produced by various combinations of gravity concentration, calcination, slaking, sieving, and washing (Stockley, 1946).

Table Tanzania 9. Chemical Analyses of Weathered Songwe Scarp Carbonatite

	MEM Sample[a]	Weathered Sample[b]
	(wt %)	
P_2O_5	17.75	3.5
CaO	25.46	53.60
SiO_2	24.82	80.0
Al_2O_3	5.97	0.5
Fe_2O_3	14.52	6.8
Na_2O	0.76	0.1
MgO	0.16	<0.1
K_2O	5.49	<0.1
TiO_2	1.59	–
MnO	0.36	–
F	–	0.21
CO_2	–	0.5
Organic	–	0.4
LOI	3.11	3.8

a. Ministry of Energy and Minerals Sample (Masao, 1986).
b. IFDC analysis.

Sulfur Resources

Based on previous drilling by the Ministry of Energy and Minerals (Madini), STAMICO evaluated a massive pyrite body at Samena Hill in the north near Lake Victoria (Figure Tanzania 1). The Madini had drilled 14 holes to a depth of 100 m. Current resource estimates are 2.0 x 10^7 tons at 13% to 26% sulfur. The pyrite occurs as 3- to 12-m-thick bodies. STAMICO drilled 10 more boreholes to 300 m depth to define the geometry of the deposit and refine resource estimates.

Native sulfur occurs in the inner crater of Kibo, Mt. Kilimanjaro. The inaccessibility of the deposit and low tonnage (6 x 10^3 tons) is likely to discourage exploitation (Harris, 1981).

Gypsum and anhydrite occur at Pindiro and Mandawa in southeastern Tanzania, about 100 km north of Lindi (Harris, 1981). The deposit is a salt dome structure. Reserves are 5 million tons containing 85% gypsum (van Straaten, 2002).

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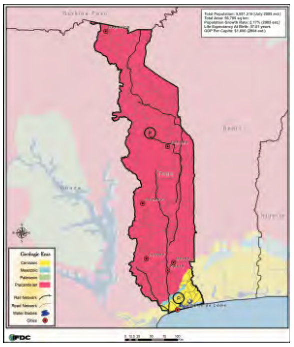
TOGO



Togo is bordered by Burkina Faso on the north, Ghana on the west, Benin on the east, and the Atlantic Ocean on the south. Total area is 56,785 km^2; approximately 46% of the land is arable. The total population was estimated as 5.7 million inhabitants in mid-2005 (World Factbook, 2006). Annual population growth is 2.2%. Approximately 65% of the labor force is occupied by agriculture. The transportation network (Figure Togo 1) is composed of 2,376 km of paved roads and 5,144 km of unpaved roads, as well as 568 km of narrow-gauge (1.0 m) railway. There are two airports with paved runways.

The geology of Togo is mainly formed by Precambrian to Early Cambrian rocks (Figure Togo 1). The north-south trending Dahomeyan Belt (Togo Belt) forms a strongly deformed series of supracrustal rocks. The Dahomeyan Belt was thrust to the west onto the sediments of the Volta Basin, which is found in the northwest of the country. Cretaceous to Tertiary sediments gently dip southward and offshore along the Atlantic Coast. These sediments form the western margin of the Dahomey Basin, which extends to the east across Benin and into Nigeria.

Nitrogen Resources

The Togolese Petroleum Law, which covers all petroleum operations from exploration to exploitation, was promulgated in 1999. In 1999 Petroleum Geoservices (PGS) concluded the interpretation of a three-dimensional geophysics survey carried out on an offshore area of 3,100 km^2, which indicated hydrocarbon potential (Palut, 2004).

In 2001 the Togolese government signed a production-sharing agreement with a subsidiary of Hunt Oil Co. of the United States for exclusive rights to carry out exploration in the entire offshore area of Togo, which is an area of about 4,067 km^2. In 2002 a subsequent agreement was signed between the Togolese government and Togo Hunt Oil Co., a joint venture between PETRONAS and Hunt Oil Co., for oil production offshore Togo. A well was to be drilled in 2003. The Hunt Oil Co. website (www.huntoil.com) indicates that exploration activities are in progress in Togo but gives no details. The PETRONAS website (www.petronas.com.my) does not indicate any activity in Togo.

Phosphate Resources

Hahotoé-Akoumapé—The Hahotoé-Akoumapé Deposit was first discovered in 1952. The deposit extends along strike approximately 35 km (Figure Togo 2) in a 2- to 3-km-wide band. The phosphate beds extend to the northeast from the Dagbati area but change in character; the main ore bed is lower in grade and contains more silica.

The Hahotoé-Akoumapé Deposit is of Lower Eocene age and occurs within the strata of the Série de la Lama, a series of clays and shales with minor sandstones and limestones. The beds dip at 1º-2º to the southeast. There are three to four phosphate beds separated by marls and clays. Several theories have been advanced concerning the formation of the deposit (Figure Togo 3). The latest theory suggests that the commercial beds formed as a result of weathering of phosphatic marls (Johnson, 1987; Van Kauwenbergh and McClellan, 1990).

Development work was carried out in the 1950s by the Société Minière du Benin (SMB). SMB was renamed Compagnie Togolaise des Mines du Bénin (COTOMIB) in 1957. The mine became operational

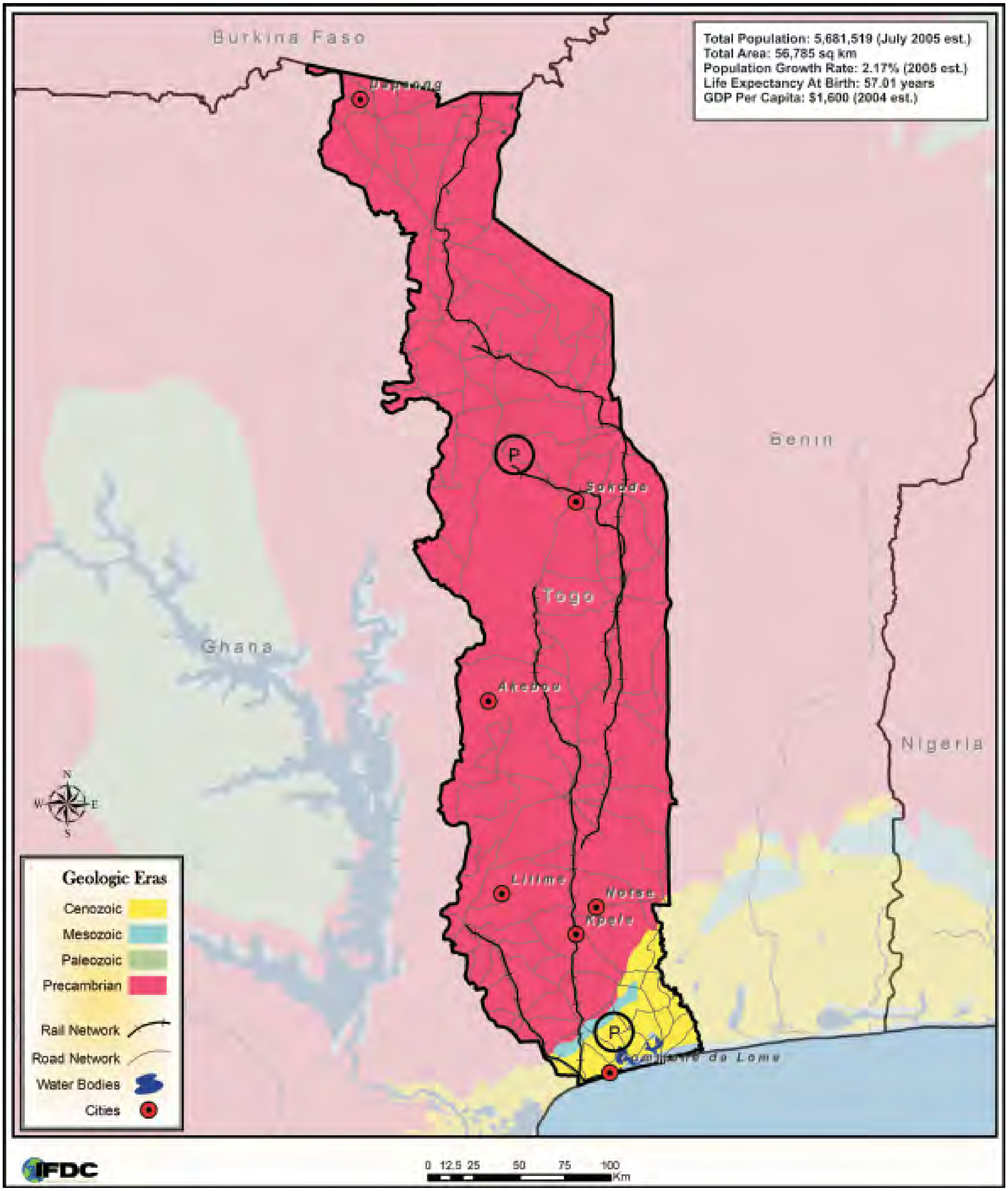
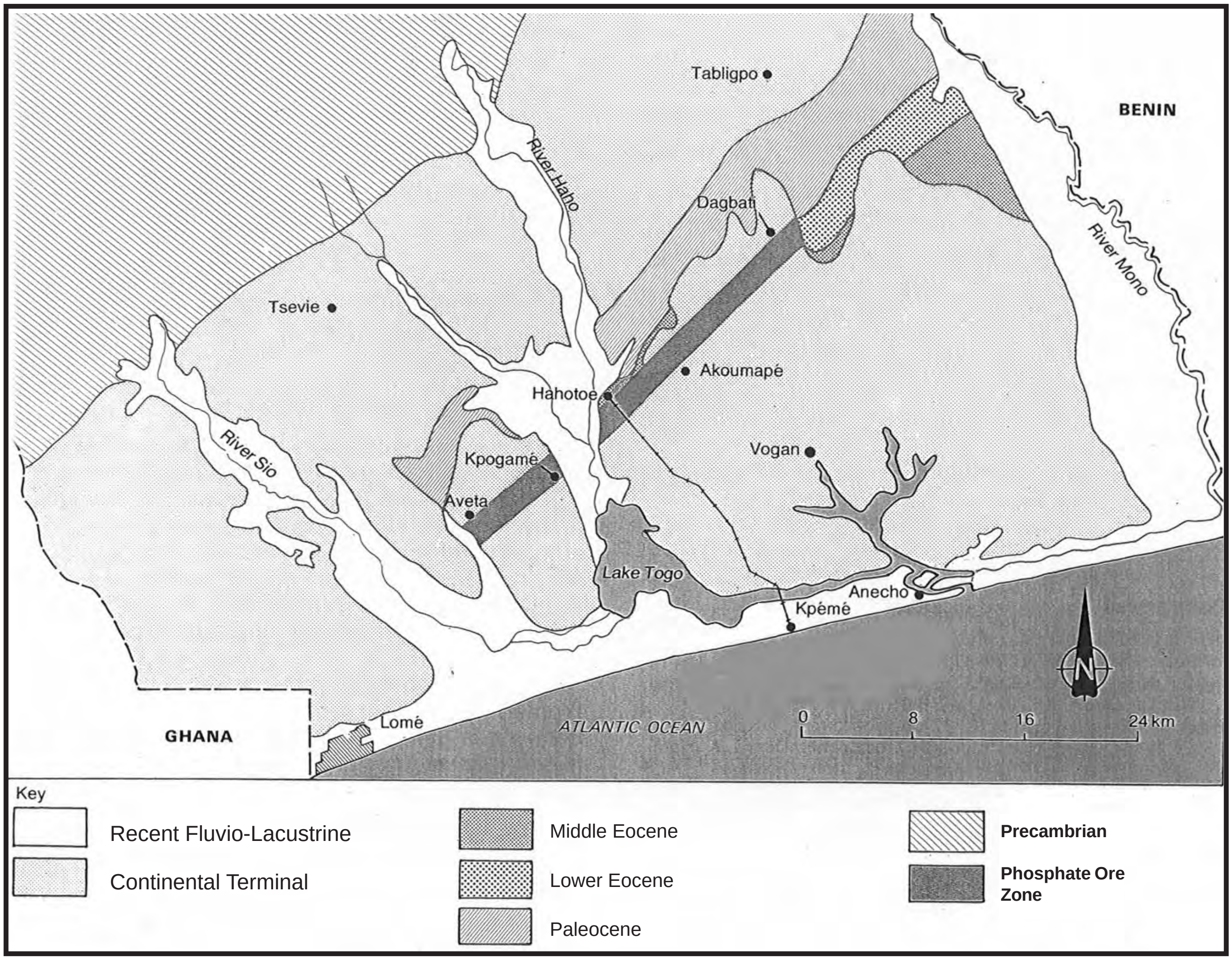


Figure Togo 1. Geology, Major Cities, and Transportation Network



Source: Adapted from Savage (1987).

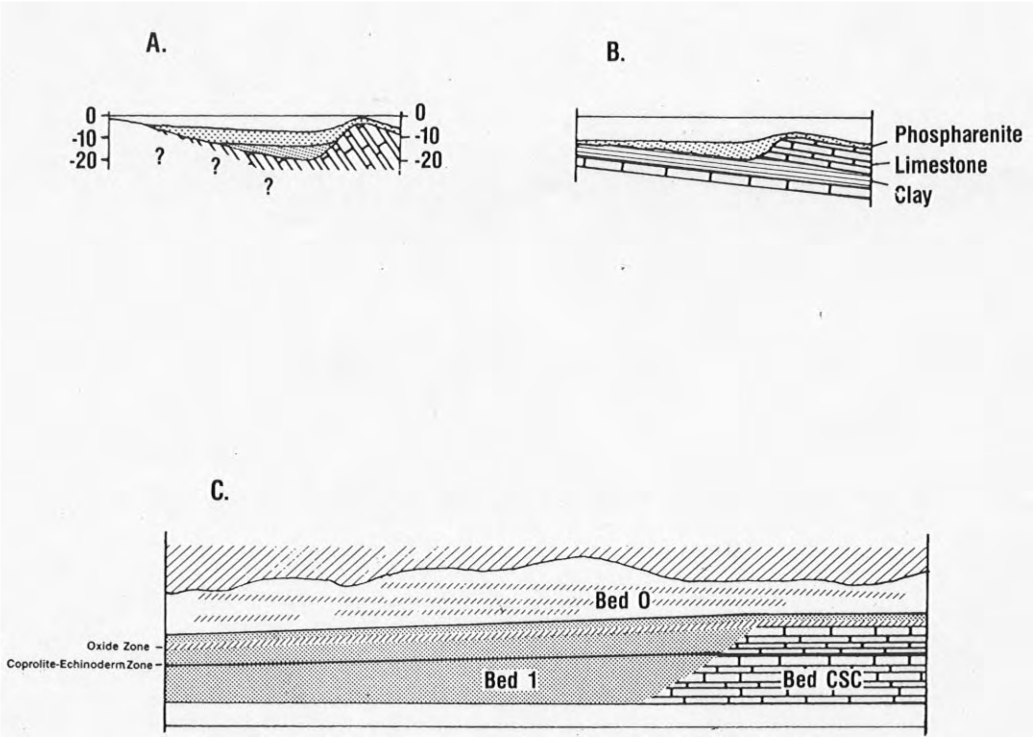
Figure Togo 2. General Geologic Map of the Hahotoé-Akoumapé Deposit

in 1961 with an installed capacity of 750,000 tpy concentrate. By 1970 the capacity was doubled to 1.5 million tpy. The Kpogame Mine was completed in 1973, and production approximately doubled.

The largest shareholder in COTOMIB was the W.R. Grace Co. of the United States. Other shareholders included French interests and the Government of Togo. The industry was nationalized in 1974. In the late 1970s and early 1980s, several proposals were put forth to increase production and build a phosphoric acid plant to consume about 1 million tpy of concentrate.

In 1979, there was an operating slimes recovery plant. Five-centimeter hydrocyclones were used to make a split in the 20- to 30-micron size range. It was expected that the slimes recovery plant would produce approximately 300,000 tpy of additional product at about 78 BPL (Khilkoff-Choubersky and Cape, 1979). The slimes product was initially combined with normal plant products for drying and shipping. The plan was to eventually use this material in a nearby phosphoric acid plant; however, the company was never able to obtain financing for the phosphoric acid plant. Slimes recovery was eventually discontinued.

In 1980 the company was renamed Office Togolais des Phosphates (OTP). In the late 1980s, Togo phosphate rock production was approximately 3.5 million tons. Production was about 1.0 million tons in 2001. Several factors contributed to decreasing production in the 1990s. In the late 1990s



Source: Adapted from Van Kauwenbergh and McClellan (1990).

Figure Togo 3. Evolution of Theories About Formation of Togo Phosphate Deposit: (A) Carbonate Barrier and Entrapment Basin (Kilinc and Cotillon, 1977); (B) Bedded Carbonate Barrier and Entrapment of the Phospharenite (Slansky, 1986); (C) Lateral Continuity of Bed 1 and the Carbonate Bed CSC (Johnson, 1987)

Agrium, Canada, developed a mine in Canada and discontinued the use of approximately 1.0 million tpy of Togo phosphate rock. In 1999-2000 Norsk Hydro stopped production of phosphoric acid at Vlaardingen in the Netherlands. The Vlaardingen plant produced about 130,000 tons of P_2O_5 as phosphoric acid and may have consumed approximately 400,000 tons of phosphate rock per year. Also, in this general time period, OTP sold its interests in Indian Ocean Fertilizers, Port Durban, South Africa. Togo phosphate rock was mixed with Palabora phosphate rock to produce phosphoric acid and diammonium phosphate (DAP). Approximately 1.0 million tpy of Togo phosphate rock was utilized at Indian Ocean Fertilizers.

In September 2001, the Togolese government partially privatized the company by forming International Fertilizer Group-Togo (IFG-TG) whose share capital was subscribed equally between the Togolese government and Brifco Ltd., a company connected with the Tunis-based MEDEX Petroleum (Palut, 2004). The new company planned to rehabilitate the operation and raise production to 3.0 million tpy. In 2002 output rose to 1.38 million tons. In 2003 production was 1.47 million tons while exports were 1.37 million tons. Numerous difficulties led to a crisis within IFG-TG in November 2003. Apparently the partnership has been dissolved.

In Togo the first several meters of overburden, containing tree roots and other debris, is extracted using bulldozers, front-end loaders, power shovels, and large dump trucks. Large bucket-wheel excavators remove the remaining overburden (from 7 to 30 m) in two benches (Figure Togo 4). Large bucket-

Figure Togo 4. Kpogame Mine, Togo, Overburden Stripping

wheel excavators are very suitable for open-pit operations when the overburden and ore are soft and dry. The overburden is transferred to mined-out areas by conveyors and offloaded by transloaders. Bucket-wheel excavators are also used to mine the ore zones, which can be as much as 6 m thick (Figure Togo 5). Conveyors move the ore to a transfer point where it is loaded into railcars for shipment to the beneficiation plant by a narrow-gauge railway (Figure Togo 6). At the beneficiation plant, the side-dumping railcars are unloaded in a facility designed to homogenize the feed (Figure Togo 7).

Figure Togo 6. Kpogame Mine, Rail Transfer Point

Figure Togo 7. Togo Beneficiation Plant, Ore Offloading Station

The beneficiation plant contains five processing trains with an overall design capacity of 3.5 million tpy (Figure Togo 8). The raw ore feed is scrubbed with seawater and wet screened at between 0.8 and 3.0 mm depending on the characteristics of the ore (Figure Togo 9). The next processing stage involves slurrying with seawater and using a series of primary and secondary hydrocyclones (Figure Togo 10). Fines (approximately minus 44 mm), which include clays, constitute approximately 40% of the composition of the feed and are removed by hydrocycloning. The wet ore concentrate is dewatered using 430-mm hydrocyclones; it then passes through centrifuges where it is given a freshwater rinse to reduce the chloride content (Figure Togo 11). A large-diameter rotary dryer with low airflow is used to reduce moisture from 17% to less than 2% (Figure Togo 12). The dry product can be passed through a vibrating screen to remove particles over 400 mm, and ferrous material can be removed by an optional electromagnetic separation step. The fine dried

Figure Togo 5. Kpogame Mine, Togo, Bucket-Wheel Excavator Used to Mine the Ore Zone

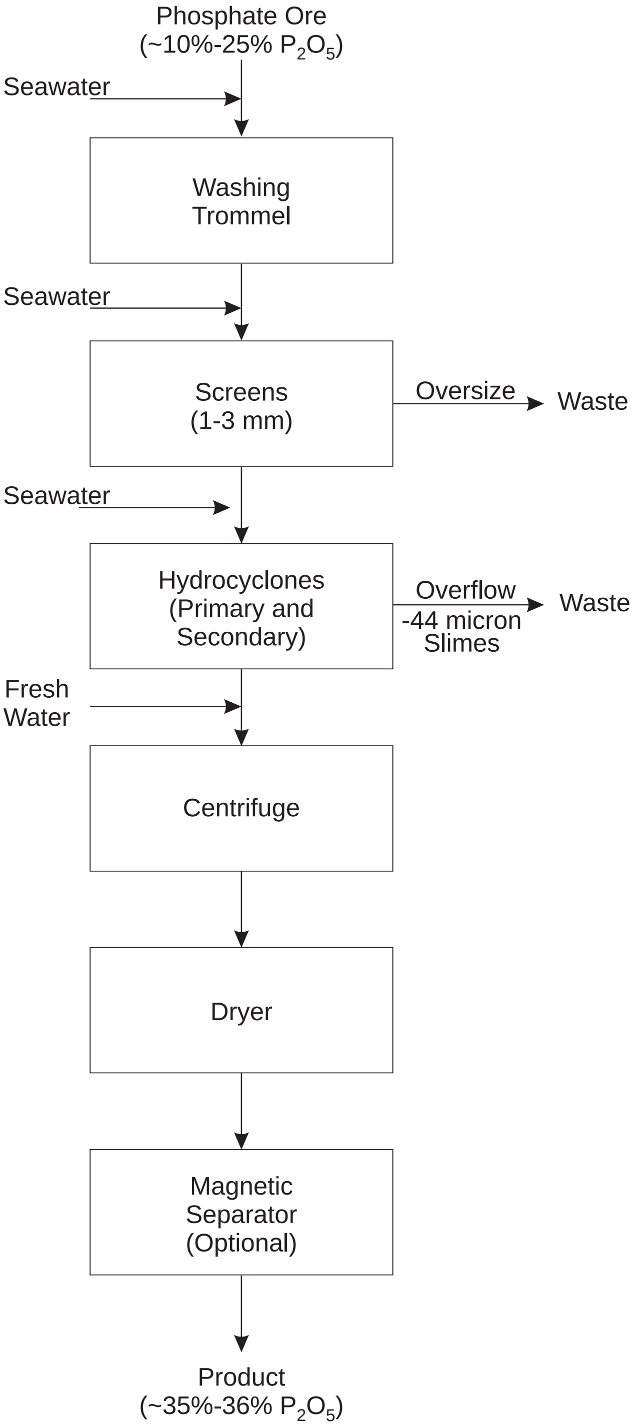


Figure Togo 8. Simplified Togo Phosphate Ore Processing Scheme

Figure Togo 9. Togo Beneficiation Plant, Initial Screening Station

Figure Togo 10. Togo Beneficiation Plant, Initial Hydrocyclone Station

Figure Togo 11. Togo Beneficiation Plant, Centrifuges

Figure Togo 12. Togo Beneficiation Plant, Rotary Dryer

Figure Togo 13. Togo Beneficiation Plant, Storage Shed

concentrate is stored in large sheds (Figure Togo 13). The concentrate is moved by a conveyor system to a dedicated loading facility directly offshore from the beneficiation plant (Figure Togo 14). The Togo phosphate rock concentrate is marketed at a P_2O_5 content of over 36%.

There are several phosphate beds (Figure Togo 3) within the Lower Eocene strata. The uppermost bed, Bed O, typically contains iron or iron and aluminum phosphates. Table Togo 1 gives a chemical and mineralogical analysis of an ore sample from the "Roof of the Mine."

Figure Togo 14. Togo Beneficiation Plant, Offshore Loading Facility

The main ore bed, Bed 1, typically does not contain iron phosphates. Table Togo 2 gives chemical and mineralogical analyses of a run-of-mine ore sample that has not been beneficiated. After beneficiation, the P_2O_5 of the concentrates is often over 36% P_2O_5. Table Togo 3 gives chemical and mineralogical analyses of a sample of Togo concentrate.

As the Hahotoe Mine moved to the east, the ore from Bed 1 changed in character, becoming more silicious. Table Togo 4 gives chemical and mineralogical analyses of a concentrate produced from ore from the Dagbati area.

Table Togo 1. Chemical and Mineralogical Analyses—Togo, Roof-of-Mine Sample

	Chemical Analyses	Francolite[a]	Kaolinite	Fe-Phosphate	Quartz (SiO_2)	Montmorillonite	Unassigned
	(wt %)						
P_2O_5	31.7	30.09	0.02	1.59			
CaO	42.9	42.87	0.02			0.01	
F	3.4	3.29					0.11
SiO_2	7.7		4.0		3.5	0.20	
Al_2O_3	3.5		3.43			0.07	
Fe_2O_3	3.7		0.04	2.99		0.01	0.66
Na_2O	0.08	0.08				0.01	
MgO	0.20	0.17	0.02			0.02	
K_2O	0.10		0.05				0.05
CO_2	2.25	1.92					0.33
S	0.06						0.06
Cl^{1-} (ppm)	<50						
C (organic)	0.2						0.2
Cd (ppm)	66						66
LOI[b,c]	6.0						
Free H_2O[b,d]	1.9						
H_2O^+ [b,e]	1.84		1.2	0.61		0.03	
NAC P_2O_5 [b,f]	2.0						
TOTAL	95.79	78.42	8.78	5.19	3.5	0.35	1.41

a. Composition based on statistical models.

b. Not included in totals.

c. Loss on ignition = weight loss, 1000ºC, 1 h.

d. Free H_2O = weight loss, 105ºC, 1 h.

e. Combined water, calculated by mineral species, included in mineral weight.

f. Neutral ammonium citrate-soluble P_2O_5 (AOAC method), second extraction.

Bed CSC, thought to be the lateral unweathered equivalent of Bed 1, contains significant carbonate as calcite (Table Togo 5). The P_2O_5 content of the sample analyzed was only 12.2%.

Below Bed 1, there are two phosphate beds separated by marl and clay layers. Collectively, these beds are known as Bed 2/3. In 1980, 19 samples from cores from three boreholes through Bed 2/3 were mineralogically characterized (IFDC, 1980). The samples ranged from 35% to 90% apatite, 5% to 15% calcite, and 5% to 15% quartz. The samples had been processed to remove silica prior to analysis. Each borehole penetrated Bed 1 and a palygorskite bed at the base of Bed 2/3, indicating full penetration of the sequence. IFDC characterized the drill cores and performed beneficiation tests on selected intervals within the cores (IFDC, 1981). Beneficiation tests included attrition scrubbing and sizing, grinding and sizing, and flotation tests. Six flotation processes were evaluated. Even at 90% P_2O_5 recovery on flotation, overall P_2O_5 recovery was low.

Table Togo 6 lists the unit cell a-values of the francolite component of various Togo ores and concentrates, the predicted carbonate substitution, and measured neutral ammonium citrate (NAC) solubility. The francolite in ores and concentrates from the top of the geologic section has higher unit cell a-values, lower carbonate substitution, and

Table Togo 2. Chemical and Mineralogical Analyses—Togo Run-of-Mine Ore, Sample R232.10

	Chemical Analyses	Francolite[a]	Kaolinite	Quartz	Goethite	Smectite	Unassigned
	(wt %)						
P_2O_5	30.0	30.0					
CaO	42.7	42.57				0.03	0.10
F	3.5	3.25					0.25
SiO_2	9.8		4.77	3.04		1.99	
Al_2O_3	4.8		4.05			0.75	
Fe_2O_3	2.9				2.79	0.11	
Na_2O	0.09	0.09					
MgO	0.27	0.16				0.11	
K_2O	0.11					0.06	0.05
CO_2	1.3	1.3					
S	0.07						0.07
Cl^{1-} (ppm)	163						163
C (organic)	0.2						0.2
Cd^{2+} (ppm)	55						55
Free H_2O[b,c]	0.5						
LOI[b,d]	3.7						
H_2O^{+}[b,e]			1.44		0.31	0.39	
NAC P_2O_5[b,f]	2.7						
TOTAL	95.76	77.37	10.26	3.04	3.10	3.44	0.67

a. Composition based on statistical models.
b. Not included in totals.
c. Free H_2O = weight loss, 105ºC, 1 h.
d. Loss on ignition = weight loss, 1000ºC, 1 h.
e. Combined water, calculated by mineral species, included in mineral weight.
f. Neutral ammonium citrate-soluble P_2O_5 (AOAC method), second extraction.

correspondingly lower measured NAC P_2O_5 solubility. NAC solubilities of 2.0-3.0 are considered low. Only the sample from the carbonate bed CSC contains a francolite with NAC reactivity that might be considered in the medium range.

Togo phosphate rock was and is considered one of the most desirable phosphate rocks in the world from a standpoint of chemical processing. With a high P_2O_5 content, combined Fe_2O_3 + Al_2O_3 contents of less than 3.0 wt %, essentially no free carbonates, a minor silica component, and a fine size range that resulted in no grinding requirement, Togo phosphate rock is particularly highly adaptable to a wide range of phosphoric acid process options.

One of the negative qualities of Togo phosphate rock, which has apparently affected its marketability, is the cadmium content. The average cadmium content of 20 Togo concentrate samples was 58.4 ppm (Van Kauwenbergh, 1997). OTP has funded studies concerning the removal of cadmium from phosphate rock and phosphoric acid. IFDC (1988) explored removal from the rock by attrition scrubbing in acid media, flotation, and calcination and attrition scrubbing. IFDC also explored cadmium removal from phosphoric acid by solvent extraction, ion exchange, ionic flotation, and chemical precipitation. Some of these techniques proved very successful in laboratory and pilot plant scale, reducing

Table Togo 3. Chemical and Mineralogical Analyses—Togo Concentrate

	Chemical Analyses	Francolite[a]	Quartz	Kaolinite	Goethite	Unassigned
	(wt %)					
P_2O_5	36.8	36.71				0.09
CaO	52.1	52.1				
F	4.3	3.98				0.32
SiO_2	3.7		2.65	1.05		
Al_2O_3	0.89			0.89		
Fe_2O_3	1.1				1.1	
Na_2O	0.15	0.15				
MgO	0.10	0.10				
K_2O	0.02					0.02
CO_2	2.4	2.2				0.2
S	0.11					0.11
Cl^{1-} (ppm)	301					301
C (organic)	0.1					0.1
Cd^{2+} (ppm)	63					63
Free H_2O[b,c]	0.5					
LOI[b,d]	3.7					
H_2O^+[b,e]				0.32	0.12	
NAC P_2O_5[b,f]	2.7					
TOTAL	101.81	95.24	2.65	2.26	1.22	0.88

a. Composition based on statistical models.
b. Not included in totals.
c. Free H_2O = weight loss, 105ºC, 1 h.
d. Loss on ignition = weight loss, 1000ºC, 1 h.
e. Combined water, calculated by mineral species, included in mineral weight.
f. Neutral ammonium citrate-soluble P_2O_5 (AOAC method), second extraction.

cadmium to less than 10 ppm in the phosphate rock and phosphoric acid.

The remaining resources of the Lower Eocene deposits of Togo are somewhat speculative. The United States Geological Survey (USGS) indicates remaining reserves of 30 million tons and a reserve base of 60 million tons (USGS, 2005). These figures have not been revised for several years. USGS generally reports tons of recoverable concentrate. Palut (2004) indicates there are reserves of 260 million tons of high-grade ore and more than 1 billion tons of “lower grade carbonate phosphate.” No figures are given for recoverable concentrate.

Bassar Deposit—The Bassar Phosphate Deposit, discovered in 1985, is located about 400 km north of Lomé (Figure Togo 1). The deposit was studied in detail by a team of German scientists (Heimbach, Lüttig, and Müller, 1987). The deposit is a Precambrian sedimentary deposit located in metamorphosed and structurally complex terrain. The deposit is subdivided into four blocks: Bassar I, II, III, and IV.

IFDC characterized four samples from Block I (IFDC, 1995). The P_2O_5 contents of the samples ranged from 37.90 to 39.22 wt %. The samples were composed of fluorapatite (90%-92%), quartz (1.6%-3.8%), clay (1.3%-2.4%), and goethite (1.0%-1.4%). The unit-cell a-value dimensions measured for the apatite samples indicated a fluorapatite composition with no carbonate substitution. The NAC solubilities of the samples ranged from 1.1% P_2O_5 to 1.5% P_2O_5,

Table Togo 4. Chemical and Mineralogical Analyses—Dagbati (Togo) Concentrate

	Chemical Analyses	Francolite[a]	Kaolinite	Fe-Phosphate	Quartz (SiO_2)	Unassigned
	(wt %)					
P_2O_5	32.8	31.63		1.17		
CaO	46.1	45.76				0.34
F	3.0	3.0				
SiO_2	8.7		2.12		6.58	
Al_2O_3	1.8		1.8			
Fe_2O_3	2.2			2.2		
Na_2O	0.29	0.29				
MgO	0.1	0.1				
K_2O	0.04					0.04
CO_2	2.2	2.2				
S	0.17					0.17
Cl^{1-} (ppm)	65					65
C	0.10					0.1
LOI [b,c]	5.1					
Free H_2O [b,d]	0.63					
H_2O^+ [b,e]			0.64	0.45		
NAC P_2O_5 [b,f]	2.6					
TOTAL	97.50	82.98	4.56	3.82	6.58	0.65

a. Composition based on statistical models.
b. Not included in totals.
c. Loss on ignition = weight loss, 1000ºC, 1 h.
d. Free H_2O = weight loss, 105ºC, 1 h.
e. Combined water, calculated by mineral species, included in mineral weight.
f. Neutral ammonium citrate-soluble P_2O_5 (AOAC method), second extraction.

Table Togo 5. Chemical and Mineralogical Analyses—Togo Sample CSC (Carbonate Bed)

	Chemical Analyses	Calcite ($CaCO_3$)	Francolite[a]	Montmorillonite	Kaolinite	Quartz (SiO_2)	Unassigned
	(wt %)						
P_2O_5	12.2		12.19	0.01			
CaO	44.4	25.58	18.49	0.33			
F	1.5		1.5				
SiO_2	7.4			6.75	0.35	0.29	
Al_2O_3	2.8			2.5	0.30		
Fe_2O_3	1.6			0.47			1.13
Na_2O	0.29		0.20	0.09			
MgO	0.70		0.14	0.56			
K_2O	0.16			0.04			0.11
CO_2	22.4	20.07	1.47				0.86
S	0.87						0.87
Cl^{1-} (ppm)	186						186
C	0.2						0.2
LOI [b,c]	26.3						
Free H_2O [b,d]	2.2						
H_2O^+ [b,e]	1.03			0.92	0.11		
NAC P_2O_5 [b,f]	3.9						
TOTAL	94.52	45.65	33.99	11.67	0.76	0.29	2.99

a. Composition based on statistical models.
b. Not included in totals.
c. Loss on ignition = weight loss, 1000ºC, 1 h.
d. Free H_2O = weight loss, 105ºC, 1 h.
e. Combined water, calculated by mineral species, included in mineral weight.
f. Neutral ammonium citrate-soluble P_2O_5 (AOAC method), second extraction.

Table Togo 6. Unit Cell Dimension of Togo Ores and Concentrates

Sample	a-Value Å	c-Value Å	Carbonate Substitution	NAC P_2O_5
	(±0.002)	(±0.002)	(wt %)	
Roof of mine	9.350	6.891	2.36	2.0
Run-of-mine ore	9.351	6.889	2.36	2.7
Concentrate	9.351	6.892	2.36	2.7
Dagbati concentrate	9.346	6.891	2.96	2.6
Bed CSC	9.333	6.897	4.82	3.9

similar to the solubilities of apatites from igneous rocks.

Müller (1992) incorporated Bassar phosphate rock samples in direct application trials in Togo. Several phosphate rocks, which had been ground conventionally or were mechanically activated, were compared with triple superphosphate in these trials.

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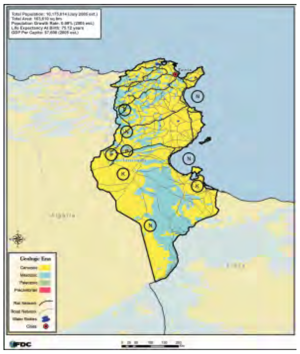
TUNISIA



The Tunisian Republic (Figure Tunisia 1) is bordered to the east-southeast by Libya, to the west-southwest by Algeria, and to the north-northeast by the Mediterranean Sea. Total area is 163,610 km^2 and approximately 17% of the land is arable. The population was estimated in mid-2005 as 10.2 million inhabitants (World Factbook, 2006). Agriculture occupies 22% of the labor force.

The transportation system consists of 12,424 km of paved roads and 6,573 km of unpaved roads, 468 km of 1.435-m-gauge railroad, 1,674 km of 1.000-gauge railroad, and 10 km of dual-gauge railroad (1.435 m and 1.000 m, three rails). Pipelines include 3,059 km for natural gas, 1,203 km for oil, and 345 km for refined products. The main ports are Bizerte, Gabes, LaGoulette, and Skhira.

While some Paleozoic age diapirs occur in northern Tunisia and Paleozoic age rocks are known from drill cores in southern Tunisia, the oldest outcropping sedimentary rocks in Tunisia are Triassic in age and are found in the southeast of the country and in the Atlas Mountains of northern Tunisia. Triassic sediments in the south are mainly red sandstones, clays with gypsum, and minor limestones and dolomites. In the north, the Triassic sediments consist of colored clays, marls with gypsum layers, and evaporites. Some diabase dikes were intruded during the Triassic in northern Tunisia. In the Jurassic, a marine transgression covered practically the entire country. Jurassic sediments in the north are limestones and marls. To the south, the Jurassic sediments become progressively more sandy.

The Cretaceous age rocks in Tunisia were laid down in a series of transgressions and regressions in basins and around topographic highs, which changed over time. In the north, Cretaceous rocks are dominantly limestones and marls. In central Tunisia, Cretaceous limestones, dolomites, sandy marls, and sandstones are found. In southern Tunisia, brackish water and continental sediments are found at the base of the Cretaceous Sequence, followed by sandstones and mudstones, dolomitic limestones, and gypsum beds. The uppermost Cretaceous age rocks in southern Tunisia are limestones and marls.

Phosphate deposits were developed in Tunisia during the Lower Paleocene to Lower Eocene ages. In southern Tunisia, the Tertiary began with the deposition of shell beds overlain by phosphates, marly limestones, and additional shell beds. The area was exposed during the Upper Eocene. In central Tunisia, the Paleocene began with the deposition of marls followed by phosphate beds. The phosphate beds may be friable or indurated. In northwestern Tunisia, black marls with carbonate nodules were initially deposited, followed by globigeria-bearing marly limestones. At the same time, light-colored chalky limestones, followed by gypsiferous marls and sandstones, were deposited in the area near Tunis.

Continental-derived sediments were deposited during the Oligocene and Pliocene when several transgressions and regressions occurred. Some igneous activity took place in northern Tunisia at the time of the Tertiary-Quaternary transition. Beach deposits formed near the sea while dunes formed in the interior during the Quaternary.

Nitrogen Resources

Tunisia's first and largest oil field, El Borma, was discovered in the southern region near the

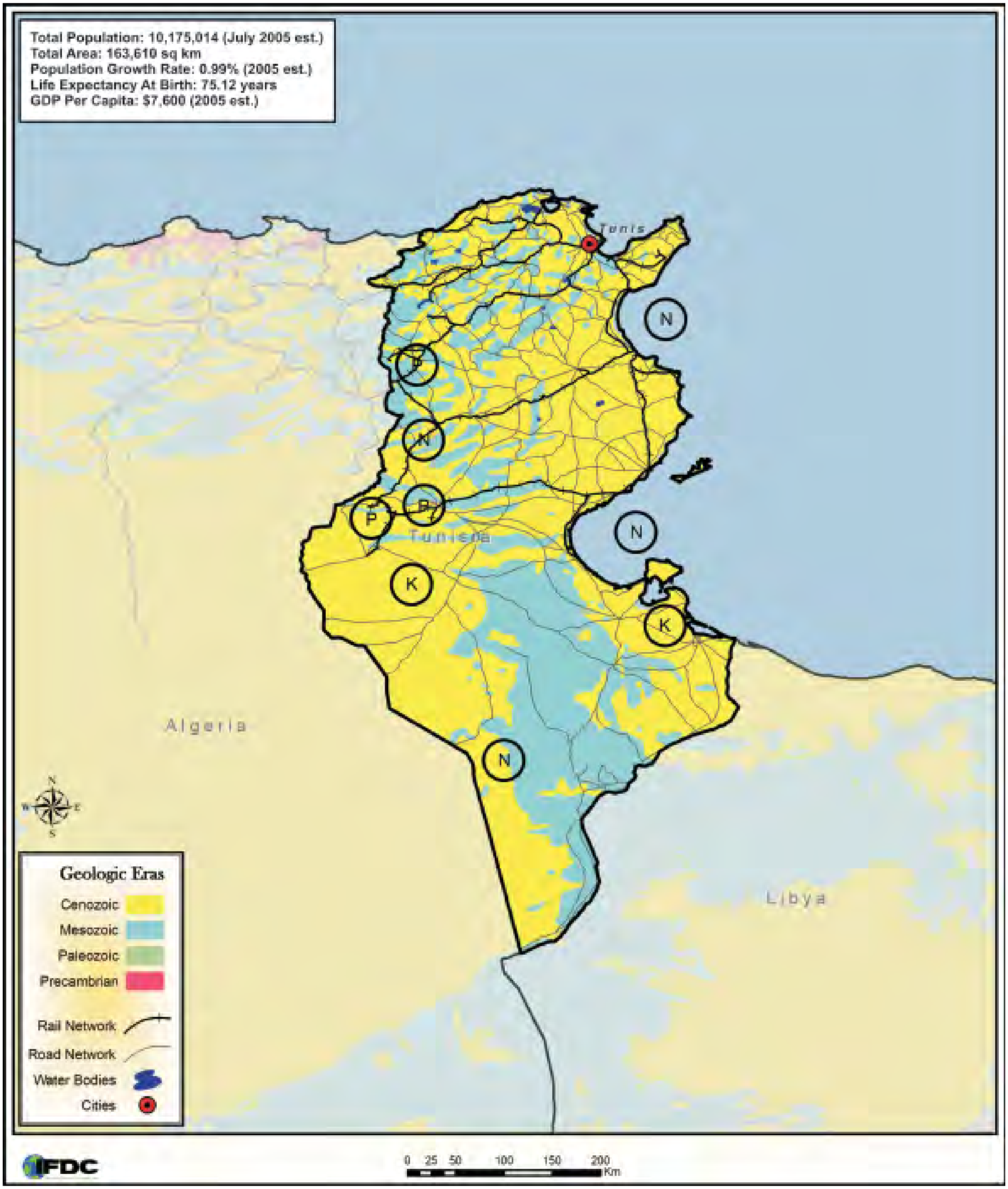


Figure Tunisia 1. Geology, Major Cities, and Transportation Network

Algerian frontier in 1964 (MBendi, 2005). The main hydrocarbon areas of significance include the Ghadames Basin in the southern part of the country, the Gulf of Gabes, the Gulf of Hammamet, and off the north coast. The main oil-producing fields are El Borma, Ashtart, and Sidi el Kilani. The main gas fields are El Borma (associated gas) and the offshore Miskar Field.

Companies involved in operations or exploration in Tunisia include Agip, Anadarko, EHT, British Gas, Centurion Oil, CMS Oil and Gas, Samedan Oil, Marathon Oil, Kuwait Foreign Petroleum Exploration Company, Total Fina, Neste Oy, Nuevo Energy, Oranje Nassau, Union Texas Petroleum, Petro-Canada, Phillips Petroleum, Pluspetrol, EGEP, Walter Enserch, Pioneer Natural Resources, ENI, Paladin Oil, PA Resources, Lunden Petroleum, and others. The Energy Information Admininstration (EIA) noted that Tunisia reformed its hydrocarbon law in 2000 in hopes of attracting investment, and apparently this effort was successful (EIA, 2004).

Peak oil output was 120,000 barrels per day (bpd) between 1982 and 1984 (EIA, 2004). Production in 2004 was about 76,000 bpd (World Factbook, 2006), up from 2003 when about 66,000 bpd was produced. Tunisian oil is a heavy crude.

The majority of Tunisian gas output comes from the Miskar Gas Field in the offshore Amilcar permit about 125 km offshore in the Gulf of Gabes. The gas field was discovered by Elf Aquitaine, but is now fully owned and operated by British Gas. Tunisia is increasingly turning to natural gas to cope with steadily increasing domestic demand for energy. Natural gas production in 2003 was 2.15 billion m^3. Natural gas consumption was 3.84 billion m^3. Natural gas imports were 1.58 billion m^3.

Estimates of oil reserves are variable. Crude oil reserves may range from about 308 million barrels (EIA, 2004) to 1.7 billion barrels (2005 estimate) (World Factbook, 2006). Natural gas reserves are estimated as 77.87 billion m^3 (EIA, 2004; World Factbook, 2006).

The only refinery in Tunisia is at Bizerte and its production capacity is 34,000 bpd (Mobbs, 2004). Tunisia exports crude oil and imports refined products. A new refinery to be built at Sakkira that would use imported oil was in the planning stages.

Nitrogen Fertilizer Production—Ammonium nitrate is produced by the Groupe Chimique Tunisien (GCT) at Ghannouch near Gabes. The annual capacity is 330,000 tons of product (Mobbs, 2004).

Phosphate Resources

Phosphate rock was first discovered in Tunisia in 1873, and production began in 1899 in the Gafsa area. Tunisia has a well-developed phosphate industry, from producing raw materials to finished products, that has evolved over the course of more than 100 years.

The sedimentary phosphate rocks of Tunisia and neighboring Algeria are thought to have formed in a restricted gulf of a shallow sea in the Late Paleocene (Thanetian). During the Eocene, this sea was divided into two distinct basins by a sometimes emergent anticlinal structure known as the Ile de Kasserine (Savage, 1987). To the south of this feature was a littoral-lagoonal environment wherein the soft phosphate rocks of the Gafsa Basin formed.

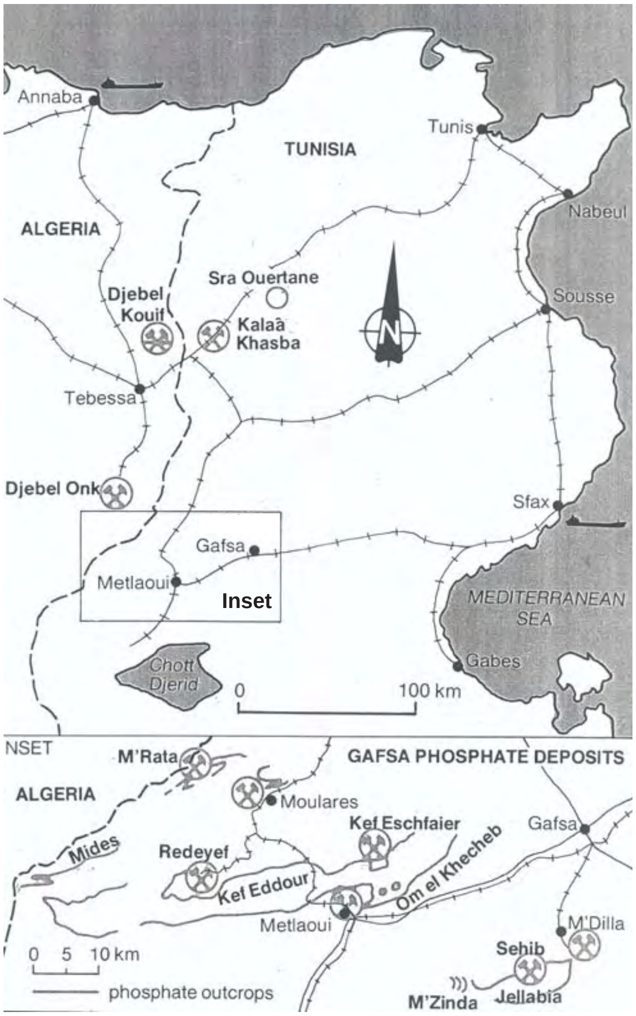
In Tunisia, almost all the important phosphate occurrences are found in Thanetian to Lower Eocene sediments of the Metlaoui Formation. The Metlaoui Formation is a highly variable formation composed of limestones, dolomites, gypsum beds, phosphatic limestones, phosphate marls, and clays with minor sandstone beds. The Metlaoui Formation may be up to 500 m in thickness in some parts of Tunisia. In the Gafsa area, nine phosphate beds have been distinguished; these beds are numbered from Bed O downward to Bed VIII. Individual beds may be missing from place to place, and the thickness and grade may vary. West of Gafsa, Beds I and II are generally worked. Southwest of Gafsa, Beds V and VI are worked. Workable beds are from less than 1 m to about 4-6 m in thickness.

In Tunisia, phosphate rock is found in two main areas—the Gafsa area and the Thala area. Phosphate rock also occurs in the eastern Tunisian Basin. However, the beds are probably lower in P_2O_5 content, and any beds of potential commercial interest may be restricted to a region south of Djebel Rechaich (Savage, 1987).

The phosphate rock industry of Tunisia was nationalized in the 1960s. All interests were merged, and the sole operating company became known as Compagnie des Phosphate de Gafsa (CPG) in 1976. In the 1970s, there were six phosphate mines operating in Tunisia, all underground. In the 1980s, CPG began closing down underground mines and developing open pits, thus improving productivity while reducing the number of employees and increasing production. In the late 1990s, there were eight mines, two of which were underground operations. The underground mines at M'Rata and Redeyef were scheduled for closure in 1999 and 2000 (*Phosphorus and Potassium*, 1999). There are currently five phosphate mines operating in Tunisia.

Gafsa Area—All the currently operating mines in Tunisia—Metlaoui, Kef Eddour, Redeyef, Moulares, and M'Dilla (or Mdhilla)—are located in the Gafsa area (*Fertilizer International*, 2006) (Figure Tunisia 2). The Metlaoui, Kef Eddour, Redeyef, and Moulares Mines are located to the west of Gafsa, while the M'Dilla Mine is located almost directly to the south of Gafsa.

The phosphate beds in the Gafsa area occur on the limbs of anticlines and can be traced along strike for tens of kilometers. In some of the anticlinal structures, the phosphate beds dip almost vertically, and underground mining techniques such as block caving were employed to exploit these beds. At the present time, all production is by open-pit methods. Chemical analyses of ore samples from the Metlaoui and M'Dilla Mines in the Gafsa area are given in Table Tunisia 1.



Source: Adapted from Savage, 1987).

Figure Tunisia 2. Locations of Previously Worked and Current Phosphate Mines of Tunisia and Algeria

Table Tunisia 1. Chemical Composition of Tunisian Phosphate Ores

Deposit	P_2O_5	CaO	SiO_2	Fe_2O_3	Al_2O_3	MgO	MnO	TiO_2	Na_2O	K_2O	SO_3	F	Cl	Ignition Loss
	(%)													
Metlaoui	25.28	43.53	8.23	0.54	1.63	0.49	0.004	0.10	1.43	0.52	3.75	2.90	–	10.28
	25.15	43.23	8.06	0.52	1.61	0.49	0.004	0.12	1.45	0.55	3.88	2.90	–	10.22
	26.09	42.85	8.90	0.60	1.53	0.50	–	–	1.45	0.38	3.90	2.98	–	4.62
	24.70	44.16	7.80	0.71	0.52	3.04	–	–	1.23	0.19	-	2.92		10.95
M'Dilla	23.08	39.45	14.07	0.76	1.73	0.72	0.006	0.10	1.50	0.30	4.21	2.90	–	11.73
	23.08	39.45	14.01	0.74	1.67	0.66	0.006	0.13	1.39	0.28	4.45	2.90	–	11.69
	28.40	46.10	1.90	0.50	1.20	–	–	–	–	–	–	3.50	–	5.30
	30.23	48.92	3.12	0.37	0.77	0.76	–	–	1.50	0.08	3.42	3.26	0.09	8.64

Prior to the 1980s, beneficiation of Tunisian phosphate rock was mainly accomplished through dry screening and air separation techniques. While dry separation techniques are still used, washing plants have been installed in many of the new or refurbished plants associated with new mines. In 1996, CPG started production of silica-bearing phosphate ore and has used washing and flotation technology to beneficiate this ore. Between 2005 and 2009, CPG is expected to spend US $40 million on plant upgrades to utilize low-grade ore (12% P_2O_5) and upgrade it to approximately 29.5% P_2O_5 (*Fertilizer International*, 2006).

Gafsa phosphate rock has been chemically and mineralogically characterized at IFDC (Table Tunisia 2). Gafsa phosphate rock contains a highly carbonate substituted francolite, calcite, and quartz. Based on the unit cell a-value, the CO_2 content of the apatite is near 6%. This is one of the most highly carbonate substituted francolites found in commercially available phosphate rock. Tunisian phosphate rock is very suitable for direct application under favorable crop and agroclimatic conditions. Table Tunisia 3 shows the solubility of Gafsa phosphate rock, compared with that of several other phosphate rocks, in common extraction media.

Table Tunisia 2. Approximate Mineralogic Modal Analysis, Gafsa Phosphate Rock Concentrate

Chemical Analysis		Francolite[a]	Calcite ($CaCO_3$)	Quartz	Unassigned
	(wt %)				
CaO	48.73	45.35	3.08		0.30
P_2O_5	29.19	29.19			
F	3.79	3.79			
Cl (ppm)	447				447
SiO_2	1.78			1.78	
Al_2O_3	0.45				0.45
Fe_2O_3	0.21				0.21
Na_2O	1.25	0.81			0.44
K_2O	0.08				0.08
MnO (ppm)	16				16
MgO	0.54	0.41			0.13
CO_2	6.62	4.21	2.41		
S	1.41				1.41
Zn (ppm)	434				434
Cu (ppm)	10				10
Co (ppm)	5				5
C (organic)	1.01				1.01
H_2O[b,c]	1.33				
LOI[b,d]	11.26				
Total	95.15	83.76	5.49	1.78	4.12

a. Unit cell a-value = 9.326 ± 0.002Å.
b. Not included in totals.
c. Weight loss, 1 h, 105ºC.
d. Weight loss, 1 h, 1000ºC.

Table Tunisia 3. Neutral Ammonium Citrate (NAC), 2% Citric Acid, and 2% Formic Acid Extractions, Gafsa, North Carolina (United States), Israel, and Brazil Phosphate Rocks

Sample	NAC[a] First Extraction	NAC[b] Second Extraction	2% Citric Acid[c]	2% Formic Acid[d]
	(% P_2O_5)			
Gafsa (unground)	3.6	4.0	5.1	12.9
Gafsa (ground)[e]	6.6	6.8	11.9	18.6
North Carolina (unground)	4.7	4.2	6.5	13.4
North Carolina (ground)[e]	7.1	6.6	15.8	25.7
Israel (Arad) (ground)	5.5	6.5	12.1	19.8
Brazil (Araxa) (ground)[f]	1.7	1.7	3.5	3.9

a. NAC solution, 100 mL, 1-g sample, shaker bath, 1 h, 65ºC.
b. Second extraction on residue of first extraction.
c. 2% citric acid, 100 mL, 1-g sample, shaker bath 1 h, 20ºC.
d. 2% formic acid, 100 mL, 1-g sample, shaker bath 1 h, 20ºC.
e. Ground under standard IFDC conditions, 7 min with trichlorotrifluoroethane, Siebtecknik Model T-250 laboratory disk mill.
f. Igneous phosphate rock.

Thala Area—Phosphate rocks in the Thala area are found on the north side of the Ile de Kasserine structure in the El Kef Basin. The phosphate beds generally occur in association with brown marls and phosphatic limestone at the top of Thanetian sediments, which include clays, marls, and argillaceous limestones. The beds are characteristically overlain by a nummulitic limestone, indicating formation under deep-water conditions.

Numerous mines were worked in the Thala area in the 20th century. The last operating mine was at Kalaa Khasba, near El Kef about 50 km from the Algeria border. The mine was an underground operation. The deposit was in the form of a perched syncline and is a continuation of the beds forming the Djebel Kouif Deposit in Algeria. The phosphate bed is 4 m thick in the area.

The product was analyzed as follows:

	%
P_2O_5	27.51
CaO	48.68
Fe_2O_3	0.47
Al_2O_3	0.63
MgO	1.52
Na_2O	1.08
SiO_2	5.14
CO_2	8.63
Cl	0.03
F	2.20
H_2O + organic C	2.30

Source: Savage (1987).

The ore was crushed and screened at 35 to 6.0 mm. The fines were removed to yield the product.

The Sra Ouertane Deposit is located close to the Kalaa Khasba Mine, about 40 km southeast of Kef. Jacobs Engineering performed a feasibility study on the deposit between February 1983 and December 1986. In the first phase of the project, the capacity was to be 1 million tpy of concentrate. The second phase of the project was to increase production up to 10 million tpy. The mine was to be a very large-scale, open-pit operation. The in-situ ore contains 12% to 15% P_2O_5. Upgrading would require flotation. Resources at Sra Ouertane have been estimated at 1,100 million tons.

Total reserves of Tunisian phosphate rock are considered by the United States Geological Survey (USGS) to be 100 million tons (USGS, 2006). The reserve base (resources) for all of Tunisia is considered by the USGS to be 600 million tons. Production of phosphate rock in Tunisia in 2005 was about 8.0 million tons. Considerable amounts of phosphate rock have been mined in the last 20 years in Tunisia to produce between 6 and 8 million tons of concentrate per year.

Table Tunisia 4 shows a Tunisian reserve estimate compiled by Svoboda (1989) based on British Sulphur Corporation sources. The total resource figure of almost 3,000 million tons differs very significantly from the USGS (2006) figure for the reserve base.

Table Tunisia 4. Estimated Reserves of Tunisian Phosphate Rock

Deposit/Mine	Estimated Reserves
	(million tons)
El Kef Basin	
Kalaa Khasba	10
Sra Ouertane	2,500
Gafsa Basin	
Jellabia-M’Zinda	100
Kef Eschfaier	82
Kef Eddour	46
M’Dilla	65
Metlaoui	66
Moularès	25
M’Rata	34
Redeyef	27
Sehib	40
Total	2,995

Source: Svoboda (1989).

Phosphate Fertilizer Production—GCT is responsible for all phosphate fertilizer production in Tunisia. Verified phosphoric acid capacity is indicated in Table Tunisia 5 (IFDC 2006a). Total 2005/06 capacity is indicated as 1.345 million tons P_2O_5 per year. *Fertilizer International* (2006) indicates capacity has been raised slightly to 1.69 million tons P_2O_5 per year.

Ammonium phosphate capacity is currently indicated as 375,000 tpy of P_2O_5 (Table Tunisia 5) (IFDC, 2006b). GCT is also planning a third plant at Gabes with a projected capacity of 600,000 tpy of product (*Fertilizer International*, 2006).

Tunisia is also a very significant producer of triple superphosphate (TSP). The Sfax plant produces 400,000 tons (product) of TSP per year, and the M'Dilla plant produces 500,000 tons of TSP product per year. The Gabes plant produces 120,000 tons of dicalcium phosphate per year.

Numerous upgrades have been performed over the last several years to raise capacities, reduce bottlenecks, improve quality, and meet environmental standards. As a result of increased production, consumption of phosphate rock has increased from 6.0 million tpy to 6.5 million tpy, leading to a reduction in the amount of rock available for export.

GCT is expanding its business, and several long-term projects are in the planning stages. A technical-grade phosphoric acid plant utilizing solvent extraction is scheduled to come onstream in 2007. The project is expected to cost about US $8.0 million.

In 2005, Coromandel Fertilizers Limited (CFL), India, announced it would form a joint venture with GCT and CPG for the manufacture of 500,000 tpy P_2O_5 as phosphoric acid. CFL will take a 15% stake in the project. The deal coincided with the announcement that Gujurat State Fertilizer Corp., India, would take an 18.33% equity stake in a joint venture to build a 500,000-tpy P_2O_5 phosphoric acid plant. If this plant (or plants) is developed, additional phosphate rock capacity will be required.

Table Tunisia 5. Tunisian Phosphoric Acid, Diammonium Phosphate (DAP), and Monoammonium Phosphate (MAP) Capacity

	Plant Status	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	Indefinite
	Phosphoric Acid Capacity (tons x 1,000, P_2O_5 basis)									
Tunisia										
Groupe Chimique Tunisien (GCT)										
Gabes I	OPR	450	450	450	450	450	450	450	450	450
Gabes II	OPR	400	400	400	400	400	400	400	400	400
Laskhira I	OPR	365	365	365	365	365	365	365	365	365
Laskhira II	PLN	-	-	-	-	178	178	178	178	178
SFAX	OPR	130	130	130	130	130	130	130	130	130
Company Total		1,345	1,345	1,345	1,345	1,523	1,523	1,523	1,523	1,523
Tunisia Total		1,345	1,345	1,345	1,345	1,523	1,523	1,523	1,523	1,523
DAP and MAP Capacity (tons x 1,000, P_2O_5 basis)										
Tunisia										
Groupe Chimique Tunisien (GCT)										
Gabes I	OPR	190	190	190	190	190	190	190	190	190
Gabes II	OPR	185	185	185	185	185	185	185	185	185
Company Total		375	375	375	375	375	375	375	375	375
Tunisia Total		375	375	375	375	375	375	375	375	375

OPR = Operating.
PLN = Planned.

Potassium Resources

Potash-rich brines occur in Tunisia in two depressions. The Sabkha el Melah is a fairly recent coastal feature located west of Zaris south of the Gulf of Gabes. The Chott Djerid Depression is located in the interior south of Tozeur about 280 km from Sfax, the closest port via rail.

The Chott Djerid Depression contains a sequence of Miocene age evaporites. Brines occur in three zones—0 to 30 m in depth, 30 to 60 m in depth, and from 60 to 100 m (British Sulphur Corporation, 1985)—based on drilling conducted in the 1960s. The uppermost zone is apparently the most saline. An analysis of the brine gave the following composition:

	%
K	0.45
Mg	0.55
SO_4	0.77
Na	7.80
Cl	13.10
Cu	0.15

A resource estimate from the late 1960s indicated 30 million tons as potassium chloride (KCl).

The Sabkha el Melah is a depression formed less than 35,000 years ago and is separated from the sea by carbonate sand dunes (British Sulphur Corporation, 1985). Halite is the most common precipitate beneath the crust of the Sabkha, reaching a thickness of 30 m. Gypsum occurs around the edges of the Sabkha and under the halite. Polyhalite is associated with the gypsum. Carnalite and magnesium salts can be precipitated from the residual brines.

There are two aquifers associated with the basin. A lower aquifer circulates beneath the carbonate sequence at the base of the evaporite zones. Concentrated brine, the so-called second aquifer, circulates within the evaporite zone.

In the late 1960s, the concession for the deposit was granted to Occidental International Corporation, a subsidiary of Occidental Petroleum Corporation. Analyses of the brine made at that time are as follows:

	%
KCl	0.52
K	0.27
$MgCl_2$	6.56
$MgSO_4$	1.34
Mg	1.94
NaCl	18.20
NaBr	0.13
Na	7.04
SO_4	1.07

At that time the reserves were estimated at 10 million tons of KCl.

In the late 1970s, the Office National des Mines of Tunisia undertook feasibility studies for the development of the Sabkha el Melah brines. Jacobs International and Dorchem International, both of the United States, completed a prefeasibility study in 1982. Two units would produce 300,000 tpy of potassium chloride and 10,000 tpy of potassium sulfate. The main focus of the project was to produce magnesium compounds, bromine, and sodium salts, and potash was to be a byproduct.

A French consortium composed of Spie Batignolles and Mines de Potasse d'Alsace, the French potash producer, was awarded a contract by Chimiques du Sud, a Tunisian government-owned company, in 1982 to study the feasibility of producing potassium sulfate by evaporation from the brines of the Sabkha el Melah. The production rate was envisioned at 140,000 tpy. The project was never implemented.

Sulfur Resources

Mobbs (2004) indicates that 130,000 tons of gypsum was produced in Tunisia in 2004. Currently, GCT phosphoric acid plants on the coast discharge phosphogypsum to the sea. GCT operates sulfuric acid plants that burn elemental sulfur. Recently the main plants have been converted from single- to double-absorption units (*Fertilizer International*, 2006).

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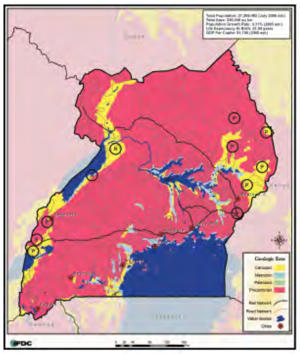
UGANDA



The Republic of Uganda is bordered to the west by the Democratic Republic of the Congo, the north by Sudan, the east by Kenya, and the south by Rwanda and Tanzania (Figure Uganda 1). The total area is 236,040 km^2 and approximately 26% of the land is arable. The population in mid-2005 was approximately 27.3 million inhabitants. Annual population growth was estimated as 3.31% (World Factbook, 2006). Agriculture occupies 82% of the labor force.

The transportation network includes 1,809 km of paved roads, 25,191 km of unpaved roads, and 1,241 km of 1.0-m-gauge railway. Uganda has 300 km of waterways on Lake Victoria and 200 km of waterways on Lake Albert, Lake Kyoga, and parts of the Nile. The main ports are Entebbe, Jinga, and Port Bell. There are four airports with paved runways and 24 airports with unpaved runways.

The geology of Uganda can be characterized by a central Precambrian age basement complex bounded largely by the Western and Eastern African Rift Valleys. The Precambrian basement was divided by MacDonald (1969) into (1) wholly granitized formations, (2) partly granitized formations, (3) non-granitized formations, and (4) other rocks. Wholly granitized or high- to medium-grade metamorphic formations include gneisses, amphibolites, and some recognizable marbles and quartzites. Partly granitized and metamorphosed formations include gneisses, metavolcanics, and metasediments. Partly granitized and metamorphosed formations are extensively found in the southern third of the country. Slightly metamorphosed Precambrian formations (sandstones, arkoses, conglomerates, and shales) are found in the center of the country, to the north and west of Lake Kyoga, and in a patchy distribution within rocks of higher metamorphic grade.

The Achwa Shear Zone crosses the Precambrian terrain in the northern half of the country from the vicinity of Mount Elgon to where the White Nile exits Uganda. The Western Rift Valley follows Lake Edward and a line to Lake Albert then to the north along the course of the White Nile. There are numerous faults and extensional features in this area. The floor of the Western Rift Valley is filled with Pleistocene volcanic and sedimentary rocks, as well as older sedimentary rocks.

The volcanics associated with the Eastern Rift Valley comprise generally sodium-rich agglomerates, lavas, and tuffs extruded by volcanoes such as Moroto, Kadam, and Elgon. Carbonatite ring structures such as Tororo, Sukulu, Bukusu, and Napak and syenite complexes such as Zulea represent the remnants of former volcanoes. Although the majority of the lavas and agglomerates are Miocene in age, the carbonatite and syenite complexes may date back to the Cretaceous age. Deep residual soils have developed over much of this area, and Pleistocene to Recent sediments fill the valley bottoms.

Nitrogen Resources

Although Uganda is mainly defined geologically by metamorphosed Precambrian and Cretaceous to Recent age volcanic activity, there is a series of sedimentary basins associated with the Western Rift Valley. The first petroleum well (Butiaba-Waki-1) in Uganda was drilled near Lake Albert in 1938 (Rigzone, 2006). Several oil companies are currently active in the Lake Albert area.

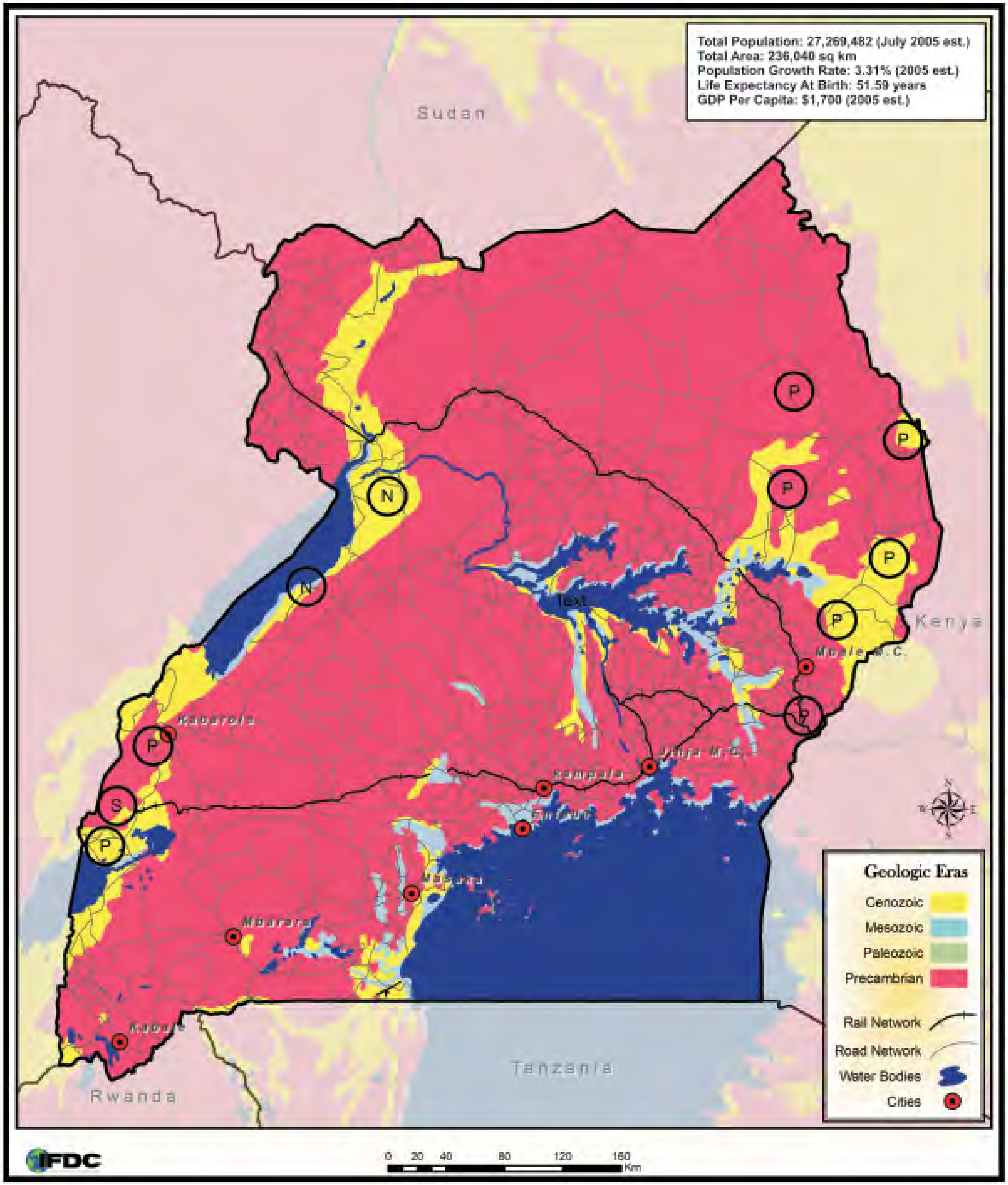


Figure Uganda 1. Geology, Major Cities, and Transportation Network

Heritage Petroleum acquired regional seismic data near Lake Albert in 1998. Heritage holds a 50% interest in Block 3 in the area, while Energy Africa holds the other 50%. The first wildcat well (Turaco-1) was drilled in late 2002 to early 2003 (Heritage Oil Corporation, 2002). Good shows of methane, higher order gases, and oil were encountered. Due to mechanical difficulties, Heritage was unable to log the well. In 2003, a 2D seismic program was performed on Lake Albert on Block 3 and on Block 2 in the northern part of the lake.

The Turaco-2 well was spudded in October 2003 near the site of the Turaco-1. Total depth was about 2,000 m. The hole was logged; however, the drill string became stuck while reaming in preparation for production testing. Heritage contracted for a 350-km 3D seismic survey after drilling the well (Heritage Oil Corporation, 2004).

The Turaco-3 well was drilled about 100 m from the Turaco-2 location. The well was completed successfully, and a production test was performed. Two potential hydrocarbon-bearing zones with a gross pay over 350 m thick were identified. Results of gas testing indicated a hydrocarbon content of 10%-20% and very high concentrations of carbon dioxide (Heritage Oil Corporation, 2005). Due to the high CO_2 concentration, the discovery was not considered economic.

In 2005 Heritage Oil concentrated on seismic work. A prospect (Kingfisher) on the shore of Lake Albert was identified, and drilling was planned for the first half of 2006.

Hardman Oil holds a 50% interest in Block 2 near Lake Albert; 50% is owned by Energy Africa (a subsidiary of Tullow Oil). In 2005 a 205-km 2D seismic survey was completed. The first well was completed in late 2005/early 2006 (*Financial Review*, 2006), and the results were very encouraging. A second well was to be drilled at the Waraga-1 site 19 km northeast of Mputa-7 in February 2006 (MBendi, 2006).

Phosphate Resources

Igneous Deposits—Carbonatites and extrusive volcanic rocks with a carbonatitic character are found in western and eastern Uganda (Figure Uganda 1). The most extensively studied of these complexes are in eastern Uganda. These eastern complexes can be divided into younger (Tertiary) and older (Cretaceous) age groups (Savage, 1987). The Cretaceous complexes—Sukulu, Tororo, Bukusu, Bitriku, and Budeda—are associated with the most significant accumulations of phosphate or potential for phosphate production.

Budeda Carbonatite—The Budeda Complex is located about 20 km east-northeast of Mbale Township in the foothills bordering the Siroko Valley. It is a relatively small complex (less than a kilometer across). The central area of the complex is an arcuate mass ranging from pyroxenite or melteigite to ijolite. Two small carbonatite masses (less than 12 m across) are found near the center. On Galala Hill and in exposures near the Siroko River, apatite pyroxenite can be found with up to 2.1% P_2O_5. Data from different rock types across the complex indicate the P_2O_5 content is generally less than 1% (King and Sutherland, 1966).

Bukusu Carbonatite—Bukusu, a broad hill rising approximately 300 m above the surrounding plain, lies about halfway between Tororo and Mbale. The complex is almost circular, measuring about 9-10 km in diameter. Incompletely exposed ultramafic and alkaline rocks constitute about 75% of the complex proper (Figure Uganda 2). Pitting on the hill

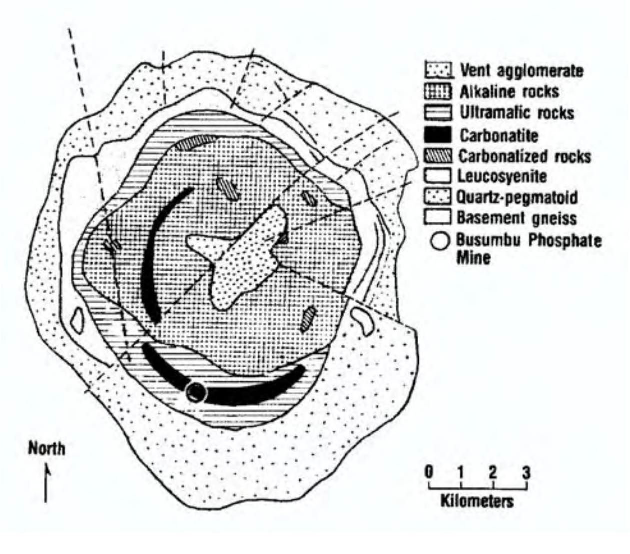


Figure Uganda 2. Geology of the Bukusu Carbonatite Complex (after Baldock, 1969) between 1930 and 1932 indicated that significant amounts of apatite were present in the soil (Davies, 1947). High-grade material (over 30% P_2O_5) was discovered on Busumbu Ridge near the southern end of the complex.

Initial mapping by Davies (1947) indicated that the magnetite-apatite-phlogopite rock which formed Busumbu Ridge was a band encircling the entire complex. Later work by Baldock (1969) indicated that, while the band encircles the complex, the apatite-containing rock is not continuous. Although Busumbu Ridge is a positive topographic feature, drilling indicates the weathered zone extends to depths of 60 m.

Phosphate occurs as a secondary francolite near the surface, with unaltered primary apatite at depth (Davies, 1947; 1956). Table Uganda 1 gives two phosphate rock analyses and a recalculated analysis by Davies (1947). Davies (1956) noted that the francolite from Busumbu Hill has a somewhat higher citric acid solubility than is found in the igneous apatites from Uganda. Van Kauwenbergh (1991) noted that the solubility of the apatite was somewhat higher than that of typical igneous apatite concentrates (Table Uganda 1). The ore is typically composed of fine, soft, earthy material. Where secondary apatite has cemented the particles together, the ore may be termed “hard rock.” Hard rock ore composes about 13% of the deposit (Davies, 1956). Chemical analyses by Mathers (1994) of phosphate rock samples from Busumbu indicate a range of P_2O_5 contents from 7.25% to 36.53% (Table Uganda 2). CaO/P_2O_5 ratios of some of the samples below approximately 1.31 indicate the presence of iron- and aluminum-containing phosphate materials. Between 1944 and 1963, the ore was mined to supply a silicophosphate (Rhenania) operation in Kenya (Savage, 1987). Typical product from the mine ranged from 22.50% to 24.21% P_2O_5 (Koenig, 1945). Upgrading of the ore was accomplished by simple screening; magnetite was concentrated in the larger size fractions. Some material was also sold for direct application (Davies, 1947).

Table Uganda 1. Chemical Analyses of Apatite Samples From the Bukusu Complex

	Impure Igneous Apatite[a]	Recalculated Igneous Apatite[a]	Francolite[a]	Bukusu PR[b]
	(%)			
P_2O_5	35.52	41.02	39.55	26.25
CaO	47.60	54.47	55.35	35.40
MgO	0.23	0.27	0.14	0.19
CO_2	0.43	0.50	1.80	1.40
Al_2O_3	0.65	–	–	–
Fe_2O_3	6.05	–	10.11	–
F	1.96	2.26	3.96	2.10
NAC P_2O_5[c]				2.30

a. Davies (1947).
b. Van Kauwenbergh (1991).
c. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).

The initial pitting and drilling on the hill indicated that 5 x 10^6 tons of ore between 8% and 35% P_2O_5 was present (Davies, 1947). The average P_2O_5 from 430 m of pitting was 11.9%. Davies

Table Uganda 2. Chemical Analyses of Phosphate Rock Samples From Busumbu

Phosphate Rock, Busumbu													
Sample	P_2O_5	CaO	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	Na_2O	K_2O	LOI	Total	CaO/P_2O_5
SM18	10.28	5.08	3.81	2.43	9.21	57.77	1.01	0.40	0.19	0.09	5.74	96.01	0.49
SM19	22.72	29.17	20.6	0.54	1.12	22.23	0.75	0.22	0.07	0.03	2.31	99.76	1.28
SM20	36.53	50.34	0.95	0.02	1.89	2.51	0.63	0.20	0.01	0.01	4.99	98.08	1.38
SM21	7.25	9.99	45.15	0.73	0.45	32.13	0.59	0.36	0.00	0.03	2.54	99.22	1.38
SM22	28.08	34.85	1.69	1.49	5.85	16.88	0.63	0.17	0.13	0.04	6.84	96.65	1.24
SM23	29.28	40.62	0.88	0.64	1.59	20.39	0.37	0.32	0.00	0.01	2.62	96.72	1.39

Source: Mathers (1994).

(1956) later speculated that as much as 5 x 10^7 tons of ore was present. In 1965 resources were estimated by the Geologic Survey of Uganda to exceed 1 x 10^6 tons of soft phosphate averaging 15% P_2O_5, 1.3 x 10^4 tons of soft phosphate averaging approximately 21% P_2O_5, and 2 x 10^4 tons of hard phosphate rock averaging approximately 30% P_2O_5 (Savage, 1987).

Reserves at Busumbu were indicated by Hadoto (1992; as quoted in Mathers, 1994) as 18,300 tons of "hard" rock (average 30% P_2O_5); 13,000 tons of "mixed" rock (average 21% P_2O_5); and at least 1 million tons of soft rock (average 15% P_2O_5). A joint team from the Department of Geological Survey and Mines (DGSM) and the United Nations Department for Development Support and Management carried out geological investigations at Busumbu indicating proven reserves of hard phosphate (average grade of 28.5% P_2O_5) at 325,000 tons and soft phosphate (averaging 13.5% P_2O_5) at more than 2,468,000 tons (Celenk and Katto, 1993; as quoted in van Straaten, 2002). The reserve estimates were limited to a pit depth of 6 m. Van Straaten cited additional work by Katto (1995; 2000), based on 125 pits, which indicated proven ore reserves of 8.5 million tons. This included 3 million tons with an average grade of 11% P_2O_5 at an average thickness of 2 m. In the underlying 4 m of weathered material (saprolite), an additional 5.5 million tons averaging 15% P_2O_5 was indicated. Van Straaten (2002) speculated that, because the deposit is thicker than 6 m, reserves are most likely higher. Van Straaten (2002) also noted subsequent work indicating 8.4 million tons on Hill 2 grading 12.6% P_2O_5. Hill 2 is one of three prominent hills located in the Busumbu Mine area.

Kretschmar (1998), working for International Business Investments (IBI) Corporation, evaluated both the Busumbu Phosphate and the Namekara Vermiculite Deposits. The Namekara Vermiculite Deposit occurs about 2 km to the northwest of the Busumbu Phosphate Deposit. Kretschmar (1998) evaluated all the previously published and unpublished work and ongoing work with the reserves. He concluded that the work by Katto (1995) was the most thorough and statistically valid work to that date indicating the proven combined reserves were 8.5 million tons. Kretschmar (1998) speculated that reserves in the probable and speculative category were 30-60 million tons of similar grade. However, no evidence was presented to support this speculation.

Kretschmar (1998) indicated that beneficiation tests were needed on bulk samples to further evaluate the ore. If the material was to be used as a low-cost locally marketed direct-application fertilizer, reserves were sufficient for many years. Further expenditure of effort and funds to define reserves was not justified at that time.

Canmin Resources Ltd. (a subsidiary of IBI) initiated production of vermiculite at Namekara: 664 tons in 2002 and 1,724 tons in 2003. Initial capacity was 25,000 tpy. In 2003, Canmin announced it had no plans to develop the Busumbu Phosphate Deposit until the Namekara project was more advanced (Yager, 2003).

Smithson, et al. (2001) tested triple superphosphate (TSP), Minjingu phosphate rock from Kenya, and Busumba phosphate rock (BPR) in field trials in Kenya (26 farms) and Uganda (16 farms). The results indicated, "although the performance of BPR was poor, its lower cost and location near to P-deficient areas make it attractive in some situations."

Butiriku (Sekululu) Carbonatite—Located west of Mt. Elgon, the Butiriku Carbonatite forms an approximately 38-km^2 circular positive topographic feature surrounded by broad valleys. Weathering under tropical conditions has resulted in the development of thick residual soils, which obscure the bedrock in the area. Davies (1947) first noted the presence of undersaturated igneous rocks (syenites, etc.) and phosphate in the area. Several samples of weathered rocks from the southwestern foot of the hill yielded over 20% P_2O_5.

Based on phosphate, niobium, rare-earth, zinc, lead, molybdenum, and beryllium anomalies of the western side of the complex, buried solvite was discovered in the west-central core of the hill (Reedman and Mullingar, 1974). Two areas of phosphate rock were delineated in close association with the carbonatite bodies and may contain large tonnages of phosphate (up to 30% P_2O_5). The residual soils over these phosphate areas may contain appreciable amounts of apatite, and surface sampling has delineated three areas of high phosphate concentration. The carbonatite appears to be of Portland cement grade and could be mined in conjunction with the apatite of the deposit.

Sukulu Carbonatite—The Sukulu Complex is located a few kilometers from the Kenya border on the southern outskirts of the township of Tororo. Reaching heights of up to 180 m above the surrounding plain, the complex is topographically expressed as a circular group of hills. The core of the hills is composed almost entirely of a large circular mass of carbonatite about 4 km in diameter (Figure Uganda 3). Three valleys—designated as the North Valley, South Valley, and West Valley—embay the hills and contain appreciable accumulations of residual soil rich in apatite.

Initial investigations in the area by the Mineral Resources Division of the Colonial Geological Survey during 1949-52 stimulated commercial interest in the area (Davies, 1956). Monsanto Chemicals, Frobisher Limited, Rio Tinto Company, and the Uganda Development Corporation undertook investigations in the area in 1952. Rio Tinto withdrew in 1953, and the remaining companies formed the Tororo Exploration Company. The ensuing survey indicated that the three valleys contained a total of 2.02 x 10^8 tons of ore at an average P_2O_5 content of 13.1%. Measured ore was considered to be 1.3 x 10^8 tons, indicated ore was 5.6 x 10^7 tons, and 1.6 x 10^7 tons was considered inferred ore. Maximum depth of the soils approaches 67 m in the South Valley. Davies (1956) indicated there are considerable extensions of the phosphate resources in the belt outside the perimeter of the hills. Work by Reedman (1984), primarily in the West Valley, confirmed the 2 x 10^8 tons resource figure and also indicated that P_2O_5 values generally increased with depth in the soils to the bedrock contact.

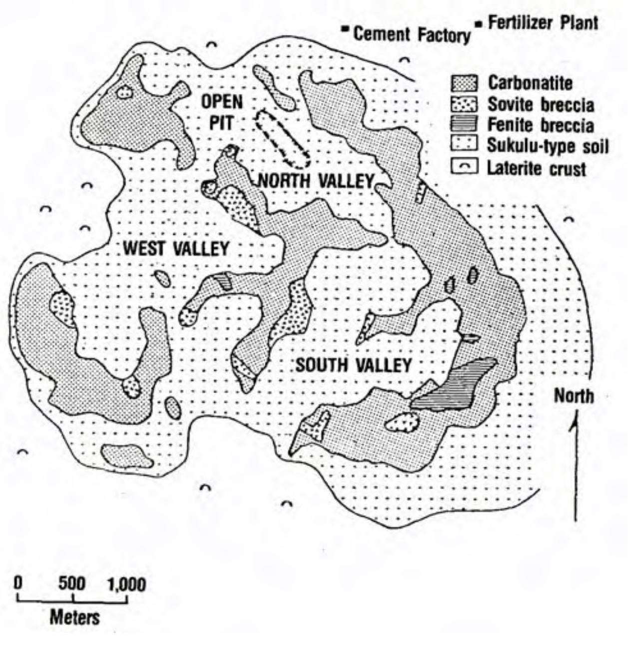


Figure Uganda 3. Geology of the Sukulu Carbonatite Complex (after Williams, 1959)

The initial beneficiation scheme for the soils involved slurrying, magnetic separation, desliming, grinding, and flotation (Fleming and Robinson, 1960). Construction of a beneficiation plant and fertilizer works began in 1961. The plant became functional in 1962 based on a mine situated in the North Valley. The concentrates produced at the plant typically analyzed near 40.0% P_2O_5 with about 1% Fe_2O_3. The concentrate was used in the adjacent fertilizer plant to produce single superphosphate (SSP) (capacity 25,000 tpy) until economic and social disruption caused the cessation of activities in 1978. Over the period of operation, about 2.16 million tons of ore was processed to produce about 160,000 tons of concentrate (Mathers, 1994). The wet concentrate was treated with 98% sulfuric acid to produce SSP, which may have had as much as 21% to 22% water-soluble P_2O_5.

In 1983/84 the Bearden-Potter Corporation reinvestigated the deposit as part of a World Bank study. Statistical analyses of resource data from previous studies increased the reserve estimates to 2.3 x 10^8 tons of ore (Bearden-Potter Corporation, 1982). Twelve pits were dug to obtain fresh ore for beneficiation-characterization studies.

Sukulu ore and concentrate samples have been studied at IFDC (Table Uganda 3) (McClellan and Cooper, 1982; IFDC, 1984a). Mineralogical analysis of the soil (Table Uganda 4) indicates it is a complex assemblage of apatite, Al-phosphates (crandallite group), iron-oxides, clays, quartz, perovskite, purpurite, and zircon. The P_2O_5 distribution for a Sukulu ore sample and beneficiation product is given in Figure Uganda 4. Apatite contains 78% of the

Table Uganda 3. Chemical Analyses of Sukulu Ore and Concentrate

	Sukulu Ore	Sukulu Concentrate
	(wt %)	
P_2O_5	12.5	41.0
CaO	14.6	53.9
Fe_2O_3	28.6	0.62
Al_2O_3	9.1	0.29
SiO_2	16.6	0.48
K_2O	0.2	0.07
Na_2O	0.06	0.19
MgO	0.24	0.04
F	0.55	2.1
SrO	0.15	0.44
BaO	0.32	0.001
ZrO_2	0.51	0.07
Nb_2O_5	0.17	–
MnO_2	0.53	0.12
TiO_2	1.67	0.002
Y_2O_3	0.03	0.02
La_2O_3	0.11	0.06
CeO	0.36	0.06
PrO	0.07	0.05
Nd_2O_3	0.15	0.08
Sm_2O_3	0.02	0.03
Eu_2O_3	0.04	0.003
Gd_2O_3	0.04	0.01
Tb_4O_7	0.08	–
CO_2	0.51	0.44
Cl (ppm)	200	60
Free H_2O[a]	0.54	0.10
LOI[b]	6.3	0.40
NAC-soluble P_2O_5[c]	–	1.60

a. Free H_2O = weight loss, 105ºC, 1 h.

b. Loss on ignition = weight loss, 1000ºC, 1 h.

c. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).

Table Uganda 4. Mineralogical Analyses of Sukulu Ore and Concentrate

	Sukulu Ore	Sukulu Concentrate
	(wt %)	
Apatite	25	97
Crandallite group	10	
Magnetite-hematite	30	1
Kaolinite	10	
Quartz	15	
Illite	1	
Perovskite	3	
Purpurite	2	
Zircon	1	Trace
Anatase	Trace	

P_2O_5 values for this sample (71% free, 7% locked). Undesirable alumino- and manganese phosphates (crandallite group and purpurite) contain 22% of the P_2O_5. The presence of these secondary phosphates decreases the CaO/P_2O_5 ratio of the ore below that of pure apatite (pure fluorapatite CaO/P_2O_5 ~1.32). The average CaO/P_2O_5 ratio for the 12 bulk samples of Sukulu ore obtained by pitting in the Bearden-Potter study is 1.01. Subsequent beneficiation increased the CaO/P_2O_5 ratio of these 12 samples to an average of 1.29, approaching that of pure apatite.

The beneficiation studies by Bearden-Potter (1982) suggested modifications in the upgrading process. In practice, the original beneficiation process resulted in 25%-35% total P_2O_5 recoveries. More thorough desliming and scrubbing were needed before flotation and grinding. The elimination of the ball mill before flotation almost doubled recovery; the apatite crystals of the ore are naturally in a recoverable size range, and ball milling increased P_2O_5 losses in the slimes. A wet-magnetic separator was added after flotation to reduce the iron content of the concentrates if it exceeded 1% Fe_2O_3. This process resulted in a concentrate with 41 wt % P_2O_5 and less than 1% combined Fe_2O_3 and Al_2O_3. The concentrate produced by this beneficiation process is approximately 97% apatite (Table Uganda 4).

The tests by Bearden-Potter Corporation (1982) suggested that about 50% of the total P_2O_5 in the ore can be recovered as concentrate (Figure Uganda 4). Typical concentration ratios (ore to product) for the Sukulu Deposit range from 7:1 to 10:1 (Bearden-Potter Corporation, 1982). At a 10:1 ratio and 2.3 x 10^8 tons of resources, 2.3 x 10^7 tons of product is potentially available.

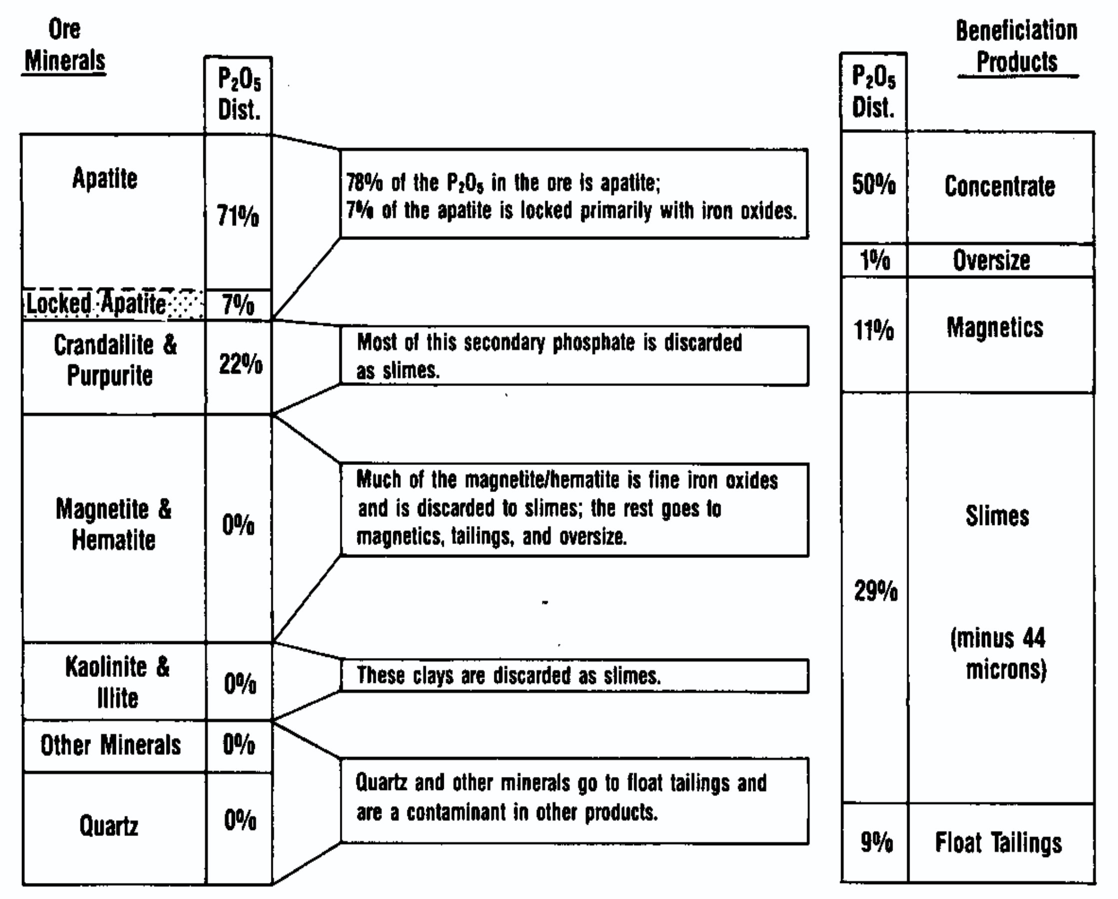


Figure Uganda 4. P_2O_5 Distribution in Sukulu Hills Ore and Beneficiation Products

As part of a World Bank-funded effort, IFDC studied the suitability of Sukulu concentrate for SSP (1983); granular SSP (1984b); partially acidulated phosphate rock (PAPR) (1984c); and wet process phosphoric acid, granular triple superphosphate, monoammonium phosphate, and diammonium phosphate (1985). The tests proved that a wide variety of products could be made with Sukulu concentrate.

Several companies and organizations have been involved in attempts to develop the Sukulu Hills Phosphate Deposit since the early 1990s. The Uganda Development Corporation (UDC), a government-owned company, facilitated an investors' forum concerning the deposit in the early 1990s, which was sponsored by the United Nations Industrial Development Organization (UNIDO)/Common Market for Eastern and Southern Africa (UNIDO, 2006). The Gujarat Company, Kavala State, India entered into an agreement with UDC in 1993. A market study by a consulting firm, Maxwell Stamp, indicated that locally produced products may be difficult to sell within the region. Gujarat subsequently withdrew from the project.

A Memorandum of Understanding (MOU) was signed in September 1997 between the Ugandan government, Sukulu Hills Fertiliser and Chemical Industries, and the Karnag Consortium. Karnag Consortium apparently secured funding for the project, whose total value was estimated at US $110 million, and expected UDC to contribute US $3.0 million. UDC was unable to raise the funding. The MOU expired in September 1998 and was not renewed. Due to nonfulfillment of the lease conditions, the Ugandan government canceled the mining lease and withdrew it from Sukulu Hills Fertiliser and Chemical Industries.

Karnag International Ltd., proposed that the government offer the land and the deposit, valued at US $7.5 million, as its contribution and a 5% share in the joint venture. The mining lease was reverted back to the Ministry of Energy and Mineral Development.

In 1999 Madhvani International S.A. and Rhodia Chemie S.A. formed a partnership to develop the deposit (Wakabi, 2002). Foskor, South Africa, was brought on board to lend technical expertise to the project. Apparently Foskor tested 30 tons of rock from the deposit. It seems that the US $300 million project fell apart or came to a standstill in February 2002.

Yager (2003) reported that Niletos Minerals Ltd. (a subsidiary of Madhvani International S.A.) and Rhodia Chemie S.A. were promoting the project. Niletos planned to start production of phosphate rock and TSP in 2006. The mine, fertilizer plant, and related infrastructure were expected to cost US $400 million during the period 2005 to 2008.

In 2003 the U.S. Trade and Development Authority allocated US $360,000 for a study of the Sukulu Hills Phosphate Deposit. The solicitation for the study appeared in February 2004 (*FBO Daily*, 2004). Madhvani International committed US $240,000 for the study for a total value of US $600,000. The study is being conducted by the U.S. firm, Steffen, Robertson, and Kirsten Consulting, Inc. The study was to be completed in late 2006 (Kunene, 2006).

As a corollary to these observations, it was reported that Madhvani International purchased Rhodia Chemie for US $40 million in November 2005 (*The New Vision*, 2005).

Toror Hills Carbonatite—The Toror Hills Carbonatite is located in the northeastern part of Uganda and rises 600 m above the surrounding Karamaja plain. The Hills represent the eroded remains of a central volcano and its associated satellites (Du Bois, 1959). Apatite is abundant in the outer margin of the carbonatite zone (Savage, 1987).

Tororo Hills Carbonatite—The Tororo Hills Complex is a pear-shaped mass running north-south about 2.5 km in length. The complex partly underlies the township of Tororo. Patches of carbonatite with a high apatite content are common on the northeast and western sides of the complex (Davies, 1947). Two deep boreholes drilled about 500 m apart on the northwest side of the complex passed through a continuous mass of an approximately equal mixture of pyroxene and apatite (Davies, 1956). Loose float of almost pure apatite has been found on the eastern side of Tororo. Because the potential deposit lies almost beneath the township, it is doubtful if further work or development will be done.

Western Uganda—Three occurrences in western Uganda—Fort Portal, Lake Kyekora, Katwe-Kikorongo—possess rocks that are considered to be of a carbonatitic character (Gittins, 1966). These fine-grained vesicular extrusive rocks contain grains of pyroxene, olivine, biotite, magnetite, apatite, and calcite. Assays of 3.32% and 3.57% P_2O_5 have been reported from the Fort Portal area (von Knorring and Du Bois, 1961).

Sedimentary Deposits—Sedimentary-subvolcanic sediments containing up to 10% apatite outcrop sporadically on the periphery of Mt. Elgon and underlie Mt. Nkokonjeru. The sediments are thought to be an indication that one or more concealed carbonatite complexes underlie Mt. Nkokonjeru or the agglomerates east of Buteya (Davies, 1956).

Sulfur Resources

Sulfide mineralization occurs in a 56-km-long belt associated with the amphibole schists of the Middle Kilembe Series in the southern Ruwenzori Mountains. The Kilembe Mine (Figure Uganda 1) was worked for copper (in chalcopyrite) from 1956 to 1977 when mining operations ceased. Pyrite tailings were stockpiled at the mine with a view to the eventual recovery of their cobalt content of 1.41% to 1.44%. The stockpile contains approximately 4.7×10^5 tons of sulfur (Kisitu, 1987). An additional 3.5×10^5 tons of sulfur resources remains to be mined. There is also a reasonable potential for discovering additional sulfide ore bodies at Kilembe.

In 1987 the *Mining Journal* reported that US $20 million was allocated to revive the mining operation (*Mining Journal*, 1987). The mine was not restarted at that time.

In 2004 Kasese Cobalt Company (Blue Earth Refineries Ltd., 75%) produced 436 tons of refined cobalt from the Kilembe tailings stockpile (Yager, 2004). In September 2004, Uganda Gold Mining Ltd. (UGM) of Canada signed an agreement with state-owned Kilembe Mines Ltd., in which UGM could earn a 70% interest in the Kilembe copper-cobalt mine by conducting exploration and performing a feasibility study. In 2004, Signature Resources Ltd. obtained a prospecting license for properties adjacent to the Kilembe Mine near Kafunzo.

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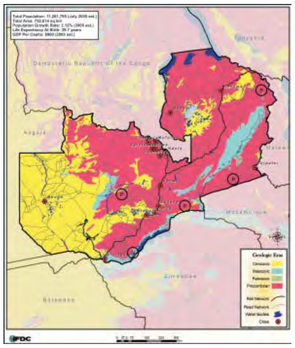
ZAMBIA



The Republic of Zambia (Figure Zambia 1) is bordered by the Democratic Republic of the Congo and Tanzania to the north; Malawi to the east; Mozambique, Zimbabwe, Botswana, and Namibia to the south; and Angola to the west. Zambia is a totally landlocked country. Total area is 752,614 km^2 and approximately 7.1% of the land is arable. The population was estimated at 11.3 million inhabitants in mid-2005 (World Factbook, 2006). Eighty-five percent of the population is occupied by agriculture.

The transportation network consists of 20,117 km of paved roads, 71,323 km of unpaved roads, and 2,173 km of 1.067-m-gauge railway. There are 10 airports with paved runways and 99 airports with unpaved runways. Lake Tanganyika and the Zambezi and Luapula Rivers provide 2,250 km of waterways. Mpulungu on Lake Tanganyika is the main port.

Zambia's complex geology is a reflection of the fact that the area is effectively sandwiched between several cratonic masses and blocks (Kasai Craton, Bangweulu Block, Tete Block, and the Zimbabwe Craton) with multiple rift and shear zones between the blocks. Differential movements between the blocks resulted in numerous tectonic-thermal events throughout geologic history.

The oldest Precambrian age rocks are known as the Basement Complex and mainly consist of granite, granite gneisses, and migmatites. The Basement Complex is found mainly in eastern, central, and southern Zambia. In some areas the Basement Complex rocks are infolded with metamorphosed carbonates, quartzites, and pelites. Most of the Basement Complex rocks are less than 2,050 Ma. However, the Lutembwe River Granulite near Chipata has been dated at 3,000 Ma (Ministry of Mines and Minerals Development, 2006). Rocks of the Basement Complex outcrop in the Kafue Anticline and the domes of the Copper Belt and in northwestern Zambia. Rocks of the Basement Complex and metasediments also form most of the Mozambique Belt in southeast Zambia.

The overlying Middle Proterozoic metasedimentary Muva Supergroup (quartzites and metapelites) is commonly infolded and imbricated with the basement rocks. These rocks form a major component of the Irumide Belt extending from Kabwe northeastward to Mpika. These rocks also form a major component of the Zambezi Belt south and east of Lusaka. In the north within the Bangweulu Block, the Muva sediments are very different, forming a 5,000-m-thick sequence of continental sediments.

Late Precambrian to Lower Paleozoic Katanga Group sediments are found in western Zambia and around Lake Bangweulu. The Lower Roan Formation of the Katanga Group is the main copper-bearing unit in the Zambian Copper Belt.

Karroo (or Karoo) age (Upper Carboniferous to Jurassic) sediments are found in the mid-Zambezi Rift Valley and the Luangwa Rift Valley. The oldest formation in the Karroo sediments hosts the coal deposits. Carbonatites penetrated the Karroo sediments in northeast Zambia. Karroo age basalts are found in southern Zambia.

A vast area of western Zambia is covered by Tertiary to Recent age Kalahari sands. Significant areas in central and northern Zambia, particularly around Lake Bangweulu, are covered with recent alluvium, colluvium, and laterites.

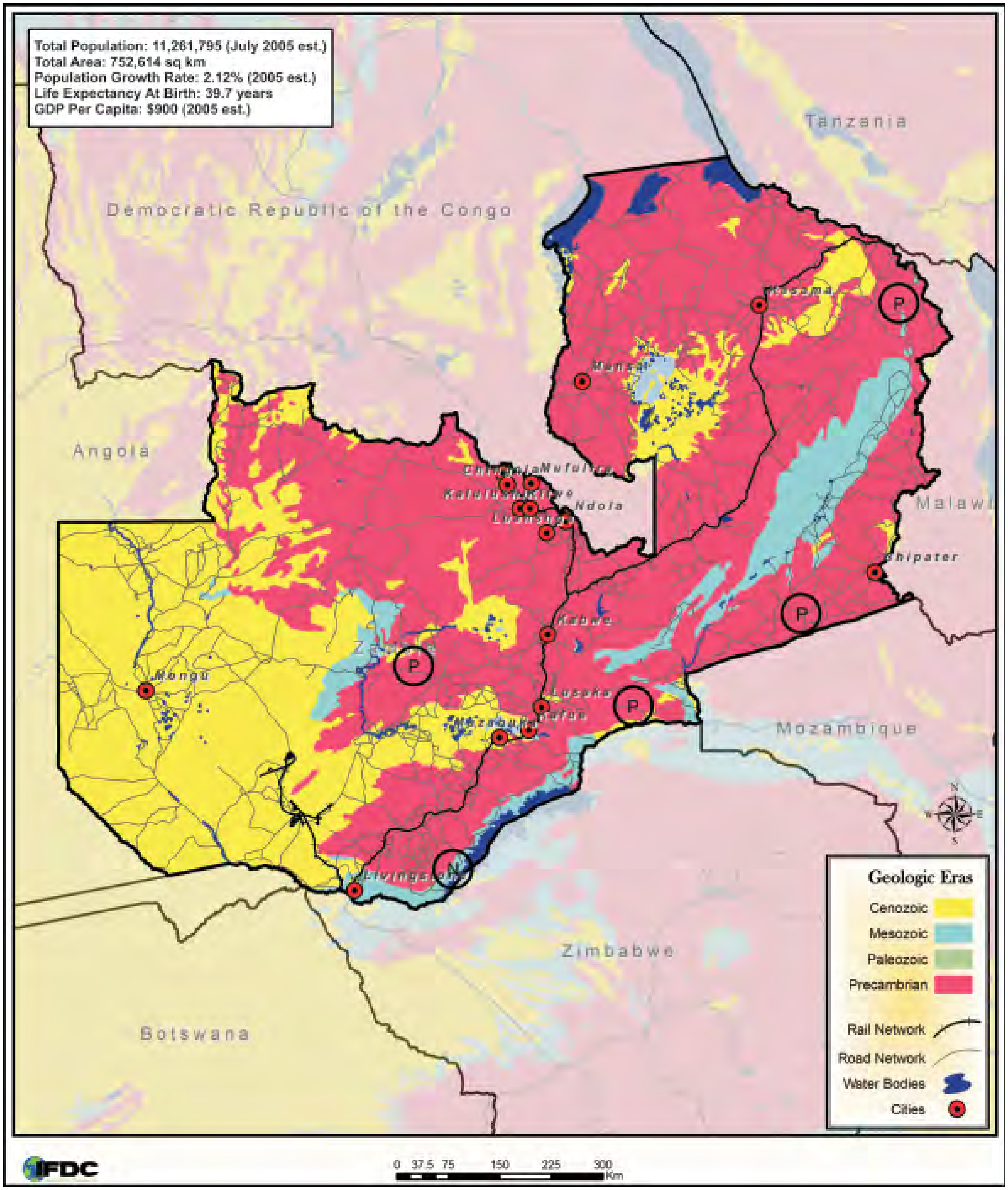


Figure Zambia 1. Geology, Major Cities, and Transportation Network

Nitrogen Resources

Petroleum—The Indeni Oil Refinery at Ndola is the only refinery in the country. The availability of fuel, from the refinery and as imported finished products, is critical to the Zambian copper industry. The refinery is owned by Total Outre Mer (50%) and the Zambian government (45%). The refinery was severely damaged by fire in 1999 and has since been repaired. The capacity is 8,950,000 barrels of refined products per year (Coakley, 2003). Crude oil is brought in on a pipeline running from Dar es Salaam.

Coal—Maamba Collieries Ltd., located 350 km south of Lusaka, is an important supplier of coal to the copper and cement industries. The mine has also exported coal to the Congo (Kinshasa), Malawi, and Tanzania. The company operates two open-pit mines in the Kanzize and Izuma Basins. The two mines had the capacity to produce between 600,000 and 800,000 tons of product per year. In recent years the mine has been operating at approximately 37% to 50% capacity (150,000-400,000 tpy) (Coakley, 2003).

After two failed private ownerships since 2000, Maamba Collieries reverted to the government. The colliery was again offered for privatization. Ten companies bid for the colliery (five foreign and five Zambian companies). The bidding was closed on August 5, 2005. The last report on the privatization process indicated the Zambia Privatization Agency (ZPA) was negotiating with the Maamba Zatuya Consortium (Zambian, French, and South African consortium) for the project (ZPA, 2006a).

A total of 78.2 million tons of coal reserves is estimated in the area assigned to Maamba Collieries Ltd. Of these reserves, 60.2 million tons is considered proven and 18 million tons is probable.

The coal preparation plant had the capacity to wash 700,000 to 800,000 tons of coal per year. The ropeway between the plant and the Masuku Railway Terminal had the capacity to transport 600,000 to 700,000 tpy (ZPA, 2006a). Both the coal preparation plant and the ropeway would require refurbishing to achieve the stated capacities. Maamba Collieries also mines and processes magnetite ore for coal washing at Namantombwa near Mumbwa. Maamba's requirement for magnetite sand is 870 tpy.

Collum Coal Mining, formerly Kandabwe Mines, located in Sinazongwe began operations in 2003. The mine was purchased by Chinese interests. In 2005 the mine produced 20,000 tons (*Mining Weekly*, 2006). In 2006 the plant was to produce over 100,000 tons, with further increases in production to 200,000 tpy.

Nitrogen Fertilizer Sources—Nitrogen Chemicals of Zambia (NCZ), located in Kafue, was incorporated in 1967 and commissioned its first plant (ammonium nitrate) in 1970 (ZPA, 2006b). Additional nitric acid capacity, an ammonium nitrate fertilizer plant, ammonium sulfate plant, and a fertilizer-blending plant were added in 1981. A sulfuric acid plant was added in 1983. Present nameplate ammonia capacity is 96,000 tpy, nitric acid capacity is 120,000 tpy, and combined explosive- and fertilizer-grade ammonium nitrate capacity is 115,000 tpy. Ammonium sulfate capacity is 50,000 tpy.

The principal activity of NCZ is the manufacture and trading of explosive-grade ammonium nitrate for the Zambian mining industry, chemical fertilizers, and chemicals. Originally coal was used as a raw material for ammonia synthesis. Coal was procured from Maamba Collieries, which is about 300 km from NCZ; the company now imports all of its ammonia. The Zambian government has approved the sale of 100% of the shares of the company.

Numerous operational problems over the last several years have led to shortfalls in production and fuel shortages. The government indicated in 2005 that it was studying leasing its portion of the refinery to private investors (*People's Daily Online*, 2006). The government decided to sell its interests, and the privatization process may be completed by the end of 2006 (privatizationbarometer, 2006).

Phosphate Resources

Igneous Deposits—There are four igneous, or very high metamorphic grade, phosphate deposits in Zambia. There are no known sedimentary phosphate deposits in Zambia.

Chilembwe Deposit—Discovered by the Mineral Exploration Department (MINEX) in 1978, the Chilembwe Deposit has been subjected to detailed geochemical, geophysical, and geological investigations (Sliwa, 1991). Five irregular ore bodies occur in a 4-km radius in coarse- to medium-grained syenites on the northeast margin of the Sinda Batholith. Resource calculations have been made on two of the five potential ore bodies (Nos. 2 and 4) and indicate 1.64 x 10^6 tons at 11.8% P_2O_5 (6% cutoff). Additional minor resources can be recovered from the three other ore bodies.

The ore bodies have widely varying compositions. Ore body No. 2, the largest, is composed of apatite and quartz with subordinate amounts of K-feldspar, biotite, hornblende, and traces of pyroxenes. Ore body No. 4 is composed of apatite with augite and hornblende and with subordinate biotite and quartz.

Six Chilembwe samples have been characterized at IFDC (1984). Samples 1-5 are very similar chemically (Table Zambia 1) and mineralogically (Table Zambia 2) and appear to be from the same ore body (possibly No. 4). Sample 6, due to its quartz content (37%), appears to be from ore body No. 2.

Table Zambia 1. Chemical Analyses, Chilembwe Samples 1–6

Chemical Analyses	Sample Number					
	1	2	3	4	5	6
	(wt %)					
P_2O_5	17.1	16.4	14.9	16.1	15.6	19.6
CaO	30.5	30.0	29.2	30.0	29.5	26.1
SiO_2	30.2	31.0	32.8	31.1	32.0	42.0
K_2O	0.11	0.09	0.09	0.08	0.09	0.36
Na_2O	0.59	0.61	0.65	0.61	0.63	0.21
Fe_2O_3	5.0	5.4	5.8	5.7	5.2	1.6
Al_2O_3	0.98	0.99	1.0	0.97	1.0	0.7
MgO	8.3	8.4	9.0	8.5	8.8	0.4
MnO	0.16	0.18	0.13	0.16	0.15	0.06
SrO	0.37	0.35	0.37	0.39	0.35	0.34
Cu	ND[a]	ND	ND	ND	ND	–
Zn (ppm)	ND	ND	24	5	13	–
Nb_2O_5	0.004	ND	ND	ND	ND	–
ThO_2	ND	ND	ND	ND	ND	–
CeO	0.28	0.27	0.25	0.27	0.26	0.48
TiO_2	0.24	0.24	0.26	0.24	0.26	0.10
BaO	ND	ND	ND	ND	ND	–
U_2O_3	0.19	0.17	0.16	0.17	0.17	0.08
ZrO_2	0.01	0.01	0.01	0.01	0.01	–
CO_2	0.8	0.4	0.4	0.6	0.8	0.7
F	0.9	0.9	0.7	0.9	0.8	1.2
C (organic)	0.1	0.1	0.1	ND	ND	0.5
Free H_2O[b]	0.09	0.16	0.18	0.16	0.18	0.3
LOI[c]	0.36	0.36	0.40	0.41	0.44	1.0
Cl^{1-}	0.44	0.42	0.40	0.43	0.4	0.0735
NAC P_2O_5[d]	1.4	1.2	1.3	1.3	1.1	1.0

a. ND = not detected.

b. Free H_2O determined by heating 1 h at 110°C.

c. Loss on ignition determined by heating at 1000°C for 1 h.

d. Neutral ammonium citrate-soluble P_2O_5, carbonates not removed.

Table Zambia 2. Approximate Modal Analyses, Chilembwe Samples 1–6

	Sample					
	1	2	3	4	5	6
	(wt %, estimated)					
Apatite	40–45	35–40	35–40	35–40	35–40	46
Augite	35–40	35–40	40–45	35–40	40–45	–
Magnesioriebeckite	5–10	5–10	5–10	5–10	5–10	6
Quartz	0.5–1	0.5–1	0.5–1	0.5–1	0.5–1	37
Microcline	2–3	2–3	2–3	2–3	2–3	2
Magnetite-Hematite-Goethite	0.5–1	0.5–1	0.5–1	0.5–1	0.5–1	–
Ilmenite	0.5–1	0.5–1	0.5–1	0.5–1	0.5–1	–

Samples 1-5 were received in a ground state, and no petrographic textural examination could be performed. Petrographic examination of Sample 6 indicates that the rock is composed of angular to rounded apatite crystals cemented by radiaxial, fibrous to blocky quartz cement. The cement and grain boundaries are stained by what appears to be organic matter. This texture is typical of a detrital sedimentary rock. The rounding of the grains suggests that transport has occurred although the angularity and well-formed crystal faces of some grains indicate a minimum amount of transport or recrystallization.

Although Mujogyatwok (1983), the Japan International Cooperation Agency (JICA, 1984), and Turner et al. (1990) have interpreted the Chilembwe Deposits as intrusions in syenitic country rock, the texture of this Chilembwe sample suggests that the deposit is of metasedimentary origin and thus represents xenolithic bodies within the intrusive syenite mass. Recognizable metamorphic rocks such as quartzites are known from the area, and the metamorphic grade in the area ranges from amphibolite to the granulite facies (Turner et al., 1990).

The apatite in Samples 1-5 differs in composition from that of Sample 6. An average of the a unit-cell dimensions for Samples 1-5 is 9.430 ± 0.001Å, and the index of refraction (N_D^{25}) is 1.636 ± 0.002. Sample 6 has an a unit-cell dimension of 9.410 ± 0.001Å and an index of refraction of 1.641 ± 0.002. All of the samples are fluorine deficient when compared with a pure fluorapatite composition (3.77 wt % F^{1-}, 100% fluorapatite basis). Chlorine appears to be substituting in the apatite structure and influencing the physical and crystallographic properties

The chlorine content of Samples 1-5 averages 4,200 ppm, whereas the chlorine content of Sample 6 is 735 ppm. Energy-dispersive x-ray analysis indicates that the chlorine is associated with the apatite. Calculated to a 100% apatite basis, the chlorine content of the apatite in Samples 1-5 would be about 1% and that of Sample 6 would be about 0.16 wt %. The apatite in Samples 1-5 is classified as a chlorfluorapatite variety, and Sample 6 appears to be a hydroxylfluorapatite with a composition about halfway between end members. The chlorine content of the apatite limits the use of the rock for the production of wet-process phosphoric acid. Corrosion in conventional wet-process phosphoric acid plants become problematic at chlorine concentrations over 200-300 ppm.

Chilembwe rock has been successfully beneficiated. A prime factor in the beneficiation process is the size of the apatite crystals. Petrographic studies of Sample 6 suggested that liberation should occur at approximately 0.5 mm. Sink-float tests at IFDC indicated that liberation occurred at approximately 0.3 mm. Tests at the University of Zambia School of Mines (Lombe and Simukanga, 1987) indicate similar results. The apatite in a sample of ore body No. 2 was liberated between 0.4 and 0.7 mm. Apatite in a sample from ore body No. 4 was liberated between 0.15 and 0.3 mm.

Various beneficiation techniques have been applied to the different types of Chilembwe ore. From a head grade of 20% P_2O_5, a concentrate assaying 37.7% P_2O_5 was obtained at 81.7% overall recovery by direct anionic flotation from the quartz-rich type of ore (IFDC, 1987). In a test of combined ore (ore bodies Nos. 2 and 4) by JICA (1984), a 30.07% P_2O_5 concentrate was obtained from a 11.5% P_2O_5 head grade at 88.4% recovery.

Tests conducted at the Zambia School of Mines (Lombe, 1991) treated rock from ore bodies Nos. 2 and 4 in separate tests. Because of the differences in specific gravity between quartz (≅2.7) and apatite (≅3.2), rock from ore body No. 2 could be treated by gravity methods (shaking table). Rock from ore body No. 4 was unsuitable for gravity separation because of the similarity in specific gravity between amphiboles (≅3.2) and apatite. High-grade concentrates with 36% to 38% P_2O_5 could be produced from ore body No. 4 by magnetic separation. The fine fractions of both ores unavoidably generated by grinding could be treated by flotation. It was estimated that about 30% of the ore would have to be treated by flotation.

The study by JICA (1984) indicated that the Chilembwe Deposit is marginally economic when compared with imported Palabora concentrate. A conceptual mining plan was designed to produce 35,000 tons of 30% P_2O_5 concentrate per year over a period of 14 years. This would supply about half of Zambia's phosphate raw material requirements over the life of the mine.

Kaluwe Carbonatite Deposit—The Kaluwe Carbonatite Deposit is the most extensively studied of four carbonatite deposits in the Feira-Rufunsa region of Zambia. The carbonatite appears to be a sill-like body in Karroo sandstones. Three facies—lower, middle, and upper—have been recognized within the deposit (Bailey, 1960). The most significant phosphate mineralization is associated with the upper and middle facies.

Phosphate is associated with both the hard rock and residual soils overlying the carbonatite. Total reserves of phosphate-bearing rocks are estimated as 2.07×10^8 tons at 2.5% P_2O_5 (0.5% P_2O_5 cutoff) (Sliwa, 1991). Two methods have been used to estimate the resources of residual soil at 6.6×10^6 tons at 5.11% P_2O_5 and 10.8×10^6 tons at 4.14% P_2O_5. Selected samples of the soils have P_2O_5 values approaching 10%.

Two samples of Kaluwe rock have been analyzed at IFDC (1984) (Tables Zambia 3 and Zambia 4). Apatite occurs as small (100-200 µm), well-formed to corroded hexagonal prisms set in a calcite matrix. The refractive index ($N_D^{25} = 1.642$)

Table Zambia 3. Chemical Analyses, Kaluwe Rock Samples

Chemical Analyses	Sample	
	11	12
	(wt %)	
P_2O_5	3.9	2.4
CaO	50.1	48.4
SiO_2	2.1	4.8
K_2O	0.12	0.26
Na_2O	0.12	0.11
Fe_2O_3	4.1	3.8
Al_2O_3	0.18	0.38
MgO	0.54	0.58
MnO	0.31	0.30
SrO	0.39	0.36
Cu	ND[a]	ND
Zn (ppm)	ND	112
Nb_2O_5	0.20	0.21
ThO_2	0.009	0.007
CeO	0.07	0.06
TiO_2	0.16	0.15
BaO	0.038	0.044
La_2O_3	0.033	0.025
ZrO_2	0.03	0.03
CO_2	32.8	35.1
F	0.2	0.1
C (organic)	1.8	0.3
Free H_2O[b]	0.78	0.54
LOI[c]	36.9	37.6
Cl	0.0144	0.0071
CV[d]	3.32	1.46
NAC P_2O_5[e]	<0.1	<0.1

a. ND = not detected.
b. Free H_2O determined by heating 1 h at 110°C.
c. Loss on ignition determined by heating at 1000°C for 1 h.
d. CV = combined volatiles = LOI - Free H_2O - CO_2.
e. Neutral ammonium citrate-soluble P_2O_5, carbonates not removed.

Table Zambia 4. Approximate Modal Analyses, Kaluwe Rock Samples

	Sample	
	11	12
	(wt %, estimated)	
Calcite	70–75	75–80
Hematite-Magnetite-Goethite	3–5	3–5
Apatite	8–10	4–6
Quartz	0.5–1	2–3
Montmorillonite	1–2	1–2
Augite	0.5–1	0.5–1
Biotite	0.5–1	0.5–1
Zircon	0.5–1	0.5–1
Braunite	0.5–1	0.5–1
Pyrochlore	0.5–1	0.5–1

indicates that the apatite is a fluorhydroxylapatite variety with a composition about halfway between end members.

It is technically feasible to produce apatite concentrates from both the Kaluwe hard rock and residual soil. Samples have been successfully beneficiated by Warren Spring Laboratory, Kemira Oy, Serrana, and the University of Zambia School of Mines. High reagent consumption and costs are associated with floating apatite from the calcite gangue. Kemira Oy estimated reagent costs at US $55 (1985) to produce a ton of 30.4% P_2O_5 concentrate at a recovery of 74% from a sample containing 2.84% P_2O_5 (Airaksinen, 1982). The Zambia School of Mines produced a 27.6% P_2O_5 concentrate at a recovery of 62.6% from 2.2% P_2O_5 hard rock feed using a cocoamine collector. The recovery ratio was 22 to 1 (rock to concentrate), and collector consumption was 700 g/ton of rock feed. Assuming US $5/kg for the cocoamine, the cost of the collector alone was US $77/ton.

Warren Spring Laboratory has produced a +33% P_2O_5 concentrate from the residual soils at 60% recovery. A combination of scrubbing-desliming, magnetic separation, and flotation using sodium oleate collector was used. Evaluations of selected parts of the soils deposit are continuing at this time.

Mumbwa North Deposit—The Mumbwa North Deposit has been known since 1958 when Mineral Search of Africa indicated that disseminated copper mineralization was associated with phosphate at Sugar Loaf Hill (Simukanga et al., 1994). Pegmatitic bodies with high P_2O_5 contents were discovered by MINEX (Mulela, 1984) and evaluated by trenching and percussion drilling (Figures Zambia 2 and 3). The pegmatitic apatite bodies occur to the northeast of Sugar Loaf Hill and are almost monomineralic, containing some feldspar crystals. The apatite is a hydroxylapatite and contains high concentrations of yttrium, strontium, niobium, and uranium (Simukanga et al., 1994). The reserves of apatite pegmatite are estimated at 220,000 tons at a cutoff grade of 5% P_2O_5.

Nkombwa Carbonatite Deposit—Prior to recognition as a carbonatite deposit in 1952 (Reeve and Deans, 1954), Nkombwa Hill was mapped as volcanic rock or highly altered sedimentary limestone. Since its recognition as a carbonatite, a number of agencies have explored the complex for niobium, rare earths, and its phosphate potential (Mulela, 1984). Resource estimates by MINEX indicate that 200 million tons of rock containing 7% to 8% P_2O_5 is present (Turner et al., 1990). In a subsequent study, Kemira Oy of Finland found an average grade of 4.54% P_2O_5.

The Nkombwa Carbonatite is characterized by a dolomitic to ankeritic composition and the absence of associated alkaline mafic rocks. Four rock types have been recognized within the carbonatite. Phlogopite carbonatite occurs around the outer rim of the plug as discontinuous brecciated bands and appears to be a product of the fenitization of the surrounding biotite and hornblende gneiss country rocks. Dolomitic carbonatite and veined ankeritic carbonatite constitute the intermediate zone of the main body. Silicified carbonatite forms the center of the plug. The phosphorus content is unevenly distributed and does not show a clear correlation with any rock type. Most of the higher P_2O_5 values appear to be concentrated in the intermediate (dolomitic-ankeritic) zone (Mulela, 1984).

Phosphate in the hard rock occurs in the form of apatite, monazite, and isokite. Three rock samples and two soil samples from Nkombwa have been chemically and mineralogically studied at IFDC

Figure Zambia 2. Trench on the Mumbwa North Deposit, Zambia

Figure Zambia 3. Block of Pegmatitic Phosphate Ore, Mumbwa North Deposit, Zambia

(1984) (Tables Zambia 5, Zambia 6, and Zambia 7). Apatite occurs as well-formed hexagonal prisms (to 500 μm) and as disseminated to patchy microcrystalline aggregates in the rock samples. Apatite in the soil samples is very fine grained (<50 pm), stained, intergrown, and locked with iron oxides. Crandallite has formed in the soils in response to weathering. The apatite is a variety of hydroxylfluorapatite with an a unit cell dimension of 9.382 ± 0.001 Å and an index of refraction of 1.637 ± 0.002.

Isokite ($CaMgPO_4F$) was detected in one of these samples. Isokite is observed as vug and vein fillings. It appears that the isokite crystallized later than the apatite and may be late-stage hydrothermal (Nalluri, 1984) or secondary in nature.

The phosphate mineralogical distribution with respect to rock types is not known. Well-formed primary igneous apatite crystals in the larger size ranges may be amenable to beneficiation. Microcrystalline aggregates of apatite with crystals of less than 50 μm would have to be crushed to minus 25 μm in order to achieve liberation. This is near the range

Table Zambia 5. Chemical Analyses, Nkombwa Carbonatite

Chemical Analyses	Nkombwa Soil		Nkombwa Rock		
	6	7	8	9	10
	(wt %)				
P_2O_5	14.3	12.1	3.6	3.7	3.7
CaO	15.7	12.7	21.7	20.8	11.6
SiO_2	7.8	9.1	2.4	3.4	28.9
K_2O	0.08	0.10	0.01	0.07	0.05
Na_2O	0.38	0.36	0.08	0.53	0.12
Fe_2O_3	38.4	42.6	22.5	16.0	19.9
Al_2O_3	0.91	1.0	0.03	0.06	0.04
MgO	0.46	0.48	11.9	15.5	8.1
MnO	4.0	3.9	1.6	1.4	1.9
SrO	1.3	1.2	1.1	1.0	0.66
Cu	ND[a]	ND	ND	ND	ND
Zn (ppm)	1,860	2,041	547	360	750
Nb_2O_5	0.30	0.30	0.023	0.03	0.16
ThO_2	0.007	0.007	ND	ND	ND
CeO	1.25	1.36	0.42	0.57	0.53
TiO_2	0.22	0.28	0.053	0.21	ND
BaO	3.25	3.02	0.96	1.80	1.05
La_2O_3	0.52	0.63	0.16	0.15	0.28
ZrO_2	0.03	0.03	0.03	0.03	0.03
CO_2	0.5	0.8	22.8	29.2	14.3
F	0.9	0.7	0.7	0.4	0.3
C (organic)	0.5	0.6	1.6	<0.1	0.4
Free H_2O[b]	0.92	1.1	0.16	0.56	0.4
LOI[c]	6.0	6.2	31.6	32.4	19.7
Cl	0.0065	0.0045	0.0083	0.0043	0.0080
NAC P_2O_5[d]	1.0	0.8	0.2	0.3	0.4

a. ND = not detected.

b. Free H_2O determined by heating 1 h at 110°C.

c. Loss on ignition determined by heating at 1000°C for 1 h.

d. Neutral ammonium citrate-soluble P_2O_5, carbonates not removed.

where separation by flotation becomes ineffective. The isokite of the deposit is not suitable for processed fertilizer products because of its magnesium content. Any mixture of isokite with apatitic phosphate would lower the quality of concentrates. The beneficiation properties of isokite are unknown.

Phosphate Fertilizer Sources—NCZ produces phosphate-containing fertilizer blends at Kafue using imported materials. The total NPK fertilizer capacity is 142,000 tpy (ZPA, 2006b).

Sulfur Resources

There is one pyrite mine in Zambia, and several copper-mining companies produce sulfuric acid. The Nampundwe Pyrite Mine is located 48 km west of Lusaka. The mine began operating in 1913 as the King Edward Mine. The mining method is sub-level open stoping (Konkola Copper Mines Plc., 2006). Four orebodies are worked. The ore contains about 16% sulfur (S). The ore is crushed, milled, screened, and floated to produce a concentrate containing 40%

Table Zambia 6. Approximate Modal Analyses, Nkombwa Rock Samples 8–10

	Sample		
	8	9	10
	(wt %, estimated)		
Dolomite	45–50	55–60	25–30
Hematite-Goethite	25–30	15–20	20–25
Apatite	8–10	8–10	8–10
Quartz	2–3	3–4	25–30
Phlogopite	3–5	3–5	3–5
Magnesioriebeckite	–	0.5–1	–
Ilmenite	0.5–1	–	–
Isokite	–	0.5–1	0

Table Zambia 7. Approximate Modal Analyses, Nkombwa Soil Samples 6–7

	Sample	
	6	7
	(wt %, estimated)	
Hematite-Goethite-Magnetite	35–40	40–45
Apatite	30–35	25–30
Quartz	5–10	5–10
Braunite	5–10	5–10
Barite	3–5	3–5
Crandallite	3–4	3–4
Pyrochlore	0.5–1	0.5–1

S. All the production is utilized to produce sulfuric acid for the copper industry.

The traditional use of reverberating furnaces for smelting copper sulfide ore in Zambia produces large volumes of sulfur dioxide gas in concentrations that may be too low for efficient sulfur recovery (Bomani, 1996). Numerous environmental laws that contain emissions standards were passed in the 1990s in Zambia. Some copper companies do recover sulfur from offgases. Mopani Copper Mines had the capacity to produce 120,000 tons of sulfuric acid (39,120 tons of contained sulfur) at the Nkarma Acid Plant (Coakley, 2003). In 2005 a new sulfuric acid plant based on copper smelter gas was installed at the Mufulira site with a capacity of 1,150 tpd (*Sulphur*, 2006). In the fourth quarter of 2006, a new 244-tpd sulfuric acid plant based on metallurgical offgas is scheduled to come onstream at the Kitwe site.

The Bwana Mkubwa and Lonshi Acid Plants of First Quantum Minerals Ltd. (2006) are elemental sulfur-burning plants. Acid production in 2005 was 260,796 tons, of which 134,633 tons was produced at Ndola and 126,163 tons at Solwezi. Of the total acid produced, 85,330 tons was used internally and 32,601 tons was sold externally.

Chambeshi Metals has the capacity to produce 65,000 tons of sulfuric acid (21,190 tons of contained sulfur) at the Chambeshi Acid Plant (Coakley, 2003). The original plant burned pyrites but was converted to burn elemental sulfur (*Sulphur*, 2001). Konkola Copper Mines has commissioned a sulfuric acid plant based on elemental sulfur and purchased stocks of sulfur (*Engineering News Online*, 2006).

NCZ commissioned a sulfuric acid plant in 1983 at a capacity of 60,000 tpy. The sulfuric acid was originally produced from pyrites. NCZ also has the capacity to produce 50,000 tpy of ammonia sulfate. Sulfuric acid is also trucked into Zambia from the coast.

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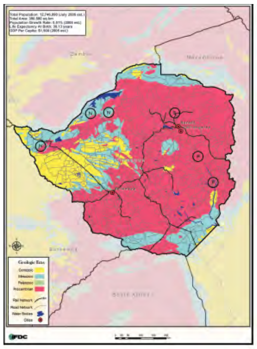
ZIMBABWE



The Republic of Zimbabwe (Figure Zimbabwe 1) is bordered by Zambia to the north, Mozambique to the north and east, South Africa to the south, and Botswana to the south and west. Total area is 390,580 km^2 and approximately 8.3% of the land is arable. The population was estimated at 12.7 million inhabitants in mid-2005 (World Factbook, 2006). Sixty-six percent of the population is occupied by agriculture.

The transportation network consists of 8,692 km of paved roads, 9,646 km of unpaved roads, and 3,077 km of 1.067-m-gauge railway. There are 17 airports with paved runways and 387 airports with unpaved runways. Lake Kariba is the only navigable waterway. Binga and Kariba are small ports on the lake. There is a 261-km-long pipeline for refined products.

Precambrian age rocks outcrop at the surface of approximately 70% of Zimbabwe (Figure Zimbabwe 1). Archean granites and greenstones of the Zimbabwe Craton form the core of the country. A large mafic to ultramafic intrusion, the Great Dyke, crosses the center of the country roughly in a north-south direction. The Great Dyke is approximately 515-550 km long, up to 12 km wide, and was emplaced about 2,600 million years ago (Mukasa et al., 1998). The Great Dyke contains significant platinum and chrome resources as well as other metals. Several mines have been developed on the Great Dyke.

The Archean Limpopo Belt consists of high-grade metamorphic rocks and is located in the south of the country between the Zimbabwe Craton and the Kapraal Craton further south in the Republic of South Africa. The Proterozoic Magondi Supergroup, consisting of folded metamorphosed continental sediments, basalts, marine sediments, and amphibolite sills, is found in northern Zimbabwe at the edge of the Zimbabwe Craton and is a part of the Zambezi Belt. The Proterozoic metasedimentary Makuti, Rushinga, and Sijarira Groups are found in the northwest of the country.

Late Paleozoic to Triassic age sediments of the Karroo (Karoo) Supergroup occur in basins in the north, northwest, and south of the country. Basalt flows cover the Karroo sediments in the north and south. Kalahari sands cover extensive areas in the west of the country. Numerous intrusions, including carbonatites, intrude the Precambrian age basement rocks and Karroo sediments.

Nitrogen Resources

Petroleum—Zimbabwe no longer has a functioning oil refinery, and all required petroleum products must be imported. The costs to rehabilitate and upgrade the 40-year-old refinery were expected to be more than the costs of building a new refinery.

Coal—Zimbabwe has 24 known coalfields located largely in the northwest and southeast of the country. One source indicates there is an 11 billion-ton inferred resource, a 1980 figure that does not appear to have been updated (*Engineering News Online*, 2006). The World Energy Council (2003) indicates coal reserves are 502 million tons.

The Hwange Colliery Co. Ltd., located in the northwest of the country near Hwange, was formerly known as the Wankie Colliery. The name was changed in 1990. The capacity of the mine is over 5 million tpy of bituminous coal and coking coal. Production has been declining over the last several

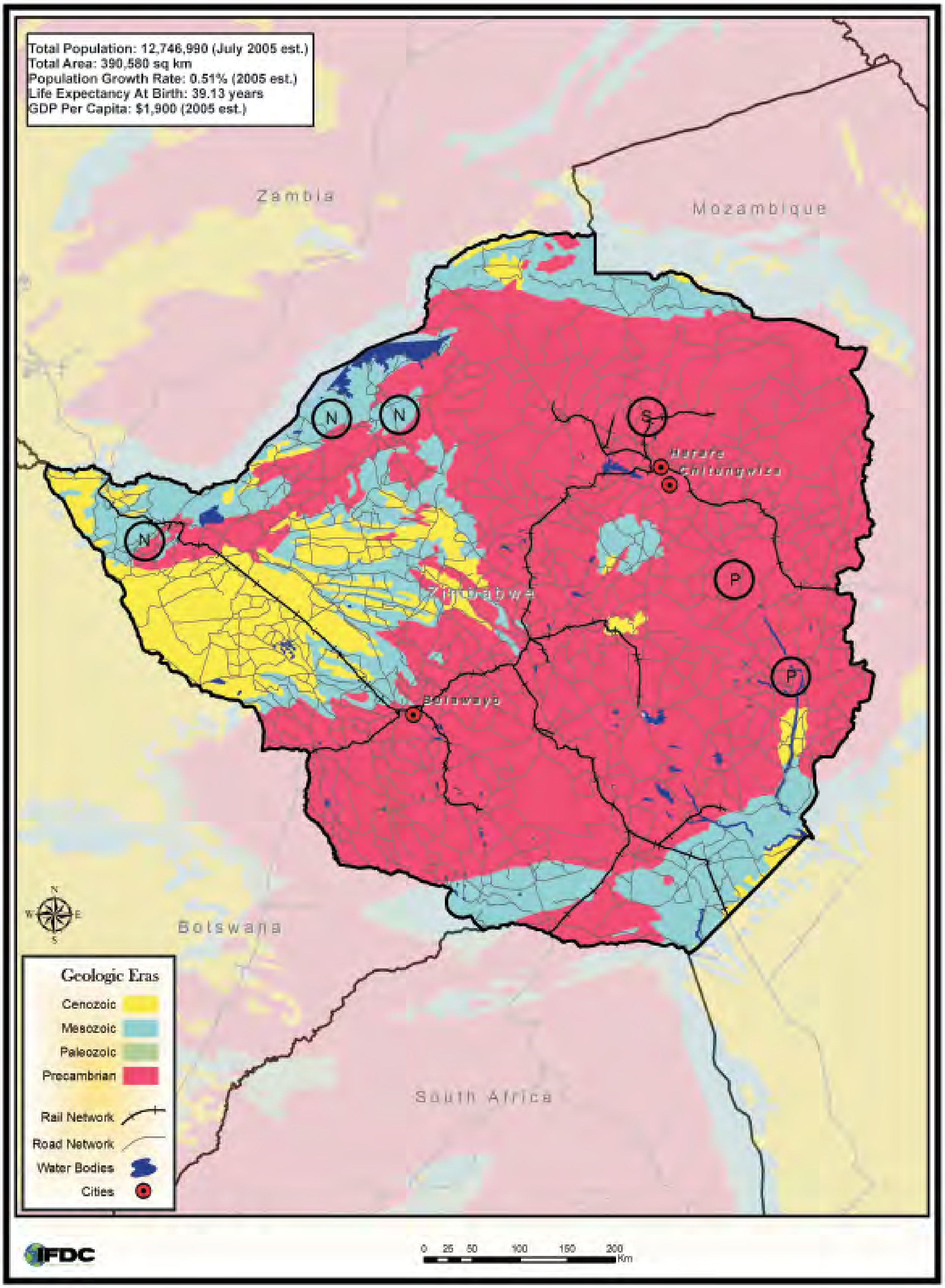


Figure Zimbabwe 1. Geology, Major Cities, and Transportation Network years as the following table indicates (Coakley, 2003; Mobbs, 2004):

Year	Bituminous Coal	Coke
	(tons x 1,000)	
1999	4,576	600
2000	3,809	600
2001	4,064	245
2002	3,721	224
2003	2,872	228
2004	2,476	180

During 2003 the Hwange Colliery produced 854,605 tons of coal for export; 1.69 million tons of coal for use in the nearby Hwange Power Station; 228,389 tons of coke, of which 127,800 tons was exported; and about 6 million m^3 of coke oven gas. In 2002, Hwange produced more than 24 million m^3 of coke oven gas (Coakley, 2003). The Hwange Colliery had plans to eventually double coking coal capacity.

In 2004 Hwange's 600,000-tpy capacity M-Block underground mine was closed after reserves were depleted (Mobbs, 2004). Development continued on the underground 1.8 million-tpy 3 Main Mine. Hwange expected to begin production of coking coal from the 3 Main Mine in early 2005 and to double coke production. In 2004 production of coking and steam coal continued from the open pit.

Hwange proposed the development of an open-pit mine on its Chaba Concession in 2004. The Chaba Concession is located about 6 km from the Hwange Power Station, and production from Chaba would cover a proposed increase in generating capacity originally proposed for 2007. Proposed plans for increased generating capacity failed. The Wankie Power Station operator, Zesa, may be developing its own coal mine (*Engineering News Online*, 2006).

Beta Holding (Pvt.) Ltd. of Zimbabwe leased the Sengwa Coal Mine from Rio Tinto Zimbabwe in 2004. Beta subsidiaries include brick and tile producers. The open-pit Sengwa Mine was developed in the mid-1990s to be a source of fuel for the government's Gokwe North Power Project, which was never built (Mobbs, 2004).

Declining production levels are reported to be due to shortages of foreign exchange, equipment, and spare parts (Coakley, 2003). The railroad is suffering similar problems (Seiler, 2005).

Coalbed methane projects in western Zimbabwe included the Lubimbi area that Hwange discovered in 2004 (Mobbs, 2004). The Industrial Development Corporation continued to seek funding for the Lupane Gas Project.

Phosphate Resources

Igneous Phosphate Deposits—All the significant phosphate deposits in Zimbabwe are igneous occurrences primarily related to carbonatites. Barber (1991) recognized 12 structures considered to be related to carbonatites within Zimbabwe.

Dorowa Deposit—The Dorowa Mine and beneficiation plant are located at the town of Dorowa, about 64 km southwest of Inyazura within 2 km of the River Sabi. Dorowa Minerals Ltd. is a 100% subsidiary of Zimbabwe Phosphate Industries Limited (ZimPhos). ZimPhos is a wholly owned subsidiary of Chemplex Corporation (Pvt) Ltd. (Chemplex). Chemplex is 100% owned by the Industrial Development Corporation of Zimbabwe. Chemplex assumed control of the deposit in 1981. Chemplex is currently listed with the Privatization Agency of Zimbabwe (2006).

The Dorowa Deposit was discovered in 1938 by F. P. Mennell and was originally prospected as a potential source of magnetite ore. Following World War II, the original samples were reexamined and the presence of apatite was discovered. In 1956 all the interests held over the complex were completely bought out by African Explosives and Chemical Industries Limited (AECI). The Government of Zimbabwe granted AECI protective tariffs concerning fertilizers in 1964. Production at Dorowa began in 1965. Capacity is 1.5 x 10^5 tons of concentrate annually.

Two ore bodies compose the deposit—the northern and southern ore bodies (Figure Zimbabwe 2). The southern ore body was the first ore body to be mined, and the northern ore body was brought into production in the early 1990s. Apatite in the southern ore body is associated with ijolites, melanocratic neptheline syenites, and dikes and veins of magnetite-pyroxene (altered to serpentine)-vermiculite-apatite (Barber, 1991). The ijolites,

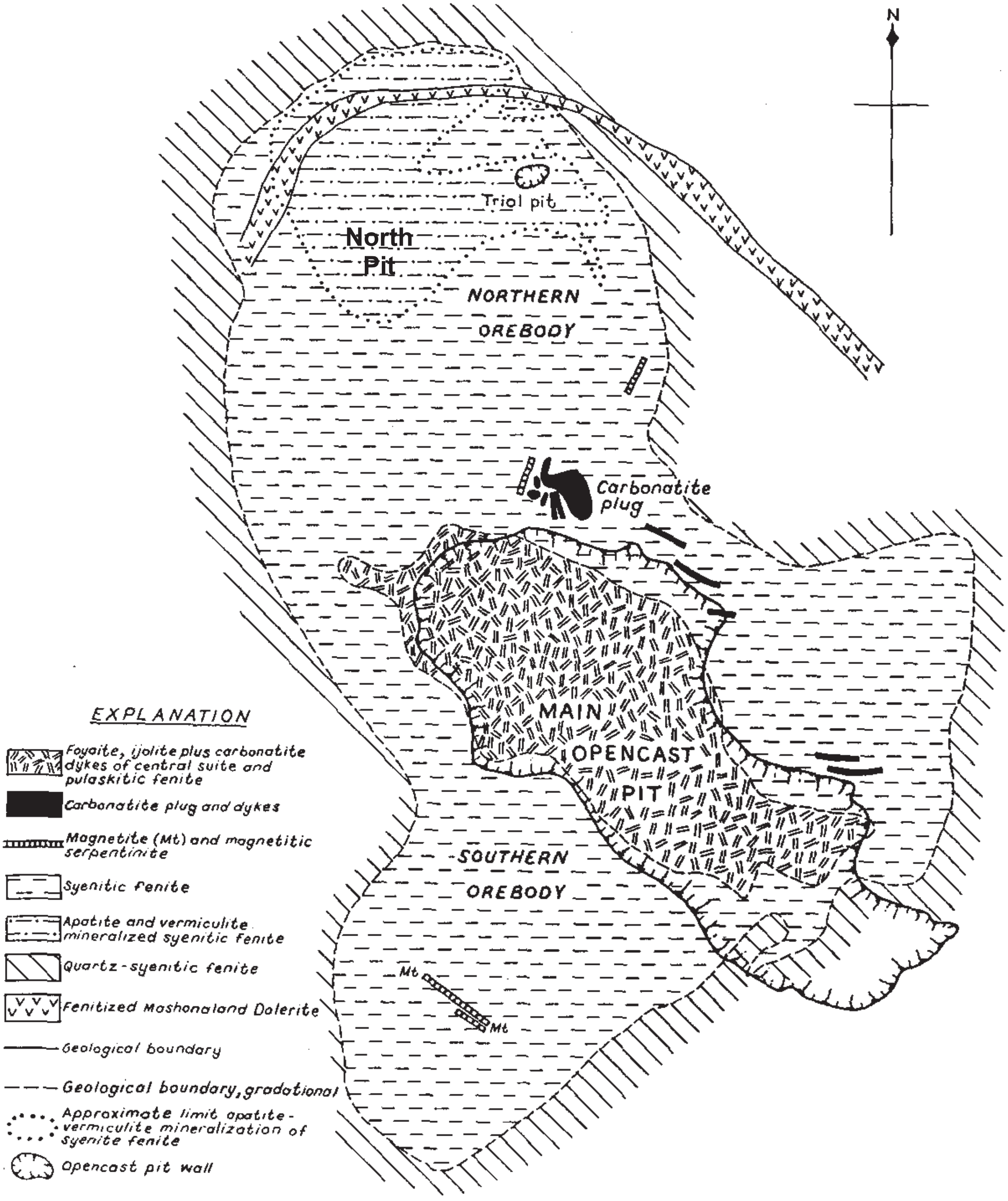


Figure Zimbabwe 2. Geology of the Dorowa Carbonatite Complex (modified from Barber, 1991) syenites, and apatite-rich dikes and veins are cut by a small plug and several carbonatite dikes.

The ore in the southern pit is deeply weathered and friable. Some blasting is required in the northern pit. Ore is mined by scraper loaders and a bulldozer. The ore has a head grade of 6% to 8% P_2O_5. From the pit the ore is screened and ground in a semiautogenous mill. The ore is ground for two purposes: (1) to break up large pieces of ore containing apatite and increase overall recovery and (2) to fracture the apatite crystals to provide fresh surfaces for flotation. Although the apatite crystals in the deposit are naturally liberated at sizes greater than 500 µm, surface alterations from weathering cause a portion of the apatite to become unresponsive to flotation (Fernandez, 1978). From the grinding circuit, the ore is deslimed, conditioned, and fed to the flotation circuit. Overall recovery is greater than 65% and may be as high as 80%. The concentrate is dried to less than 1% moisture.

Chemical and mineralogic analyses of a sample of Dorowa concentrate (Table Zimbabwe 1) indicate

Table Zimbabwe 1. Chemical Analysis and Approximate Mineralogic Modal Composition, Dorowa Concentrate

	Chemical Analysis	Apatite	Calcite	Aegerine-Augite	Vermiculite	Riebeckite	Unassigned
	(%)						
P_2O_5	33.1	33.1					
CaO	50.2	43.4	4.46	0.41			1.93
F	1.6	1.6					
SiO_2	5.4			3.55	1.28	0.57	
Al_2O_3	0.58				0.58		
Fe_2O_3	2.6			1.77	0.30	0.53	
Na_2O	0.76			0.69		0.07	
K_2O	0.08						0.08
MgO	1.28			0.29	0.85	0.14	
SrO	0.52						0.52
MnO	0.05						0.05
CeO	0.03						0.03
TiO_2	0.05						0.05
La_2O_3	0.01						0.01
ZrO_2	0.02						0.02
CO_2	3.5		3.5				
S (total)	0.05						0.05
C (organic)	0.1						0.1
Cl^{1-} (ppm)	69						69
NAC-soluble P_2O_5[a,b]	0.8						
Free H_2O[a,c]	0.18						
LOI[a,d]	3.7						
-O≡F[e]	99.94	78.10	7.96	6.71	3.01	1.31	2.85
	–0.67	–0.67					
	99.27	77.43	7.96	6.71	3.01	1.31	2.85

a. Not included in totals.

b. Neutral ammonium citrate-soluble P_2O_5 (AOAC method).

c. Free H_2O = weight loss, 105°C, 1 h.

d. Loss on ignition = weight loss, 1000°C, 1 h.

e. Fluorine correction, two F^1 substitute for one O^{2-}.

that the sample is approximately 78 wt % apatite. Based on the fluorine content of 1.6 wt % and unit-cell measurements (a = 9.390 ± 0.0010), the apatite is a hydroxylfluorapatite variety with the following composition: $Ca_{10}(PO_4)_6$, $(F_{1.08}, OH_{0.92})$. Calcite (8 wt %), aegerine-augite (7 wt %), vermiculite (3 wt %), and magnesioriebeckite (1 wt %) have passed through the beneficiation process and constitute the gangue minerals.

In 1987 Savage indicated that reserves at Dorowa were 35 million tons at 17% P_2O_5. Lauderdale (unpublished report, cited in Barber, 1991) indicated the ore reserves at Dorowa as of mid-November 1981 to be:

	Tonnage x 10^6	Grade
Southern Ore Body (to limit of weathering)	39.60	6.71
Northern Ore Body (measured)	33.18	6.39
Total tonnage and average grade	72.78	6.56

Considering that it takes between 3,000 and 3,500 tons of ore to make 400 tons of concentrate (Barber, 1991), the ratio of concentration (ton of ore per ton of concentrate) is between 7.5 and 8.75 to 1. Savage (1987) indicated that the ratio of mined ore to concentrate averages 7.5:1. The United States Geological Survey (USGS) Minerals Yearbook data indicate that about 2.9 million tons of concentrate have been produced at Dorowa since 1981 or an average production rate of 121,000 tpy. Therefore, between 21.7 x 10^6 to 25.4 x 10^6 tons of ore have been mined since 1981. Remaining ore resources at Dorowa may be on the order of 47.4 x 10^6 to 51.1 x 10^6 tons or 5.4 to 6.8 million tons of concentrates. At the average production rate of 121,000 tpy of concentrate, this would be enough ore to last 45 to 56 more years. This reserve estimate should be considered speculative. The beneficiation characteristics and recovery ratios may change with depth in the southern ore body or may differ in the northern ore body.

A road was built between Dorowa and Inyazura, and the Harare-Umtali railroad line runs through Inyazura. Trucks haul the concentrate to Inyuzura where it is unloaded and transferred to silos using compressed air. The concentrate is loaded into rail cars at a rate of 3 tons/min (Savage, 1987).

Production at times has been over 150,000 tpy (1987, 1993, 1994, and 1995). However, production in the late 1990s and early 21st century has been rather erratic. The following table indicates the production from 1994 to 2004:

Year	Concentrate Production
	(tons)
1994	151,000
1995	154,000
1996	123,000
1997	94,000
1998	91,000
1999	126,000
2000	77,662
2001	86,611
2002	107,854
2003	95,496
2004	83,391

The concentrate is railed to Harare where it is utilized at the ZimPhos factory. ZimPhos produces single superphosphate, phosphoric acid, triple superphosphate, and monocalcium phosphate for animal feed (ZimPhos, 2006). Shortages of fertilizer in recent years have adversely affected the Zimbabwe agricultural sector. Failure to meet fertilizer needs has been attributed to a lack of foreign exchange to buy needed raw materials or spare parts and rail transportation problems (Zimbabwe Briefcase, 2003; Zimbabwe Situation, 2006).

Shawa Deposit—The Shawa Carbonatite Complex is located 16 km south-southwest of Dorowa on Save Communal lands in Buhera District. From the 1930s to the 1960s, the complex was investigated by a number of concerns for various minerals (Barber, 1991). In 1970 and 1971, Prospecting Ventures Limited performed extensive drilling and pitting for phosphate on behalf of AECI. The claims over the phosphate-rich center of the deposit are held by Dorowa Minerals Limited.

The best known area of apatite concentration is a partial ring of ijolite on the southwest side of the complex, as well as soil over this occurrence and soil collected in the depression at the very center of the complex. Dodd (unpublished report, cited in Barber,

1991) indicated that P_2O_5 concentrations increase with depth in the regolith; he calculated resources of 20.3 million tons in the weathered zone at 10.8% P_2O_5, 31.4% Fe_2O_3, and 1.3% CO_2. Dodd postulated that there was another 2.7 million tons at 16% P_2O_5 in another area. Resources containing less than 1% CO_2, suitable for treatment in the flotation plant at Dorowa, were estimated at 16.3 million tons containing 10.4% P_2O_5, 32.5% Fe_2O_3, and 0.8% CO_2. The deposit will probably be exploited when Dorowa reserves are exhausted.

Chishanya Carbonatite—The Chishanya Carbonatite Complex lies in the Buhera District 9 km west of the confluence of the Odzi and Save Rivers. Several companies prospected the area for phosphates and other minerals, starting in the 1940s and through the 1970s (Barber, 1991). The complex is about 5 km long and 1.5 km wide. The Messina Development Company prospected in the region around and between Baradanga and Chishanya Hills. The resources were estimated to be 1,600 tons/m of depth with an average grade of 8% P_2O_5.

The apatite is associated with ferrosövite. Ferrosövite analyses in Barber (1991) indicate P_2O_5 values from 2.97% to 24.96%. The ferrosövite appears to occur as dikes that are 2 to 3 m wide. Fine grinding would be needed to liberate the apatite, and it may be difficult to reduce impurity contents to suitable levels. Concentrates containing up to 32% P_2O_5 were produced in laboratory experiments. Barber (1991) indicated that only a portion of the complex had been subjected to detailed investigations.

Other Carbonatite Occurrences—The Gungwa Metacarbonatite Complex occurs in the Mafigu area of Masoso Communal Land approximately 70 km northeast of Mount Darwin Township. Apatite is reported to be a commonly visible accessory constituent, and the rock was stated to contain 1.64% P_2O_5 (Barber, 1991). There are no resource estimates.

The Katele Carbonatite Complex is found some 50 km northeast of Hwange Township in the Binga District of northwestern Zimbabwe. Data in Barber (1991) indicate P_2O_5 contents in the carbonatite to be 0.16% to 0.94% P_2O_5. The P_2O_5 is present as monazite ([Ce,La,Di]PO_4), not apatite.

The Nanuta Metacarbonatite Complex is located in Chiswite Communal Land in the Darwin District of northeastern Zimbabwe 4 km north of Mount Darwin Township. Apatite is reported to be present in the carbonate, but no information concerning grade or resources is available (Barber, 1991).

Several carbonatite structures were under investigation in the 1990s. The occurrences include the Murambini Carbonatite Complex, a carbonatite complex northeast of Kariba, and four structures in the vicinity of N'tondgwe Hill in northern Zimbabwe. No details are available on these potential deposits.

Sedimentary Deposits—The only sedimentary phosphate deposits in Zimbabwe are guano deposits. The title to a bat guano deposit is vested with the landowner in Zimbabwe.

Bashungwi Caves—The caves are located in Rengwe Communal Land, Harangue District. There is no record of the caves being worked or resources estimated (Barber, 1991).

Chigwena Caves—The Chigwena Caves occur in the Kaduna Administrative District. The deposit was worked between 1910 and 1964 by the Hoffman family who applied the guano on their farm. Analyses found in Barber (1991) indicate P_2O_5 contents from 3.5% to 9.2% and nitrogen (N) contents from 0.3% to 1.8%. There are no reserve estimates.

Mabura Caves—The caves are located in the Zhombe Communal Land, Kwekwe District. The deposit was worked shortly after World War I. Magalela (unpublished report, cited in Barber, 1991) reported 2 million tons of reserves. Barber (1991) questioned this estimate. Chemical analyses indicate P_2O_5 contents from 3.4% to 14.99% and N contents from 1.2% to 9.29%.

Mburunge Caves—The caves are located in the Chitomborgwizi small-scale farming district of Makonde District. Only some restricted exploitation of this guano for local use is known to have occurred (Barber, 1991).

Mgweta Caves—The Mgweta Caves are located in the Hurungwe Communal Land, Hurungwe District. Resources were estimated at over 2,700 tons (Barber, 1991).

Munyati River Caves—The Munyati River Caves are located in Gokwe Communal Land, Gokwe District. The No. 1 cave had been mined prior to 1920. Material from Cave No. 1, Cave No. 1A, and Cave No. 2 had P_2O_5 contents from 5.12% to 31.32% and N values from 0.17% to 10.31% (Barber, 1991).

Odzi Caves—Situated on the Golden Valley Farm 40 km west-southwest of Odzi Station on the railway linking Harare with Mutare, the Odzi Caves were worked for a short time between World Wars I and II. The deposit is small and difficult to work (Barber, 1991).

Siso Cave—The Siso Cave is located on the Siso Farm in the Makonde Administrative District. There is no record of the cave being worked (Barber, 1991). The guano contained about 4% to 5% P_2O_5 and up to about 10% N.

Sulfur Resources

Sulfuric acid is manufactured in Zimbabwe from iron pyrite (FeS_2) and is obtained as byproduct acid and from metallurgical and coal process gas. Sulfuric acid has been exported to Zambia for use in the copper industry.

The Iron Duke Mine lies some 45 km south of Harare and 10 km south-southwest of Garwen Siding on the Harare-Shamva railway. The mine was worked for gold from 1914 to 1920. The pyrite is mined underground by the underhand stoping method. Production is blended to produce an average ore grade of 35.5% sulfur (Barber and Muchenje, 1991). Most of the production is utilized by ZimPhos.

Sulfur production in Zimbabwe—using pyrite, byproduct acid, and metallurgical coal process gas—is listed in the following table (Coakley, 2003).

Sulfur Production		
Year	Pyrite	Other
	(tons)	
1999	48,793	2,500
2000	69,119	2,500
2001	98,037	2,000
2002	87,592	2,000
2003	93,016	2,000

Over 900,000 tons of gypsum is stockpiled at the ZimPhos plant near Harare (van Straaten, 2002).

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