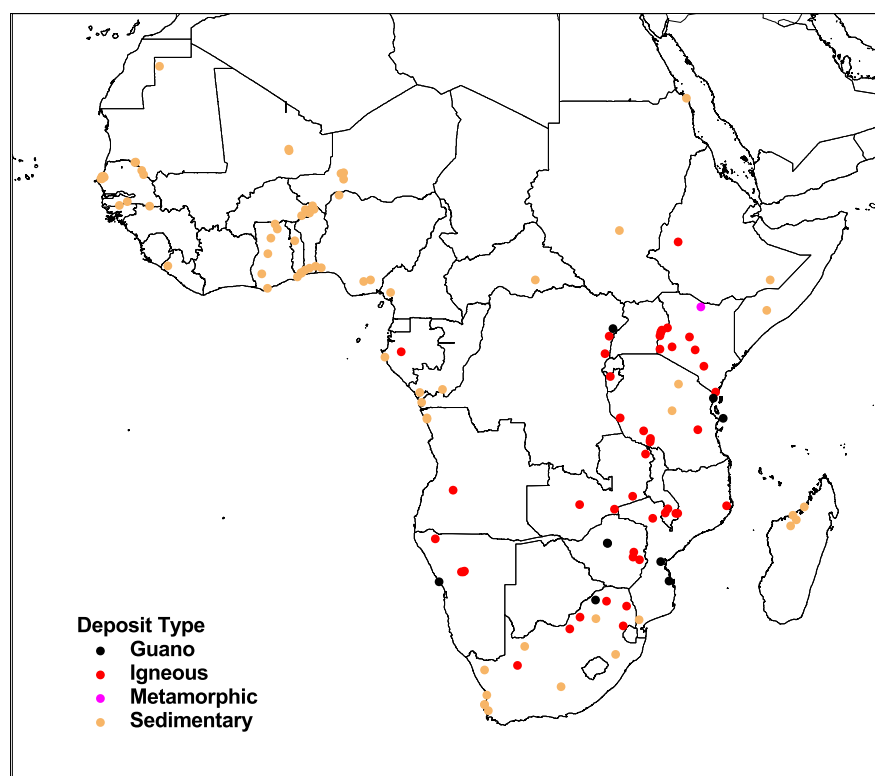




Local phosphate resources for sustainable development in sub-Saharan Africa

Economic Minerals and Geochemical Baseline Programme

Report CR/02/121/N



BRITISH GEOLOGICAL SURVEY

REPORT CR/02/121/N

Local phosphate resources for sustainable development in sub-Saharan Africa

J D Appleton

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Foreword

This report is an output for the Department for International Development (DFID) funded research project R7370 *Local Phosphate Resources for Sustainable Development* and is a contribution towards DFID Infrastructure and Urban Development Department's Goal G1: *Environmental Mineral Resource Development*. It was compiled and collated from readily available existing information including archive material held by the BGS; digital bibliographic data bases; IFDC reports; and through contacts with mineral resources and agricultural organisations including FAO, IFDC, ICRAF, UNIP, UNIDO, IFA. An *Endnote* database was compiled of bibliographic references and abstracts together with information from web sites and this now includes over 2400 records.

This report was commissioned by the UK Department for International Development (Contract R7370) but the views in it are not necessarily those of the Department.

Acknowledgements

A number of individuals have freely given their advice, provided local knowledge and reviewed drafts of this report. The compiler of this report would particularly like to thank the following for their advice and comments: Norman Chien, Steven Van Kauwenberg and Upendra Singh (International Fertilizer Development Centre, Muscle Shoals, Alabama, USA), Henk Breman (Director, IFDC Africa Division, Lomé, Togo), Anne-Claire Landolt (DFID), and David Highley (BGS).

Arthur Notholt, the renowned phosphate mineral resource expert, who died suddenly in 1995, had been working for many years on a comprehensive review of world phosphate deposits and the international phosphate mining industry. Arthur's widow, Agnes, kindly gave permission for the compiler of this report to make extensive use of information from Arthur's unpublished papers (Notholt, 1999).

This review has been developed out of a brief report "Indigenous rock phosphate mobilization, processing and use in sub-Saharan Africa" that was compiled for the FAO in November 1995. Permission to include some of the text from the FAO report in this review is gratefully acknowledged.

Maps illustrating the location of phosphate resources and major transport routes in each country were compiled using coastlines, international boundaries, roads, railroads, water features and the gazetteer from Edition 1 of the Digital Chart of the World (DCW) July 1992.

Summary

Soil degradation and infertility are major constraints to the sustainability of agricultural systems in many developing countries, particularly those located in the tropical humid lowlands of Sub-Saharan Africa (SSA) where phosphorus (P) and nitrogen (N) deficiencies are recognised as major constraints to sustainable agricultural productivity. Whereas nitrogen deficits can be restored, at least in part, through the application of organic crop residues and manure or by the use of cover crops, the restoration of soil P-status can only be achieved by the use of phosphate fertilisers. The socio-economic situation for most African farmers is, however, such that they are unlikely to be able to afford to purchase manufactured mineral fertilizers required to replenish this deficit. The most vulnerable groups of subsistence farmers, such as those practising shifting cultivation or cultivating marginal lands are already seeing production levels fall as soil fertility declines. Most developing countries in SSA need to meet the needs of growing populations without damaging the resource base. DFID's *Sustainable Agriculture Strategy* [, 1995 #1760] clearly identifies the need to increase crop yields through the prevention of erosion, the introduction of stable farming systems, improving genetic material, and the use of organic and, inorganic fertilisers.

Agronomists, agricultural economists, renewable natural resources and mineral resources advisers in local and national governments, international bodies including development agencies, and NGOs working with poor farmers, may not be adequately aware of locally available phosphate rock resources and their agronomic potential, as a low-cost source of phosphate, for the enhancement of soil fertility and productive capacity of relatively poor, smallholder farmers. There is a need to ensure that the use and development of local resources is considered as an option for restoring the P-status and productive capacity of degraded soils. Unfortunately, much of the information required to inform the consideration of this option is widely dispersed in reports, scientific publications, symposia and workshop proceedings that may not be readily available to advisers working in the developing countries of sub-Saharan Africa. This report presents the first of a series of three regional reviews (covering sub-Saharan Africa, Asia, and Latin America) that seek to provide advisers with a concise summary of national and regional information on locally available phosphate resources. The report deals with the Sub-Saharan Africa region with special emphasis on Angola, Burundi, Ghana, Kenya, Malawi, Mozambique, Namibia, Nigeria, South Africa, Tanzania, Uganda, Zambia, and Zimbabwe.

The first section of the report contains regional or generic reviews of:

- Phosphate mineral resources of Sub-Saharan Africa including information on phosphate rock and phosphate fertilizer production, consumption, and export
- Phosphate rock products and processing options
- Estimated investment required for mining, infrastructure and processing options
- Constraints for utilisation of phosphate rock resources
- Environmental constraints related to heavy/hazardous elements contained in the rock phosphates or their by-products.
- Existing or anticipated direct use of phosphate rock in agriculture including general results of agronomic and economic assessments.
- Role of phosphate rock in strategies for dealing with soil fertility

The second section of the report comprises thirty-one country profiles, each of which summarises:

- Quantity, quality and location of local phosphate rock deposits/sources in each country. Maps indicate the location of the phosphate resources and major transport routes.
- Past and current phosphate rock production including export as intermediate/raw materials and local use in agriculture
- Agronomic and agro-economic assessments of rock phosphates and associated phosphate fertilizer products, including information on the soil types and crops likely to show a positive response to direct application of rock phosphate fertilisers.

A summary of the quantity, quality, production, agronomic testing, use and development potential of the phosphate resources of sub-Saharan Africa, together with their geological type and age is provided in the final section of the report.

Local Phosphate Resources for Sustainable Development is an ‘enabling project’ which aims to support the context for poverty reduction and elimination. In order to enable poverty alleviation, the project focuses on the promotion of local use rather than the export of phosphate. The project cannot ensure that poor communities and farmers will not be adversely affected, for example, by ensuring that areas that are currently used, for whatever purpose, by poor people are not recommended as areas for phosphate rock extraction. Only the appropriate advisers and local authorities can achieve this. This review report is not targeted to ensure that the knowledge in them will be readily accessible by the poor, but is directed at people who work with and on behalf of the poor.

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INTRODUCTION

Soil degradation and infertility are major constraints to the sustainability of agricultural systems in many developing countries, particularly those located in the tropical humid lowlands of Sub-Saharan Africa (SSA) where phosphorus (P) and nitrogen (N) deficiencies are recognised as major constraints to sustainable agricultural productivity. The average annual nutrient loss from African soils is of the order of 0.6 million tons (Mt) for phosphorus whereas annual P-fertiliser consumption is only about 0.26 Mt (IFA, 2000a; IFA, 2000b). Whereas nitrogen deficits can be restored, at least in part, through the application of organic crop residues and manure or by the use of cover crops, the restoration of soil P-status can only be achieved by the use of phosphate fertilisers. The socio-economic situation for most African farmers is, however, such that they are unlikely to be able to afford to purchase manufactured mineral fertilizers required to replenish this deficit. The most vulnerable groups of subsistence farmers, such as those practising shifting cultivation or cultivating marginal lands are already seeing production levels fall as soil fertility declines. Most developing countries in SSA need to meet the needs of growing populations without damaging the resource base. DFID's *Sustainable Agriculture Strategy* (1995) clearly identifies the need to increase crop yields through the prevention of erosion, the introduction of stable farming systems, improving genetic material, and the use of organic and, inorganic fertilisers.

A recent DFID overview of thirteen soil fertility reviews highlighted the inherent low nutrient status of weathered tropical soils as well as the losses of nutrients through erosion and leaching (Pound, 1997). The reviews recognised that phosphorus is a key element in many situations and several reviews suggested further study and exploitation of phosphate rock deposits together with the increased use of mineral fertilisers. The overview identified a number of development issues including (a) the urgent need to rebuild soil fertility and maintain increased levels of productivity, and (b) that farmer financial resources and poor distribution systems limit fertiliser use to a very low level. Low soil nutrient status could be resolved by increasing inorganic fertiliser use although this would be constrained by the lack of adequate knowledge regarding, amongst other things, (a) the potential for the production of fertiliser materials from local phosphate rock resources and (b) non-industrial techniques for increasing the solubilities of native phosphate rock. For Forest/Agriculture Interface Production Systems, it was recommended that the application of a wide range of rock based phosphate sources should be considered as a method of dealing with the degradation of natural resources at the forest margin.

Agronomists, agricultural economists, renewable natural resources and mineral resources advisers in local and national governments, international bodies including development agencies, and NGOs working with poor farmers, may not be adequately aware of locally available phosphate rock resources and their agronomic potential, as a low-cost source of phosphate, for the enhancement of soil fertility and productive capacity of relatively poor, smallholder farmers. There is a need to ensure that the use and development of local resources is considered as an option for restoring the P-status and productive capacity of degraded soils. Unfortunately, much of the information required to inform the consideration of this option is widely dispersed in reports, scientific publications, symposia and workshop proceedings that may not be readily available to advisers working in the developing countries of sub-Saharan Africa. This report presents the first of a series of three regional reviews (covering sub-Saharan Africa, Asia, and Latin America) that seek to provide advisers with a concise summary of national and regional information on locally available phosphate resources. The report deals with the Sub-Saharan Africa region with special emphasis on Angola, Burundi, Ghana, Kenya, Malawi, Mozambique, Namibia, Nigeria, South Africa, Tanzania, Uganda, Zambia, and Zimbabwe.

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records. Internet searches alone revealed over 3500 sites with information on 'rock phosphate' and another 5600 with information on 'phosphate rock'.

The first section of the report contains regional or generic reviews of:

- Phosphate mineral resources of Sub-Saharan Africa including information on phosphate rock and phosphate fertilizer production, consumption, and export
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RESOURCES & PRODUCTION

Phosphate rock deposits of potential economic significance occur at more than 100 locations in at least thirty-one countries in sub-Saharan Africa (Figure 1). The quantity of resources varies from less than 100,000 tonnes (t) P_2O_5 to greater than 800 million tonnes P_2O_5 and the average P_2O_5 concentration ranges from 5% to 33%. Resource estimates are available for 48 phosphate rock deposits in sub-Saharan Africa (Table 1). Major quantities of phosphate rock are produced commercially from the Taiba and Pallo deposits in Senegal (579,200 t P_2O_5 in 1994), the Palabora and Varswater deposits in South Africa (987,460 t), the Hahotoe and Akoumape deposits in Togo (780,090 t), and the Dorowa deposit in Zimbabwe (53,910 t). Small quantities are produced from the Kodjari deposit in Burkina Faso (605 t) and the Minjingu deposit in Tanzania (500 t). Phosphate rock has been produced commercially from at least thirteen other deposits since 1900; the majority of these are located in South Africa.

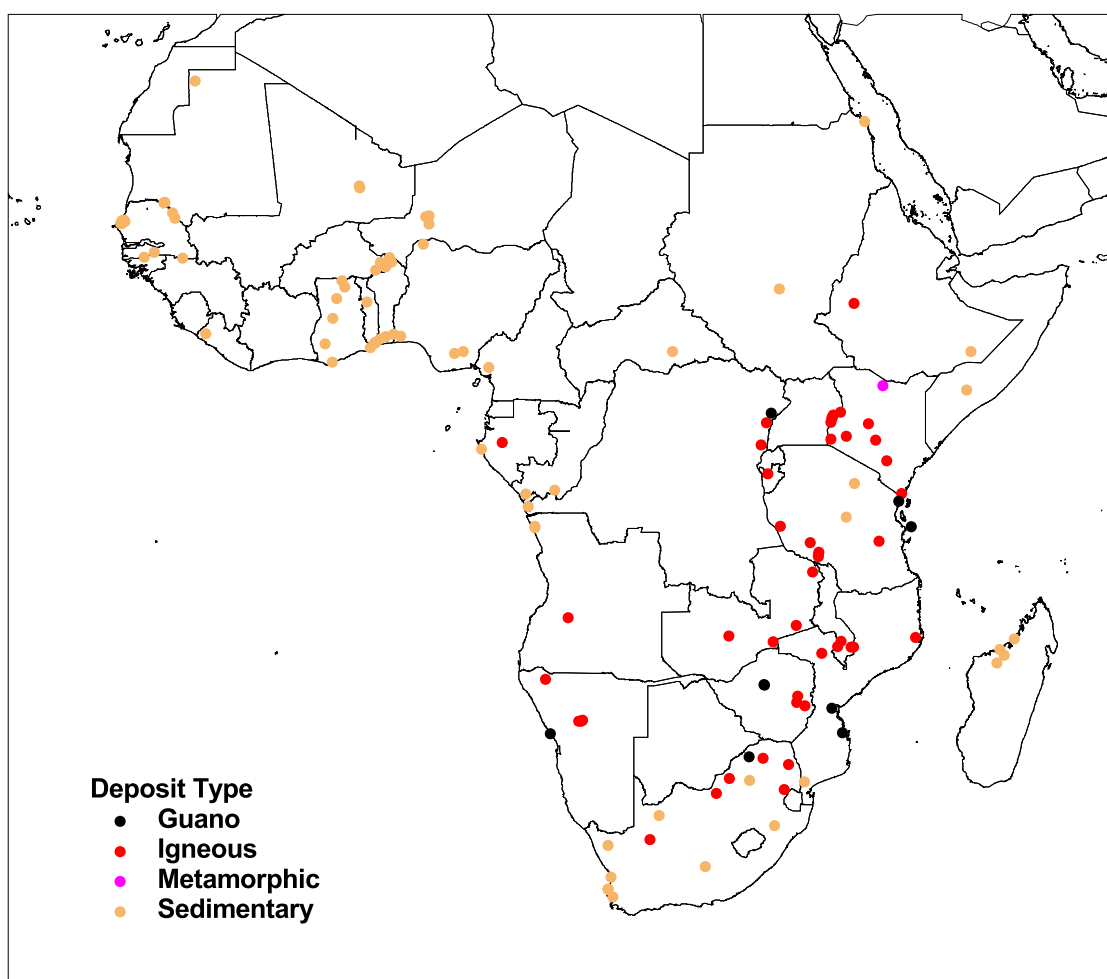


Figure 1. Location of phosphate deposits in sub-Saharan Africa

Phosphate rocks in sub-Saharan Africa are of two major types. Sedimentary deposits of phosphate rock, formed in coastal marine or lacustrine environments as the result of biogenic activity, are predominant in western Africa. The major Mediterranean or Tethyan Phosphogenic Province, to which the Cretaceous-Eocene commercial deposits in Togo and Senegal belong, covers extensive areas of northern and western Africa. Cretaceous-Eocene sedimentary phosphate deposits also occur in Angola, the Congo, Guinea Bissau, Mali, Mauritania, Niger, and South Africa. Precambrian sedimentary phosphate rock deposits occur in Benin, Burkina Faso, the Congo, Kenya, Liberia, Niger, and Somalia. Recent deposits also occur in sediments off the coasts of Gabon, Namibia, Mozambique and Malagasy. In many other sectors of sub-Saharan Africa, the palaeogeographic conditions are not particularly favourable for the development of major sedimentary phosphate rock deposits. In southern and eastern Africa, most of the phosphate deposits are associated with alkaline and carbonatite igneous complexes, most of Jurassic, Cretaceous and Tertiary age, although the major Palabora deposit in South Africa is Precambrian in age. Some of the igneous deposits are hard-rock, for example the Tundulu phosphate deposit in Malawi, whilst in other cases weathering of the apatite bearing carbonatites or alkaline rocks has led to the concentration of phosphate in residual soils (e.g. Sukulu, Uganda). The distinction between sedimentary and igneous phosphate rocks may not be of major importance if these are beneficiated and used for manufacturing chemical fertilizers. However, the low reactivity of igneous phosphate rock generally makes it unsuitable for use as direct application fertilizer apart from in special circumstances such as for tea plants grown on very acid soils in areas with high rainfall (Appleton, 1994). Extensive lateritisation of phosphatic sedimentary rocks has produced aluminium phosphate deposits at a number of localities of which the most important is the Pallo deposit, which extends over an area of 490 km² of the Thies plateau. Relatively small bat and bird guano deposits occur at a number of localities.

Table 1 Measured phosphate rock resources, average grades and phosphate resources in sub-Saharan African countries.

Country	Deposit	Resources Mt PR	Average % P ₂ O ₅	Resources Mt P ₂ O ₅
Angola	Quindonacaxa	200.0	22.5	45.00
Angola	Cabinda	16.0	23.0	3.68
Benin	Mekrou	5.0	23.5	1.18
Burkina Faso	Kodjari	80.0	27.5	22.00
Burkina Faso	Diapaga	224.0	15.0	33.60
Burkina Faso	Arly	4.0	29.0	1.16
Burundi	Matongo-Bandaga	25.0	11.0	2.75
Congo	Holle	15.0	23.0	3.45
Congo	Sintou-Kola	0.3	21.0	0.06
Guinea Bissau	Farim	112.0	30.0	33.60
Liberia	Bomi Hill, Bambuta	1.0	32.0	0.32
Malawi	Tundulu	0.8	20.0	0.16
Mali	Tamaguelet (Tilemsi Valley)	20.0	24.0	4.80
Mauritania	Near Matam (Senegal)	1.0	26.5	0.27
Mauritania	Ornolde	4.0	26.5	1.06
Mauritania	Bofal & Loubboira	94.0	19.5	18.33
Mozambique	Evate, Monapa	155.5	9.0	14.00
Mozambique	Muande, Tete	83.0	5.0	4.15

Country	Deposit	Resources Mt PR	Average % P ₂ O ₅	Resources Mt P ₂ O ₅
Niger	Tahoua	100.0	26.0	26.00
Niger	Tapoa	1250.0	23.0	287.50
Nigeria	Abeokuta	1.0	27.0	0.27
Senegal	Matam	40.0	29.0	11.60
Senegal	Taiba	100.0	24.0	24.00
Senegal	Lam Lam	4.0	33.0	1.32
Senegal	Pallo, Thies Plateau	90.0	28.0	25.20
South Africa	Palabora	13000.0	6.8	884.00
South Africa	Glenover	3.0	33.0	0.99
South Africa	Bandolier Kop	0.1	18.0	0.02
South Africa	Schiel	36.0	5.0	1.80
South Africa	Varswater (Langebaan)	37.5	10.0	3.75
South Africa	Sandheuwel, Cape Province	23.6	6.0	1.42
South Africa	Paternoster, Cape Province	10.0	5.0	0.50
South Africa	Duyker Eiland, Cape Province	3.6	9.5	0.34
South Africa	Constable Hill, Cape Province	0.3	27.5	0.08
South Africa	Mamre, Cape Province	0.1	24.0	0.01
Tanzania	Minjingu	10.0	20.0	2.00
Tanzania	Panda Hill (Mbeya)	125.0	6.0	7.50
Tanzania	Morogoro	2.0	6.5	0.13
Togo	Hahotoe-Kpogame	100.0	30.0	30.00
Uganda	Sukulu	230.0	12.0	27.60
Uganda	Bukusu, Busumbu	150.0	9.0	13.50
Zaire	Lueshe Valley	30.0	7.0	2.10
Zambia	Chilembwe	1.6	12.0	0.19
Zambia	Mumbwa North	0.6	5.0	0.03
Zambia	Nkombwa	200.0	4.5	9.00
Zambia	Kaluwe	6.6	5.1	0.34
Zimbabwe	Dorowa	73.0	6.6	4.82
Zimbabwe	Shawa	20.0	10.8	2.70

Detailed information on the geology, resources and characteristics of the phosphate deposits of sub-Saharan Africa is available in a number of key sources (Atkinson and Hale, 1993; BGS, 2001; British Sulphur Corporation, 1987; FAO, 1999; IFDC, 1988; Johnson, 1995; Johnson et al., 1989; McClellan and Notholt, 1986; Notholt, 1986; Notholt, 1991; Notholt, 1994a; Notholt, 1999; Notholt and Hartley, 1983; Notholt et al., 1989; USGS, 1997; Van Kauwenbergh, 2001b; Van Kauwenbergh et al., 1991a a; Van Kauwenbergh et al., 1991b b) as well as in hundreds of scientific papers, and reports produced by Geological Surveys and mining companies. Only a very brief summary of the quantity, quality and location of the main phosphate rock deposits in sub-Saharan Africa is given in this report. The interested reader should refer to the sources listed above for greater detail. It is important to note that the information available on individual phosphate rock occurrences or deposits may be inaccurate, out of date, or insufficient for their quantity and quantity to be assessed. Thus the potential use as fertilizer raw material of phosphate rock from some of the occurrences cannot be accurately assessed. It should also be noted that resource and reserve estimates quoted by different sources vary considerably (e.g. from 57 to 884 million tonnes P₂O₅ for the Palabora deposit in South Africa and from 15.5 to 27.6 million tonnes for the Sukulu deposit in Uganda). It is assumed that this is because different criteria have been used to quantify the phosphate rock resources.

Phosphate rock occurrences with undefined resources are recorded in the country profiles.

The major phosphate rock producers in sub-Saharan Africa are South Africa, Togo, Senegal and Zimbabwe (Table 2). South Africa, Senegal and Zimbabwe produce manufactured chemical fertilizers - most of which are used domestically in South Africa and Zimbabwe whereas most of the Senegalese fertilizer is exported (Table 3). South Africa, Senegal and Togo are major exporters of phosphate rock. Very small amounts of phosphate rock are also produced in Burkina Faso and Tanzania. It is estimated that less than 1% of the phosphate rock produced in sub-Saharan Africa is used as direct application fertilizer.

Table 2 Production and utilization of phosphate rock ('000 tpy) in sub-Saharan Africa

Country	Production					Home Deliveries		Exports			Imports		
	1991	1993	1995	1997	1999	1993	1997	1993	1997	1999	1993	1997	1999
Burkina Faso	0	0	2	5	nd	0	0	0	0	nd	0	0	nd
Ivory Coast	0	0	0	0	0	0	0	0	0	0	nd	1.6	1.5
Nigeria	0	0	0	0	0	0	0	0	0	0	nd	14	1.0
Senegal	1741	1689	1584	1593	1861	823	976	846	617	525	0	0	nd
South Africa	3180	2496	2790	2717	2940	1496	1814	1197	903	995	428	655	280
Tanzania	2.4	2.2	21.0	3.0	2.0	1.8 ^e	0	0.4 ^e	0	nd	0	0	nd
Togo	2965	1794	2569	2631	1715	0	0	1567	2687	1624	0	0	nd
Zimbabwe	275	151	154	94	85	151	0	0	0	nd	6	0	nd

Source: IFA, BGS World Mineral Statistics and IFDC; some figures may be unofficial or estimates; ^e = estimate; nd = no data

Table 3 Utilization of manufactured phosphate fertilizers (tpy P₂O₅) in phosphate rock producing countries in sub-Saharan Africa¹

Country	Consumption	Production	Imports	Exports
	1993/94	1993/94	1993/94	1993/94
Burkina Faso	8000	300 ^{PR}	8000	0
Senegal	6000	38000	7300	33900
South Africa	301180	340000	10000	74000
Tanzania	8000	0	8000	0
Togo	3000	0	3000	0
Zimbabwe	44800	38500	1600	2000

¹ Source: FAO; some figures may be unofficial or estimates
^{PR} ground rock phosphate

Fertilizer production statistics for selected countries in sub-Saharan Africa are compared with production data for the whole of Africa and the World in Table 4.

Table 4. Fertilizer production in selected countries of sub-Saharan Africa in 1990 and 1998 ('000 tonnes P₂O₅ ; Source: IFA)

Country	Ground rock, direct applien.			SSP + TSP			Ammonium phosphate P			NPK P			Total Phosphate			
	Prod.	Import	Export	Consum.	Prod.	Import	Export	Consum.	Prod.	Import	Export	Consum.	Prod.	Import	Export	Consum.
1990/91 - 1990																
Cameroon	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0
Côte d'Ivoire	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	2.9	0.0	2.5	0.0	0.0	0.0	8.2
Ethiopia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	71.5	0.0	35.0	0.0	0.0	0.0	71.5
Kenya	0.0	0.0	0.0	0.0	3.2	0.0	0.0	3.2	0.0	38.3	0.0	38.3	0.0	7.7	0.0	49.7
Nigeria	0.0	0.0	0.0	0.0	21.0	0.0	0.0	25.0	0.0	0.0	0.0	0.0	82.0	0.0	0.0	109.0
Senegal	0.0	0.0	0.0	0.0	11.2	0.0	10.5	0.4	1.8	0.0	2.0	0.0	30.6	0.0	0.0	3.5
South Africa	11.7	0.0	0.0	11.7	98.7	0.0	17.2	43.1	140.6	0.3	59.2	19.0	110.7	0.0	0.0	270.5
Sudan	0.0	0.0	0.0	0.0	15.6	0.0	0.0	15.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.6
Tanzania	0.0	0.0	0.0	0.0	4.6	0.0	0.0	8.3	0.0	0.0	0.0	0.0	1.5	3.3	0.0	10.9
Zambia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.1	8.1	0.0	15.9
Zimbabwe	0.0	0.0	0.0	0.0	42.3	6.7	0.2	4.1	0.0	0.0	0.0	0.0	0.0	1.5	37.2	41.6
Africa	33.6	0.0	21.9	11.7	1022.9	67.0	642.7	372.0	1216.4	156.3	1152.3	145.7	310.5	90.7	66.1	400.5
1998/99 - 1998																
Cameroon	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.8	0.0	2.6	0.0	2.6	0.0	4.2	0.0	7.6
Côte d'Ivoire	0.0	0.0	0.0	0.0	5.2	0.0	0.0	0.0	0.0	32.3	0.0	0.0	0.0	1.0	16.0	25.0
Ethiopia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	88.3	0.0	88.9	0.0	0.0	0.0	88.9
Kenya	0.0	0.0	0.0	0.0	4.6	0.0	0.0	4.6	0.0	43.5	0.0	43.5	0.0	9.0	0.0	57.1
Nigeria	0.0	0.0	0.0	0.0	10.0	0.0	0.0	10.0	0.0	4.7	0.0	4.7	10.5	14.0	0.0	39.2
Senegal	0.0	0.0	0.0	0.0	1.7	0.6	0.0	0.0	37.8	0.0	31.0	0.0	28.0	0.0	18.0	11.0
South Africa	0.0	0.0	0.0	0.0	35.5	2.4	23.5	18.0	183.3	14.4	76.3	48.0	160.0	0.0	16.0	378.8
Sudan	0.0	0.0	0.0	0.0	11.5	0.0	0.0	11.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.5
Tanzania	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.8	0.0	1.8	0.0	1.8	0.0	2.3	0.0	4.9
Zambia	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	13.0	0.0	13.5
Zimbabwe	0.0	0.0	0.0	0.0	35.5	0.2	0.0	2.0	0.0	6.1	0.0	0.0	0.0	0.0	2.0	42.0
Africa	0.0	0.0	0.0	0.0	862.8	39.6	625.4	212.9	1280.9	242.0	1083.0	258.2	286.5	146.6	61.0	467.5
WORLD 98	214.6	241.1	20.1	187.9	11802.2	1911.2	1758.2	10724.5	16659.6	8861.2	9112.1	14073.4	4487.7	1726.3	1593.2	6476.6
																33349.2

PRODUCTS AND PROCESSING OPTIONS

Introduction

Phosphate rock, formed as the result of sedimentary or igneous processes, is the essential raw material for the manufacture of phosphate fertilizers. The physical and chemical characteristics of a phosphate rock will constrain the potential methods that may be used for its transformation into a marketable fertilizer product. Equally processed phosphatic fertilizers have a range of economic and agronomic characteristics that may constrain their development. Most phosphate fertilizers, such as single superphosphate (SSP), triple superphosphate (TSP) and di-ammonium phosphate (DAP), are water soluble and manufactured in relatively large industrial plants using rock from large phosphate rock deposits with a production capacity of more than 250,000 tonnes per annum (Binh and Fayard, 1995; Ghumdia and Yusuf, 1995; Hignett, 1985; Roy, 1995; UNIDO, 1980).

The major types of fertilizers produced from phosphate rock are summarised in Table 5.

Table 5 Phosphate fertilizers: processes and products

Process*	Fertilizer Product
Fine grinding	Phosphate Rock (PR) powder for direct application
Partial Acidulation of PR with 25% - 50% sulphuric acid	Partially Acidulated Phosphate Rock (PAPR)
Complete Acidulation of PR with sulphuric acid	Single Superphosphate (SSP)
Complete acidulation of PR with phosphoric acid	Triple Superphosphate (TSP),
Reaction of phosphoric acid and ammonia	Diammonium Phosphate (DAP)
Fused phosphate rock and magnesium silicate (olivine or serpentinite)	Fused Calcium Magnesium Phosphate
Slag by-product derived from steel production using high-phosphorus iron ore	Basic Slag
Calcined phosphate rock, sodium carbonate and silica (1250°C)	Rhenania Phosphate

*For additional details on production processes see UNIDO Fertilizer Manual (Hignett, 1985).

A range of chemical or thermal processes may be used to convert the phosphate rock into chemically reactive and/or soluble fertilizers. For example at Pallo in Senegal, thermal treatment is used to convert the Fe and Al rich ore into a form that can be used and is effective over a range of soil conditions (Anon., 1966; Mokwunye and Vlek, 1986). Adequate energy supplies or chemicals may be unavailable or very expensive so this will, in some cases, constrain the adoption of high energy or sulphuric acid consuming technologies.

Ground phosphate rock for direct application

The direct application of ground or simply processed phosphate rock may be an effective and appropriate fertilizer when applied under specific soil and climatic conditions, and to certain crops. For many years, phosphate rock from large scale mines in Tunisia (Gafsa) and Jordan has been exported for use as a direct application fertilizer in Europe and Australasia for use in forestry (Binns, 1975), pastures (Bolan et al., 1990b; Syers and Gregg, 1981), and plantation crops (Ling et al., 1990). Other countries have developed

small phosphate deposits to provide ground phosphate rock for local use (Sheldon and Treharne, 1980). This mode of development is common when the size of the deposit is too small or low grade and the market for chemical fertilizers too restricted to justify investment in a conventional fertilizer plant. Small-scale mines produce 1.5 – 1.7% of the total world production of phosphate rock and most of this is used as direct application fertilizer (Maene, 2001; Van Kauwenbergh, 2001b). Examples of such mines are the opencast Purulia mine in West Bengal, India producing 14,000 tonnes/year in a non-mechanised operation employing 400 miners (Chakravorty, 1993), the semi-mechanised Eppawala mine in Sri Lanka producing 25,000 tonnes/year, the Mussoorie sedimentary phosphate deposit in Uttar Pradesh, India which produces 150,000 tonnes/year, and the Minjingu mine in Tanzania which formerly produced about 20,000 tonnes/year. Phosphate rock extracted by labour-intensive methods from small mines for use as direct application fertilizer often does not need to be so pure as the phosphate rock required for large chemical fertilizer plants (Hignett, 1985) but the mines need to be situated relatively close to the agricultural areas in order to reduce transportation costs.

Grinding and direct application of phosphate rock is technologically simple and may be particularly appropriate if resource and market sizes are small. The capital investment required for utilisation is small although there are a number of constraints including low reactivity; processing costs; high transport costs per unit P_2O_5 if the phosphate rock is low grade; low agronomic effectiveness. In addition, direct application of ground phosphate rock is effective only for certain climates, soils and crops (Appleton, 1994).

Compaction or blending of ground phosphate rock with chemical fertilizers may be a cost-effective method of providing both short and long-term nutrients.

Partial or complete acidulation with sulphuric acid

Reaction of phosphate rock with mineral acids, of which sulphuric is the most common, may be used to produce soluble fertilizers such as SSP. If the cost of acid is high and it is necessary to reduce the fertilizer cost, partial acidulation may produce a cheaper fertilizer with adequate solubility. Manufacture of partially acidulated phosphate rock (PAPR) using locally produced or imported sulphuric acid or indigenous pyrite/pyrrhotite resources is being considered as an alternative to conventional fertilizers such as TSP in some countries (Bationo et al., 1990; Bolland, 1994; Bolland et al., 1992; Chien and Hammond, 1988; Chien and Hammond, 1989; Chien and Menon, 1995a; Garbouchev, 1981; Goedert et al., 1990; Golden et al., 1991; Hagin and Katz, 1985; Hammond, 1990; Hammond et al., 1986; Hammond et al., 1989; Haque et al., 1999a; Kumar et al., 1993; Lewis et al., 1997; Mackay and Wewala, 1990; Mokwunye and Chien, 1980; Nkonde et al., 1991b; Panda and Misra, 1970; Simukanga et al., 1994; Zambezi and Chipola, 1991). PAPR is an under acidulated product that has been treated with only a portion of the quantity of sulphuric or phosphoric acid required to convert all the calcium phosphate (apatite) in the rock into the water-soluble monocalcium phosphate monohydrate (Schultz, 1986). Following earlier agronomic evaluations of PAPR in India (Panda and Misra, 1970; Panda and Panda, 1970), the International Fertilizer Development Centre (IFDC) initially advocated the manufacture and widespread use of PAPR in developing countries on the basis of the following advantages:

- it should be less expensive to manufacture as less sulphuric acid is required
- the process is tolerant of higher levels of impurities in the phosphate rock (up to 7% $Fe_2O_3+Al_2O_3$ compared with 3% for the full acidulation process (Chien, 2001b)) and it is efficient in its use of acid.

Whereas PAPR is produced and used successfully in some developing countries, such as Venezuela (Casanova, 2001), several site specific studies concerning the possible production of PAPR based on indigenous phosphate resources have revealed that PAPR is not always a viable alternative to fully acidulated P fertilizers (Steven van Kauwenberg, personal communication, 18 June 2001).

Manufacturing variables influence the characteristics and the agronomic value of partially acidulated phosphate fertilizers (Bolan et al., 1990a).

There is reported to be an increase in the number of producers of PAPR both in Europe, the Middle East and Latin America often using processes that have been designed to match the characteristics of the local

phosphate rock deposits (Roy and McClellan, 1986). Small-scale fertilizer production units using raw and partially solubilized phosphate in West Africa have been reviewed by Binh and Fayard (1995).

Complete acidulation with phosphoric acid

Phosphoric acid is produced from phosphate rock as an intermediate in the production of TSP and ammoniated phosphate products such as DAP (Hignett, 1985). High quality rock is required which will often require expensive and technically complex beneficiation. Financial, market and other economic and technical constraints are likely to be of major importance. Major world-class phosphate rock deposits and major markets are required before the manufacture of TSP-DAP can be justified.

Thermally altered phosphates

Thermally altered phosphates include fused calcium magnesium phosphate, rhenania phosphate, and defluorinated phosphate (Hignett, 1985).

Compacted mixtures of PR and soluble fertilizers

A great amount of interest has been shown over the last decade or so in the potential for producing compacted fertilizers with finely ground phosphate rock combined with other soluble mineral fertilizers (P as well as N and K). The following references provide information on production techniques as well as information on the relative agronomic efficiency of compacted fertilizers (Adediran and Sobulo, 1998; Anon., 1991; Butegwa et al., 1996a; Casanova and Solorzano, 1994; Chien and Menon, 1995a; Chien et al., 1987; Chileshe et al., 2000; Fernandes, 1996b; Lupin and Le, 1983; Menon and Chein, 1996; Menon et al., 1991; Mnkeni et al., 2000; Van Straaten et al., 1994; Van Straaten et al., 1995).

Bioconversion

Bioconversion of phosphate rock is a novel conversion method that may eventually have industrial applications. However, there is a lack of adequate knowledge regarding non-industrial techniques for increasing the solubilities of native phosphate rock (Pound, 1997).

Bojinova, Velkova, et al. (1997) described a study of the bioconversion of Tunisian phosphorite using *Aspergillus Niger*. The production of phosphoric fertilizers by traditional methods produces environmental problems, particularly related to use of acids during the decomposition of natural phosphates. In addition, plants assimilate only 15-20% of the phosphorus contained in superphosphates. The authors observed that the development of methods to process natural phosphates without acid precipitation has potential advantages and suggested that biotechnological processing of natural phosphates in order to obtain organo-mineral fertilizers is very promising. The possibility of bioconverting the phosphorus of natural phosphates by using *Aspergillus niger* fungi through their deep incubation has been investigated. The investigations aim to achieve a high degree of P₂O₅ extraction from the phosphates with conversion from a non-utilizable to a utilizable form. Bojinova, Velkova, et al. (1997) evaluated the influence of the fungal strain, the kind of nutritive medium and the time of incubation of the process of biological mobilisation of the phosphate rock. They established that the time of incubation, the kind of micro-organisms of the *Aspergillus niger* group, as well as the kind of nutritive medium, influence significantly the process of bioconversion and the conversion of phosphorus from non- utilizable to water-soluble and utilizable for plants form. A maximum degree 90% of phosphorus extraction in the form of water-soluble and citrate-soluble-P was reached after 10-days incubation. Physicochemical examinations proved a process of decomposition of the initial Tunisian phosphorite takes place as a result of the production of organic acids (Bojinova et al., 1997).

In a subsequent paper, Bojinova, Velkova, et al. (1999) presented the results of the agrochemical effect of two kinds of organic mineral fertilizers in their sub-variants on growth, development and yield of spring barley. The fertilizers were produced through biotreatment of Tunisian phosphorite with microorganisms of *Aspergillus niger A* and *Aspergillus niger G* strains in three states (solid, filtrate and

suspension). Results showed that barley grain yield was higher from the application of the solid phase compared to that of the suspension and the filtrate. Comparison shows that grain yield resulting from the application of solid fertilizer bioprocessed with the strain *Aspergillus A* is 15.2% greater than the grain yield obtained by using traditional fertilizers such as ammonium nitrate and superphosphate (Bojinova et al., 1999).

Goenadi, Siswanto, et al. (2000) investigated the bioactivation of poorly soluble phosphate rocks with a phosphorus-solubilising fungus. In general, the ineffectiveness of finely ground phosphate rock (PR) is largely due to the low solubility of P minerals. The authors evaluated a simple, effective, and environmentally sound process to improve P availability from PR to crops by using a phosphate-solubilising fungus (PSF), *Aspergillus niger*, isolated from tropical acid soils. The possibilities of using the liquid culture supernatant (LCS) of the fungus instead of sulphuric acid in superphosphate (SP) production and using lower phosphoric acid concentrations were investigated with Morocco PR as the test PR. Replacement of sulphuric acid by the LCS in the SP production process yielded a comparable 2% citric acid-soluble P content. Combining the LCS and sulphuric acid reduced the consumption of phosphoric acid that occurs in standard SP production. The authors concluded that this LCS technique provides a practical means for effective bioactivation of PR intended for use both as a P-fertilizer and a raw material for the production of superphosphate (Goenadi et al., 2000).

Pyrite-PR mixtures

Combining phosphate rock with pyrite is another technique that has been proposed for increasing the solubility of native phosphate rock. Lowell and Well (1995) examined the combination of PR and pyrite as a means to increase the availability of P from five PRs of African origin. In all cases, soluble P measured in the leachate increased with increasing levels of pyrite. Soluble P measured in the leachate was greatest from Togo and Uganda PR mixtures, much less from Zimbabwe PR, and virtually nil in all but the highest pyrite treatments for both Tanzania and Malawi igneous PR mixtures. Citrate-soluble P was a less reliable predictor of P release than total P and the percentage of CO₂, Al, and Fe in the PR and associated minerals. Lowell and Well (1995) reported that high pyrite levels with low-quality rocks generated P release comparable with that from untreated high-quality rocks. The addition of Fe from the pyrite apparently did not lead to precipitation of substantial amounts of P as it was released from PR. The rocks responded very differently to the pyrite treatment. The authors concluded that although the method is promising for some rocks (e.g. Togo and Uganda), it does not appear to be useful for other phosphate rocks, such as those from Malawi (Lowell and Well, 1995).

Mechano-milling

Mechano-milling is a process where materials are ball-milled at high-energy to induce chemical and physical reactions. Lim (2001) investigated the effect of milling on the properties and agronomic effectiveness of six apatite phosphate rocks (PR) using x-ray diffraction, BET-N₂ surface area measurements, electron microscopy and solubility in 2% citric acid. Milling increased the solubility of PRs by increasing the proportion of amorphous material and reducing the size of remaining apatite crystals, however milling also caused agglomeration of particles, which reduced the surface area. Milling increased the unit-cell a dimension of apatite, possibly due in part to the formation of low reactive fluorapatite such as occurs during calcination. Solubility increased due to amorphisation. The fertilizer relative effectiveness of PRs based on phosphorus content of wheat was increased by a factor of up to three by milling. Lim (Lim et al., 2001) concluded that beneficiation of apatitic PRs by mechano-milling will greatly improve their agronomic effectiveness and may provide economically and environmentally superior options for the manufacture of phosphate fertilizers and utilization of impure PRs.

INVESTMENT COSTS

Although the estimated cost of investment in mining, infrastructure, processing and fertilizer manufacturing will vary greatly from one deposit and one country to another, the following order of magnitude investment costs for the main phases of the development of phosphate rock resources and the major potential manufacturing technologies, provide an indication of the relative costs.

Mining and beneficiation

The cost of investment in mining, beneficiation, infrastructure and processing depends on a number of complexly inter-related factors. For mining and mineral beneficiation (concentration) these factors include:

Mining: annual production; total reserves (life of mine); thickness, structural regularity, continuity and homogeneity of phosphate rock deposits; overburden thickness (stripping ratio); life of mine; mode of exploitation (open-cast or underground mining); hardness of phosphate rock.

Grinding and beneficiation: annual production; chemistry, mineralogy and hardness of phosphate rock and size distribution of phosphate minerals; work index; beneficiation technology (e.g. size fractionation by dry or wet screening, magnetic separation, flotation, and/or calcination).

Average surface operation phosphate rock mining and beneficiation production costs in 1989 were US\$ 33.4/tonne whereas underground operation phosphate rock production costs were US\$ 46.5/tonne (Fantel et al., 1989). These costs increase to \$36 and \$50/tonne respectively if converted to 1994 prices using the US Industrial Production Index (World Bank International Financial Statistics Yearbook, 1995). Direct mining costs in major phosphate rock mines in west Africa (1983 prices) were US\$ 2.60/tonne for an ore with a total production cost of \$31/tonne of concentrate (McClellan and Notholt, 1986) although these costs increase to \$3.6 and \$43/tonne respectively if converted to 1994 prices. Prices of high-grade phosphate rock ex-North Africa varied between US\$ 38 and US\$ 42 in 1991-93 (FAO, 1995: Current World Fertilizer Situation and Outlook, 1991/92 - 1997/8).

Grinding costs for highly indurated ores will be high (15-20 kWh/tonne) compared with softer sedimentary phosphate rocks (10-12 kWh/tonne, McClellan and Notholt, 1986). It is difficult to assign a global figure to beneficiation costs as these are process specific and vary widely. Some processes, such as flotation and calcination are particularly expensive. In West Africa, McClellan and Notholt (1986) reported that beneficiation costs were \$20/tonne of concentrate and that calcination added at least \$3-4/tonne to the beneficiation costs (equivalent 1994 costs would be approximately \$25 and \$4-5 respectively).

Estimation of the capital investment and production costs for a major phosphate rock deposit (Table 6) illustrate that the capital investment required for a developed site results in production costs which are approximately the same as the current world market price of phosphate rock, whereas the much higher investment costs for an undeveloped site result in production costs which are approximately twice current world market prices.

Table 6 Estimated investment and production costs for phosphate rock*

	Developed site	Undeveloped site
Investment Costs (US\$/annual tonne)		
Plant investment	81.1	307.3
Working capital	5.5	8.1
Total capital investment	86.6	315.4
Production Costs (US\$/tonne)		
Mining	9.1	9.1
Beneficiation	11.7	11.7
Storage, administration, and other charges	4.5	4.5
Operating costs	25.3	25.3
Depreciation	4.2	15.2
Transportation and loading	4.5	10.8
Capital charges (10%)	8.7	31.5
Total production costs	42.7	82.8

* cost calculations based on production of 3 million tonnes per year of concentrate from low-grade ore with low recovery and high processing requirements; adapted from McClellan and Notholt, 1986, Table 7; US\$/annual tonne 1984 prices converted to 1994 prices using US Industrial Production Index, World Bank International Financial Statistics Yearbook, 1995.

The estimates of capital investment costs for a range of scenarios representing small and large scale, soft and hard rock, surface and underground mining and mineral beneficiation are illustrated in Table 7. Although it is difficult to make direct comparisons between the costs for the different scenarios, the capital cost/annual tonne of phosphate rock extracted from surface mines is approximately US\$20. The total capital investment per annual tonne of product (marketable concentrate) for large mines in developed sites (i.e. with a developed infrastructure) is about US\$65/tonne marketable concentrate although this rises to US\$80-95/annual tonne if the capital costs of permitting, pre-mining and reserves are included. The capital investment per tonne of marketable concentrates is much higher at an undeveloped site where it rises to US\$315/tonne for a large, soft rock mine (3 million tonnes concentrate per year) and US\$460 for a small, hard rock mine (35,000 tonnes concentrates per year). These are *order of magnitude* estimates and should be treated with due caution.

Manufacture of fertilizer products

The investment costs for manufacturing will vary according to the processing technology, annual production, expected life of plant, cost and availability of raw materials, location of plant, risk and capital investment criteria, quality of the phosphate rock, and availability of raw materials (including sulphuric acid).

Infrastructure capital investment costs will depend on the whether the phosphate rock deposit is located in an industrially developed or undeveloped environment; on the nature of transport connections between the phosphate rock deposits, manufacturing plants and markets; existence of utilities (water, electricity etc.), housing, and other infrastructure as well as the human resources required to develop and run the mine and processing facilities.

Table 7 Mining and beneficiation capital investment costs for eight hypothetical phosphate rock mines

	1	2	3	4	5	6	7	8
Mine characteristics								
Mine scale	Small	Small	Small	Medium	Large	Large	Large	Large
Hard / soft rock	Hard	Hard	Hard	Soft	Soft	Soft	Soft	Soft
Surface (S) / underground (U)	S	U	S	S	S	S	S	S
Site	UD	UD	UD	UD	UD	D	D	UD
Capacity t/d rock	150	150	1,100	na	na	na	na	na
Capacity Mt/y concentrate	na	na	0.035	0.16	±2.0	na	±3.0	±3.0
Costs								
Mine capital cost	0.85	1.8	na	na	na	na	na	na
Mining capital investment/annual tonne rock	19	40	na	na	na	23	na	na
Capital investment mining and concentration	na	na	16.2	64.1	185	na	na	na
Concentration capital investment/annual tonne concentrates	na	na	na	na	na	42	na	na
Capital investment/annual tonne concentrates	na	na	460	400	93	65	86	315

Costs US\$ millions, 1994 prices; prices converted using US Industrial Production Index, World Bank International Financial Statistics Yearbook, 1995.

1,2 Lewis et al., 1983, Table 13-3; based on **used** major equipment.

3 Unpublished feasibility study, site in sub-Saharan Africa; based on **new** major equipment; low-grade ore (10-12% P₂O₅).

4 Tapoa, Niger feasibility study (Van Kauwenbergh et al., 1991a)

5 Bofal-Loubboira feasibility study (Van Kauwenbergh et al., 1991a); including capital costs of transport and handling facilities.

6 Phosphorus and Potassium, No. 198, 1995 (p. 36); not including permitting, pre-mining and reserves capital costs (US\$29.75 million).

7,8 McClellan and Notholt, 1986, Table 7; low grade ore, low recovery, high processing requirements

na not available

NOTE Consult sources for basis of investment cost calculations

Small scale plants. Capital investment for the manufacture of a range of fertilizer products suitable for small-scale production and small-scale markets are illustrated in Table 8. These IFDC investment estimates for plants with annual production of about 20,000 tonnes P₂O₅/year are compared with more recent IFDC capital investment costs for 30,000 tonnes P₂O₅/year production units (Schultz and Parish, 1989) and with capital investment cost estimates from a feasibility study for 10,000 tonnes P₂O₅/year SSP and Fused Magnesium Phosphate (FMP) plants at an undeveloped site in sub-Saharan Africa (Table 9). The IFDC total capital investment costs are in proportion to the plant outputs (Table 9). Although the total capital investments for the 20,000 tonne/year and 10,000 tonne/year plants are similar, the capital investment costs per annual tonne are approximately double for the smaller scale plants reflecting both production scale and higher costs of establishing a plant at an undeveloped site. Economic analysis indicated that the return on investment for the proposed SSP and FMP projects at the undeveloped site in sub-Saharan Africa would be negative; the phosphate rock deposit remains undeveloped.

Vanvuuren and Hamilton (1992) investigated the financial and economic viability of developing a small-scale phosphate mine and beneficiating operation that would be used to produce rock phosphate (for direct application) for distribution to farmers in the Mbeya region of Tanzania. They conclude that local production of phosphate fertilizer would reduce both fertilizer shortages and foreign currency requirements through import substitution. Furthermore, they considered that it would also benefit the local economy by providing employment in the mining and beneficiating operation. Calculations based on preliminary data showed that the development of the project would be highly beneficial for farmers, for the local economy of the region, and for the nation.

Table 8 Estimates of total capital investment (US\$ millions) required for small scale production of ground phosphate rock (PR), SSP, granulated SSP, PAPR, and granulated PAPR ¹

	Ground PR	SSP	Granulated SSP	PAPR	Granulated PAPR
Plant capacity, tpd					
Product	200	315	315	270	270
P ₂ O ₅	60	60	60	60	60
P ₂ O ₅ content of product	30	19	19	22	22
Annual production - product	66000	103950	103950	89100	89100
Annual production - P ₂ O ₅	19800	19800	19800	19800	19800
Direct plant cost					
PR grinding plant	1.47	1.47	1.47	1.47	1.47
Sulphuric acid plant	-	2.81	2.81	1.83	1.83
SSP or PAPR plant	-	0.97	3.91	0.88	3.59
Storage and handling facilities	0.92	2.20	2.20	1.83	1.83
Utility facilities	0.31	1.22	1.47	0.98	1.34
General service facilities	0.31	0.73	0.86	0.61	0.73
Other costs ²	1.05	3.29	4.45	2.66	3.78
Total Plant Cost	4.04	12.68	17.16	10.26	14.58
Other fixed investment costs ³	1.22	4.52	6.75	3.95	5.76
Total fixed investment	5.39	17.58	23.93	14.21	20.35
Working capital	0.84	2.88	3.49	2.20	2.77
Total capital investment	6.10	20.46	27.42	16.41	23.11

¹ adapted from Schultz, (1986); Table 11; 1986 prices converted to 1994 prices using US Industrial Production Index, World Bank International Financial Statistics Yearbook, 1995; refer to Schultz 1986 for basis of cost estimates, cost estimating factors etc.

² including engineering, supervision, construction overhead and expenses, contractor's fee

³ including spare parts, start up & related expenses, project management services, contingencies, interest during construction

Large scale plants. Capital investment cost estimates for the manufacture of TSP and DAP, suitable for large-scale production and large-scale markets are illustrated in Table 10. These investment estimates are for plants with annual production of 120,000 and 150,000 tonnes P₂O₅/year. It is clear that the estimates extrapolated from 1980 UNIDO publication are less than half those extrapolated from Schultz and Parish (1989). The former estimates are for a developed site whereas the higher costs are for a developing country location. Differences in raw material sources used for the capital investment estimates will also be reflected in the capital investment estimates. It is emphasised that these are *order of magnitude* estimates and should be treated with due caution.

Table 9 Comparison of investment costs for small-scale fertilizer manufacturing plants (US\$ 1994 prices¹)

Fertilizer product	tonnes P ₂ O ₅ / year	Total capital investment (US\$ millions)	Capital investment cost (US\$)/tonne P ₂ O ₅ in product
PR ²	20,000	6	310
PR ³	30,000	10	330
SSP ²	20,000	20	1030
Granulated SSP ²	20,000	27	1380
Granulated SSP ³	30,000	37	1220
PAPR ²	20,000	16	830
Granulated PAPR ²	20,000	23	1170
Granulated PAPR ³	30,000	34	1130
SSP ⁴	10,000	20	2000
Fused Magnesium Phosphate ⁴	10,000	22	2200

¹ prices converted to 1994 prices using US Industrial Production Index, World Bank International Financial Statistics Yearbook, 1995

² data from Table 8 above

³ data from Table 5, Schultz and Parish (1989).

⁴ data from unpublished feasibility study at undeveloped site in sub-Saharan Africa (see Table 7 above for mining and beneficiation investment costs)

Discussion and conclusions

It was reported recently that a minimum tender of \$US 452 million has been received for the construction of a new mine and chemical complex in Syria which would also involve a major expansion to the existing rock mines (Metals & Minerals Annual Review, 1993 p. 101). It is assumed that annual production would be of the order of 150,000 to 300,000 tonnes phosphate rock and 50 - 100,000 tonnes P₂O₅ as TSP/DAP). The African Development Bank is reported to have offered a loan of \$US 60 - 80 million to establish a fertilizer industry based on the Sukulu deposit (29 million tonnes P₂O₅ resources) but further capital was being sought in 1988. A new beneficiation plant at the Foskor plant in South Africa (presumably with a design capacity greater than the current average annual production of 2,500,000 t 39% P₂O₅, equivalent to about 1 million t P₂O₅/y) has an estimated cost of \$US 810 million (R 3 billion). These diverse investment estimates indicate that although the capital investment costs given in Tables 7 to 10 may be adequate for order of magnitude estimates for phosphate rock mines, beneficiation plants and fertilizer manufacturing plants of the stated capacities, characteristics and locations, it is not possible to use these figures as guidelines to estimate the precise investment costs for mines and plants of smaller or larger capacities, different raw material qualities and sources and different locations. The influence of scale and methods of mining, beneficiation and fertilizer production, together with location and infrastructure exert a major influence on investment cost estimates for a particular site and deposit.

PR resources large enough to supply a large-scale mine exist at very few locations in sub-Saharan Africa. Even in these cases, the mining, beneficiation and fertilizer manufacturing capital investment costs may be so high, especially for undeveloped sites requiring major investments in infrastructure, that it is unlikely that their utilisation could ever be justified economically. The situation may be different for small-scale mining and fertilizer production where capital investments are likely to be relatively small. However, each case will be substantially different and it is difficult to make any general conclusions on the potential economic viability of small-scale mines and fertilizer manufacturing plants. Each phosphate rock deposit requires a preliminary (order of magnitude) economic evaluation prior to the initiation of full-scale feasibility studies.

Table 10 Estimated capital investment costs (US\$ million¹) for large TSP and DAP production facilities in developed and developing country locations

	TSP	DAP
<i>Capital Investment: Developed country location²</i>		
Sulphuric acid plant	20.6	25.6
Phosphoric acid plant	29.9	36.8
Granulation	27.2	19.1
NH ₃ storage	-	3.6
Product storage	3.3	3.2
Total	81.0	88.2
<i>Capital Investment: Developing country location³</i>	228.0	259.0

¹ 1978 prices converted to 1994 prices using US Industrial Production Index, World Bank International Financial Statistics Yearbook, 1995

² adapted from UNIDO, 1980, Table 1, p.220; these cost estimates should be treated with caution - they are based on a number of premises that are discussed in detail in UNIDO, 1980. Production of 120,000 tons of P₂O₅ per year, 297 operating days.

³ from Schultz and Parish (1989), Table 5 to which reference should be made for details of cost basis. Production of 150,000 tons of P₂O₅ per year.

CONSTRAINTS FOR UTILISATION

Introduction

Many developing countries wish to utilise indigenous phosphate rock resources for a variety of reasons including independence of foreign suppliers and the vagaries of world market prices; import substitution; potential saving of foreign exchange currently used for importing phosphate fertilizers; improved food security; and generation of local employment. Production of phosphate fertilizers in sub-Saharan African countries is much less than demand so there is some potential for mobilising new phosphate rock resources, either for the manufacture of phosphatic fertilizers or for use as direct application fertilizer. The undeveloped phosphate rock deposits in sub-Saharan Africa exhibit a wide range of characteristics with respect to their geology, chemistry, mineralogy, and amenability to beneficiation. Many of these deposits have unusual geological, mineralogical and chemical characteristics, which will present major problems in mining, beneficiation and processing. Although it is technically possible to produce fertilizer products from many of the phosphate rock deposits in sub-Saharan Africa, this may not be technically feasible in some cases.

Utilisation of phosphate rock resources is constrained by a complex range of interrelated economic, technical, environmental and socio-political factors that determine the economic potential of individual phosphate rock deposits (Van Kauwenbergh, 1991). Utilisation of a particular phosphate rock deposit is inevitably linked to its economic potential, which depends on a spectrum of factors, any of which may hinder it being brought into use. These include:

- quantity of phosphate rock resources and reserves
- geological characteristics of the deposit
- quality and grade of the phosphate rock deposit
- stripping ratio, ore waste and concentration ratios
- technical problems of mining and beneficiation
- recovery efficiency; quality and grade of the beneficiated output
- method, scale and cost of mining, processing and fertilizer manufacturing plants and technology
- availability and price of sulphuric acid for manufacture of fertilizer products
- location of the phosphate rock deposit relative to processing facilities, ports and consumers (market) including transport costs
- size and location of local and international markets
- availability of equipment
- existence of infrastructure or cost of installing infrastructure (roads, power lines, etc.)
- world market supply and productive capacity situation
- market price of phosphate rock and fertilizer products; influence of donations of manufactured fertilizers on local market prices
- fertilizer price subsidies and government fertilizer policy including investment strategies
- financial constraints including evaluation and feasibility study costs; capital and production costs; availability of investment capital or donations of processing equipment, plant etc.
- environmental impacts of mining, processing and fertilizer application
- agronomic effectiveness of fertilizer products (ground phosphate rock and/or manufactured fertilizers)
- availability and technical qualifications of human resources
- availability and quality of information on phosphate rock resources, processing and marketing.

Quantity of resources

The majority of the major phosphate rock deposits in the world comprise one or more, 1 to 10 m thick beds of sedimentary phosphate rock that is mined by open pit methods using huge earth moving equipment

including drag lines and bucket excavators. Annual production from the larger mines is 3 - 5 Mt and it is considered that any important new mines will produce 5 - 10 Mt/year with sufficient reserves of recoverable phosphate rock (100 - 200 Mt) to cover the high capital costs of establishing a new mine.

In general, major economic sedimentary phosphate rock deposits are associated with particular periods in geological time (Cook and McElhinny, 1979). The major Mediterranean or Tethyan Phosphogenic Province, to which the commercial deposits in Togo and Senegal belong, covers extensive areas of northern and western Africa. In many other sectors of sub-Saharan Africa, the palaeogeographic conditions are not particularly favourable for the development of major sedimentary phosphate rock deposits. In these situations, there would be little justification for making major investments in geological exploration and resource evaluation programmes directed towards the discovery and utilisation of phosphate rock for export or large-scale phosphoric acid, TSP or DAP manufacture. Small phosphate rock deposits may occur in unfavourable palaeogeographic environments, but the quantity of resources may constrain or prevent their utilisation for export or as feed for a fertilizer-manufacturing complex. However, smaller phosphate rock deposits may be of adequate size to supply a local demand for direct application fertilizer, assuming that the ground phosphate rock is agronomically and economically effective, and acceptable to the local farmers. In other cases, the quantity of resources may be adequate to supply a small SSP or PAPR plant. In some cases, resource estimates overlook the critical distinction between *resources* and *reserves* and do not consider the technical and economic feasibility of producing a marketable product, be it ground rock or phosphate rock concentrates for a fertilizer plant.

Quality of resources

The quality of a particular phosphate rock, indicated by its mineralogical, chemical and textural characteristics, will profoundly affect its economic potential and hence its suitability for various types of beneficiation adaptability for chemical processing by various routes, and suitability for use as direct-application fertilizers. The factors that are most important in the assessment for direct application are grade, suitability for beneficiation, and the reactivity of the apatite (Van Kauwenbergh, 2001a). The quantity and nature of impurities in a particular phosphate rock may place major constraints on its development and use as primary raw material for fertilizer manufacture or as direct application fertilizer. Reduction of ore grade is usually caused by the dilution of the phosphate bearing minerals (normally francolite or apatite), by other minerals such as quartz, clay and carbonate minerals. The impurities in these minerals (Mg, Fe, Al, CO₂, U and Cd) affect the chemical processing of the phosphate rock and may prevent the production of fertilizers of acceptable agronomic quality.

Some of the undeveloped phosphate rocks in Sub-Saharan Africa contain high concentrations of major element impurities, such as iron, aluminium, silica and carbonates which make the processing of these phosphate rocks and the production of concentrates of the required quality for fertilizer manufacture both technically difficult and very expensive. Many of the phosphate rocks have characteristics which would necessitate the development of complex metallurgical and chemical beneficiation processes if phosphate rock concentrates were to be produced with the required quality, price and specifications for a particular end-user (e.g. fertilizer manufacturer or the farmer if the phosphate rock was to be used for direct application). In some cases, for example the Nkombwa phosphate deposit in northern Zambia, the low quality and unusual mineralogical and chemical composition of the phosphate rock resources prevents their beneficiation to marketable concentrates suitable for fertilizer manufacture.

Some examples of mineralogical and chemical characteristics that may constrain utilisation are:

- Many sedimentary phosphate rocks contain elevated concentrations of Fe, Al and Mg, mainly as clay minerals, weathered oxides and hydroxides that may be difficult to remove during beneficiation in order to meet strict phosphate rock quality standards for production of SSP, and phosphoric acid. Calcination of Fe and Al ores increases their agronomic effectiveness whereas calcination of apatitic phosphate rock decreases agronomic effectiveness (Chien and Hammond, 1991).

- Highly siliceous ores are frequently difficult to mine and expensive to grind and process, due to their hardness and erosive properties. Beneficiation costs may also be high for siliceous ores. Impurities may be produced in chemical fertilizer products by some silicate minerals.
- Sedimentary phosphate rocks frequently contain high concentrations of carbonate minerals such as calcite and/or dolomite. Such ores are unsuitable for production of SSP and phosphoric acid unless flotation or calcination, both of which are costly, can be used to remove the carbonate minerals. High-energy consumption and the need to enhance P₂O₅ concentrations may constrain the utilisation of some carbonate-rich sedimentary phosphate rocks.
- High concentrations of elements that may be potentially harmful if they are transferred via the food chain to people. These include Cd, Hg, As, V, Cr, and U.
- High concentrations of certain elements (e.g. Cl) and other impurities (e.g. organic matter) that cause processing problems such as corrosion.

Acceptable levels of the major chemical impurities decrease linearly with decreasing phosphate rock grade (Lehr, 1984, in McClellan and Notholt, 1986). These are summarised in Table 11 below.

Table 11 Quality requirements for the production of phosphoric acid and practical levels of impurities in phosphate rock.

Chemical variable	Range or limit
P ₂ O ₅	28-42 wt%
SiO ₂	0.7-8 wt%
CaO: P ₂ O ₅	1.32 - 1.61 in apatites
Al ₂ O ₃	0.2-3 wt%
Fe ₂ O ₃	0.1-2 wt%
MgO	0.2-0.6 wt%
Fe ₂ O ₃ + Al ₂ O ₃ : P ₂ O ₅	< 0.10
MgO: P ₂ O ₅	< 0.022
Fe ₂ O ₃ +Al ₂ O ₃ +MgO: P ₂ O ₅	< 0.12
Organic carbon	0.1-1.5 wt%
F	2-4 wt%
F:P ₂ O ₅	> 1.05
Cl	< 300 mg/kg (0-500 mg/kg [*])
U	average about 100 mg/kg (35-400 mg/kg [*])
Potentially harmful elements(Cd, As, Pb, Cr, Hg)	10 mg/kg
Micronutrients (Cu, Zn, Mn)	variable mg/kg levels

Sources : McClellan and Notholt (1986 Table 8) and Notholt (1994b, Table 4*).

Phosphate rock deposits have sometimes formed as a result of weathering over many millions of years. This particularly applies to the igneous deposits in east and southeast Africa (such as Dorowa, in Zimbabwe), but also applies to some of the sedimentary phosphate rock deposits (e.g. Minjingu in Tanzania). Whereas the mining and processing of such phosphate rock resources may be relatively easy, weathering may reduce the reactivity of the phosphate minerals and this may constrain their use as direct application fertilizer or as raw materials for chemical fertilizers. In other cases, the weathered material is highly indurated so high cost, hard-rock mining techniques will be required, as opposed to the low-cost mining procedures employed in the majority of international-scale phosphate rock deposits.

If the phosphate rock is to be developed for use as direct application fertilizer, the type of apatite is critically important to the potential agronomic effectiveness of the phosphate rock. Highly carbonate substituted francolites typical of sedimentary ores will be much more effective than many apatites in igneous ores. The reactivity (solubility) of phosphate rocks, and hence their potential agronomic effectiveness, is conventionally determined on the basis of dissolution in reagents such as citric acid, formic acid and neutral ammonium citrate (Table 12), or by the evaluation of in-soil dissolution (Hanafi et al., 1992; Riggs and Syers, 1991; Robinson et al., 1994).

For greater detail on the quality and characterisation of individual phosphate rock resources, refer to the country profiles. The Appendices of IFDC (1988) include characterisation data for Ethiopia, Kenya, Tanzania, Uganda, Zambia, Zimbabwe and beneficiation results for the Chilembwe PR from Zambia.

Table 12 Reactivity of phosphate rocks and concentrates from sub-Saharan Africa

Location	P ₂ O ₅ (wt %) in rock / concentrate	Solubility in neutral ammonium citrate (wt % P ₂ O ₅)
<i>Igneous deposits</i>		
Malawi (Tundulu)	27.7	1.6
Uganda (Sukulu)	37.9	1.2
Zambia (Chilembwe)	17.1	1.4
Zimbabwe (Dorowa)	33.1	0.7
<i>Sedimentary deposits</i>		
Angola (Cabinda)	37.0	4.5
Benin (Mekrou)	29.3	1.9
Burkina Faso (Kodjari)	25.4	2.3
Mali (Tilemsi)	28.6	4.2
Niger (Parc W, Tapoa)	28.5	2.6
Niger (Tahoua)	28.0	1.5
Senegal (Matam)	28.7	4.5
Senegal (Taiba)	37.4	3.1
Senegal (Thies, Pallo)	32.0	12.0
Tanzania (Minjingu)	29.0	5.6
Togo (Hahotoe)	35.7	3.1

Sources include: McClellan and Notholt, 1986; Appleton, 1994, Van Kauwenberg et al, 1991

Mining and beneficiation problems

Phosphate deposits in sub-Saharan Africa exhibit a wide range of geological, chemical and mineralogical characteristics that may affect the economic viability of mining and beneficiation. These include the thickness of phosphate rock beds in sedimentary deposits; overburden thickness and ore-waste (stripping) ratio; physical characteristics of the phosphate rock such as hardness; mining recovery efficiency and dilution with gangue (waste rock); beneficiation recovery efficiency. All these factors have a substantial influence of the mining and beneficiation costs and hence on the economic value of phosphate rock resources. Ideally phosphate rock deposits should be amenable to the production of large tonnages by opencast mining of thick, nearly horizontal and structurally undeformed beds of high-grade phosphate rock with uniform physical and chemical characteristics that permit efficient beneficiation (upgrading) of the phosphate rock to a product suitable for either domestic or international markets. These ideal conditions are not met in the case of most of the undeveloped phosphate rock resources in sub-Saharan Africa, so if they are to be utilized, a range of mining, beneficiation and processing techniques will have to be adapted to the specific characteristics of each individual deposit.

Many of the deeply weathered igneous phosphate rock deposits in east and south-east Africa can be cheaply mined but high mining and grinding costs of some hard-rock igneous deposits, including the Tundulu carbonatite phosphate rock in Malawi and the Chilembwe deposit in Zambia, may prejudice their utilisation. In addition, the economic potential of an individual phosphate rock deposit will change with time as new mining and mineral processing techniques are developed. For example, whereas the minimum grade for the production of a commercial concentrate used to be about 20% P₂O₅, this has now been reduced to less than 10%.

Most phosphate rocks have to be beneficiated to produce a marketable phosphate rock with more than 30% P₂O₅. Size fractionation, frequently following carefully controlled grinding, may provide a concentrate of

acceptable quality. In other cases, simple size fractionation does not enhance concentrate grade and more complex beneficiation processes will be required, thereby substantially increasing the cost of the phosphate rock concentrate. Beneficiation by washing and screening can be relatively inexpensive but if the more complex and expensive flotation and thermal treatments are required to produce a marketable concentrate, this may prevent the commercial development of a phosphate rock resource. Washing, screening and flotation will be more difficult and expensive in semi-arid countries where water may not be readily available. In regions where there is a shortage of fresh water, and the sea is not very far from the beneficiation plant, sea water may be used instead of fresh water in flotation of carbonate-rich phosphate rock resulting in an appreciable reduction in operating costs as well as conservation of fresh water resources (Ozbelge et al., 1993).

The chemical and mineralogical characteristics of many of the phosphate rock deposits in sub-Saharan Africa prevent their utilisation under present economic conditions using beneficiation technologies currently available. This applies particularly to phosphate rock resources with high concentrations of carbonate minerals (e.g. Panda Hill in Tanzania) or in deposits in which P is held in earthy secondary phosphates, for example at Kaluwe in northern Zambia, from which the production of commercial grade concentrates may be either technically or economically impossible.

Beneficiation of low-grade igneous deposits used to be a problem but is now technically feasible. However the high capital costs of setting up a beneficiation plant for low-grade deposits may prevent their utilisation.

Further detail on beneficiation of phosphate rock resources may be obtained from a number of sources (Benson and Martin, 1996; Briggs and Mitchell, 1990; Chileshe et al., 2000; DANIDA, 2000; Lawver et al., 1978; Lombe, 1991; McClellan et al., 1985; Notholt, 1994a; Prasad et al., 1998).

Processing problems during fertilizer manufacture

The quality of phosphate rock and beneficiated products will affect the economics and viability of processing. Phosphate rocks with low carbon dioxide and organic carbon concentrations, low corrosion potential and low acid consumption will have the greatest potential for successful utilisation.

Location and transport costs

Phosphate rock is a low value, high volume commodity with high transport costs, so the economic potential of a phosphate rock deposit will be determined to a large extent by its location in relation to domestic and international markets. Most commercial phosphate rock deposits are located close to the coast and in countries with efficient deep-water port facilities. If the transport infrastructure in a country is poorly developed and especially if railways or slurry pipelines are not available to transport the phosphate rock, it may be more cost effective to import high-analysis fertilizers such as DAP, rather than to develop local resources. Phosphate rock resources sited in geographically remote and/or unfavourable locations at great distances from markets or from efficient transport facilities are unlikely to be economic to utilise for international markets, whereas local or perhaps regional use may be an economically viable option. Conversely, for agricultural areas located at a great distance from the coast, especially in landlocked countries, it may be more cost effective to develop local phosphate rock resources for use as direct application fertilizer rather than to import manufactured fertilizers. High transport costs may be of less importance if the phosphate rock can be converted into a high value manufactured fertilizer product, although the quantity and quality of the phosphate rock resources may prevent this.

Transport charges are such a major factor affecting the economic value of fertilizer raw materials that this may tip the balance in favour of mobilising national resources. High-grade concentrates, such as Sukulu (40% P_2O_5) will have a significant transport cost advantages over typical lower grade sedimentary phosphate rocks (26-36% P_2O_5).

Infrastructure

Many of the phosphate rock deposits in sub-Saharan Africa are in remote, undeveloped locations lacking the infrastructure required for their development. This may include roads, railways, port facilities, utilities (water, electricity), and housing. Water supply may be a major problem in semi-arid countries. The high capital cost of installing the necessary infrastructure will constrain the utilisation of many phosphate rock resources.

World market supply and capacity

Although phosphate fertilizer demand is growing strongly in developing countries, an increasing proportion of the demand is being satisfied with imported finished fertilizer products (Metals and Minerals Annual Review, 1995). Oversupply and over-capacity in the world market has precluded most new investment and the utilisation of major new phosphate rock deposits. Capacity use is increasing gradually (69% in 1993 to 85% in 1999; Mining Annual Review 2000) and it is predicted that both demand and production will remain at this level over the next few years. Even though there is currently oversupply of phosphate raw materials and excess production capacity in the international market, there are a number of major world-class phosphate deposits, including the Farim deposit in Guinea Bissau, for which potential investors are being sought. In addition, new capacity will need to be developed to replace declining reserves in many major production centres over the next five to ten years (Mining Annual Review, 2000). However, world market conditions will preclude the large-scale development of most of the undeveloped phosphate rock deposits in sub-Saharan Africa as few have the quality and quantity of resources suitable for utilisation to supply world markets. Development for local or regional markets may be an option in some cases.

Economic constraints

There is a wide range of economic constraints to the development of a phosphate rock for in-country (domestic) use. These include the relative costs of using imported phosphate rock or imported fertilizer compared with the cost of developing local resources based on the actual and projected demand for phosphate fertilizers. A comprehensive economic evaluation of all related factors is required prior to making a decision on the utilisation of new phosphate rock resources. Manufacturing, distribution and marketing costs, as well as foreign exchange requirements to provide capital for development compared with foreign exchange costs of fertilizer importation, are important factors that will constrain decisions related to development of domestic phosphate rock resources.

The economic viability of the developing new phosphate rock resources depends on a range of economic factors including the relationship between development cost, capital investment as well as the value and potential life of a phosphate rock deposit (which is largely control by the quantity and quality of the resources). In some cases, the high investment required will render the phosphate rock deposit sub- or marginally economic (e.g. Chilembwe in Zambia).

Government and donor support

Adequate financial resources are required to cover the evaluation of the phosphate rock deposit. If the outcome of the evaluation is positive, then major capital investments will be required for mining, infrastructure, and in some cases the parallel development of fertilizer manufacturing facilities. In some cases, technical assistance has been provided for evaluation and processing plant donated to help bring the phosphate rock resources into use (e.g. in Burkina Faso and Mali; see country profiles), thereby removing a major constraint to their utilisation.

Large-scale direct use of PR in the past has been usually a national programme to trigger agricultural intensification through soil improvement. For example in South Africa, the government previously invested in the improvement of soil fertility for white commercial farmers by support for liming and increasing P-availability (Henk Breman, personal communication 22 June 2001). Even the World Bank accepts that support is required for investments like large-scale PR application such as the proposed Soil Fertility Initiative (Gerner and Baanante, 1995).

Rural credit is rare in most of Africa, and is generally not accessible for those small holders that cannot afford to pay for fertilisers. In cases where credit is accessible, it is usually available for one single growing season, and not for several years. This is a problem because the economic benefits from directly applied phosphate rock usually accrue over a number of years because of the residual effect associated with the slow release of P.

Fertilizer prices and subsidies

The local market price of phosphate rock and fertilizer products, fertilizer price subsidies and government fertilizer policy may constrain the utilisation of new phosphate rock resources. Some sub-Saharan African countries receive donations of manufactured fertilizers and this may influence local market prices. In sub-Saharan Africa, the utilisation of some phosphate rock deposits has only been possible economically because equipment and plant have been donated or because of Government subsidies. This situation applied in Mali, but when the phosphate rock project was privatised and subsidies and credit programmes discontinued, the phosphate rock project ceased to function (personal communication, S Van Kauwenbergh, October 1995).

Environmental factors

Environmental factors may constrain the use of phosphate rock resources where mining and mineral processing are likely to cause significant damage to the environment and pollution of surface and ground water supplies. In other situations, high concentrations of potentially harmful elements, such as Cd, in the phosphate rock may prevent its use for fertilizer manufacture.

Agronomic factors

Agronomic trials and an assessment of the relative agro-economic effectiveness of domestic phosphate rock resources compared with imported fertilizers will provide information required to assess the economic benefits of using a particular phosphate rock resource. Use of a phosphate rock resource will be constrained by the agronomic effectiveness of the fertilizer products for a range of crops as well as by the acceptability of the products, both in financial terms and ease of use, by the farmers. Climatic, soil, and crop characteristics will also constrain the effectiveness of both ground phosphate rock and manufactured phosphate fertilizers. Ground phosphate rock may be both cheap and agronomically effective, but if the farmers do not like the product because of its dustiness, it will not be acceptable or economically successful. Many examples can be quoted of this problem, such as Mali, west Africa where farmers have not accepted ground phosphate rock mainly because they do not like its dusty characteristics during fertilizer application. Others including IFDC Africa Director Henk Breman (personal communication, 22 June 2001) are not convinced that 'dustiness' is a major constraint if the phosphate rock is promoted and applied as a soil amendment that can be useful if other conditions (including N availability) are fulfilled. PR is too often promoted as a cheap replacement for chemical fertiliser (e.g. the "Burkina phosphate; l'engrais national" campaign). In addition, PR is too often tested where P is not the main limiting factor. For example, the Compagnie Malienne Des Textiles, supported by government, donors and manufacturers, re-launched the use of Tilemsi phosphate in the cotton zone, making it part of the cotton input package (and obliging farmers to buy it). This contradicts agronomic advice that PR has limited impact on productivity because P is often not limiting any more in the ancient cotton basin, largely because of the extensive use of 'cotton fertiliser' over a long period (Henk Breman, personal communication, 22 June 2001). See Mokwunye (1986) and Chien (1995b) for further details on agronomic factors.

Human resources

Highly qualified personnel are required during the assessment, development and production stages of the phosphate rock resources. This may be a major constraint in some developing countries in sub-Saharan Africa.

Information

Decisions concerning the development of phosphate rock resources can only be taken if the information required to make a decision on the economic feasibility is both reliable and comprehensive. In some cases, information on all aspects of a PR deposit, including geology, mineralogy, chemical composition, resources, reserves, mineral processing, mining, marketing etc. is comprehensive and complete. However, for many of the sub-Saharan Africa deposits, information is incomplete and of variable quality.

Farmers' perceptions and attitudes

Soil fertility enhancing technologies (SFETs), such as the use of ground phosphate rock, have been promoted in the West African Semi-Arid Tropics for many years with limited success. Enyong, Debrah, et al. (1999) examined farmers' perceptions and attitudes towards introduced soil-fertility enhancing technologies in western Africa and concluded that farmers are knowledgeable about, and practise SFETs that encompass rock phosphate application, crop residue and farm yard manure, chemical fertilizer and crop rotation to combat soil fertility decline. Their attitudes to and rationales behind adoption decisions are influenced by a number of factors including land use policies, labour resources, food security concerns, perceived profitability, contribution to sustainability and access to information. Enyong, Debrah, et al. (1999) observed that some of these factors are beyond farmers' control and require a broad and integrated effort from research, extension and government to promote the use of the SFETs (including PR) in the region.

Conclusions

A few major sub-Saharan African phosphate rock deposits produce phosphate rock for export (e.g. Togo and Senegal), and national downstream chemical fertilizer facilities (e.g. Senegal, South Africa, Togo) some meet nearly all domestic requirements for phosphate fertilizers (Dorowa, in Zimbabwe). Others have, in the past, supplied small fertilizer manufacturing plants supplying local or regional markets (e.g. the Rhenania plant in Kenya using phosphate rock from Busumbu and the Tanga plant in Tanzania fed by the Minjingu phosphate rock deposit). Although the use of undeveloped phosphate rock resources is constrained by a wide range of factors, there is some potential for the development of small-scale mining and mineral processing which requires relatively low technology and low capital investment. There appears to be less potential for the use of known phosphate rock deposits in sub-Saharan Africa to supply the international market. Each deposit requires a thorough multi-disciplinary assessment before its potential for utilisation can be adequately evaluated.

ENVIRONMENTAL ISSUES

This sub-section of the report deals with the environmental issues related to heavy/hazardous elements contained in the rock phosphates or by-products derived from them. Phosphate rock and manufactured phosphate fertilizers contain a range of potentially harmful elements including As, Cd, Cr, Hg, Pb, Se, U and V. Of these, the greatest concern has been with the potentially harmful effects on humans of Cd and U. The accumulation of Cd in New Zealand agricultural systems as a result of the extensive use of phosphatic fertilizers manufactured from the Cd-rich Nauru phosphate rock, has been recognised as a potential problem following the appearance of unacceptable levels of Cd in some animal products (Bramley, 1990).

Disparate results have been reported concerning the effects of phosphate fertilizer use on Cd levels in soils and plants. In a recent World Bank-IFDC-ICRAF review (World Bank, 1994), it was concluded that few research studies have identified problems with Cd accumulation in agricultural soils due to phosphate fertilizer use. Observations from long-term fertilizer experimental sites in the tropics indicate that whereas Cd in soils has increased, no corresponding increase of Cd in plants was recorded. In other experiments it was demonstrated that the application of high-Cd NPK fertilizer (adding 12.5 $\mu\text{g Cd kg}^{-1}$ soil) significantly increased both extractable soil Cd and crop Cd concentrations, and that the highest Cd concentrations in crops were obtained when the high-Cd NPK fertilizer was applied (He and Singh, 1994a; He and Singh, 1994b; He and Singh, 1995). In the same experimental environment, it was found that application of phosphate rock containing the same level of Cd as the NPK fertilizer increased neither the extractable soil Cd nor the Cd concentration in plants. The low recovery of Cd from phosphate rock might be due both to low solubility of the phosphate rock and also to a generally lower recovery of Cd when the amount added increases. Whereas the DTPA- and NH_4NO_3 -extractable soil Cd were significantly increased by repeated applications of high-Cd NPK fertilizer, the increases in plant Cd concentration over the years were not consistent (He and Singh, 1995). Cadmium concentration in plants generally decreased with increasing soil pH confirming the view that maintenance of soil pH to above 6.5 may be the most effective way of limiting the uptake of Cd by crops (Phosphorus and Potassium, No.198, 1995). High organic matter content is also considered to play an important role in the retention of Cd in soil.

Iretskaya, Chien, et al. (1998) investigated the effect of acidulation of high cadmium containing phosphate rocks on cadmium uptake by upland rice. Greenhouse experiments were used to study the effect of acidulation of two PRs having high Cd content (highly reactive North Carolina phosphate rock (NC-PR) and low-reactive Togo-PR) on Cd uptake by upland rice grown on two acid soils. The results show that Cd uptake by rice grains followed the order of NC-SSP > NC-PR and Togo SSP > Togo PAPR > Togo PR. The results also showed that most of the Cd uptake was retained in rice roots and straw. Total uptake of Cd, Ca, and P by rice plant (root, straw, and grain) was higher from NC-PR than from Togo-PR. Cd concentration in rice grains showed no significant difference between NC-PR and Togo-PR, whereas Cd concentrations in root and straw were higher with NC-PR than that with Togo-PR.

In response to concern over the risks of cadmium passing into the human food chain, some western European countries have imposed strict limits on Cd concentrations in fertilizers. Proposed or implemented limits range from 35 mg Cd/kg P in the Netherlands to 200 mg/kg P in Germany and Belgium. However, Cd is not added to the soil only through the application of phosphate fertilizers. Other major Cd inputs include emissions from smelters, power stations, and waste incinerators as well as sewage sludge.

The cadmium concentration in a fertilizer depends not only on the type and source of the phosphate rock, but also on the manufacturing process. Cadmium concentrations are generally higher in sedimentary phosphate rocks compared with those from igneous sources (Table 13). Sedimentary phosphate rock from Senegal and Togo in sub-Saharan Africa contain up to 115 mg/kg Cd. Even average Cd

concentrations from these sources exceed the highest limiting value for fertilizers in western Europe, which has led to a decline in exports to countries that were formerly the traditional markets for Togo and Senegal phosphate rock.

SSP contains the same quantity of Cd/kg P as the phosphate rock from which it was manufactured, whereas TSP and DAP typically contain only 60-70% of the Cd in the rock (Phosphorus and Potassium, No. 198, 1995). Although processes such as solvent extraction and ion exchange can be used to remove Cd from phosphoric acid, these are probably too costly for commercial use at current fertilizer market prices. High temperature calcination may not be economically viable due to the high-energy costs. Therefore the only way to manufacture phosphate fertilizers with Cd concentrations below the European limiting values is to use phosphate rock with low Cd. If low limiting values for Cd in phosphate rock and fertilizers were adopted in sub-Saharan Africa, it would impede the use of some phosphate rocks resources which are needed to help increase food production; importation of low Cd phosphate rock or fertilizer products may increase prices to a level which would not make their use economically effective. In addition, the adoption of low limiting values for Cd in fertilizers in sub-Saharan African countries may not be justified by the potential environmental impacts, especially as the evidence for transfer of Cd from fertilizers into the human food chain is equivocal and fertilizer application rates to food crops tend to be much lower than in western Europe.

Additional information on cadmium and fertilizers is available in other sources (Bramley, 1990; Hanafi and Maria, 1998; He and Singh, 1994a; He and Singh, 1994b; He and Singh, 1995; King et al., 1992; Kpombrekhoua and Tabatabai, 1994; Leyval et al., 1993; Loganathan et al., 1996; McLaughlin et al., 1997; Mortvedt, 1996; Ramachandran et al., 1998; Rutherford et al., 1995b; Schnug et al., 1996; Semu and Singh, 1996; Sery et al., 1996; Sillanpää and Jansson, 1992; Singh and Myhr, 1998).

Table 13 Phosphorus and cadmium concentrations in phosphate rocks

Phosphate rock source	% P	mg Cd/kg rock	mg Cd/kg P
<i>Igneous</i>			
Kola, USSR	17.2	0.15	0.9
Palabora, South Africa	17.2	0.15	0.9
<i>Sedimentary</i>			
Jordan	14.6	5	34
Morocco(Bou Craa)	15.9	35	220
Morocco (Khouribga)	14.2	16	113
Senegal (Taiba)	15.8	80	506
Togo (Hahotoe)	15.7	55	350
Tunisia (Gafsa)	13.2	50	380
USA (Florida)	14.4	8	56
USA (Texasgulf)	14.4	40	278

Source: Bøckman et al, 1990 quoted in *Phosphorus and Potassium*, No. 198, 1995

Whereas most Cd and U are retained in phosphoric acid, some is retained in pore waters of the phosphogypsum by-product. It has been suggested that leachates of phosphogypsum washed free of process water may be environmentally benign and pose little hazard except for slightly elevated levels of F⁻ (Rutherford et al., 1995a; Rutherford et al., 1995b). Thus the environmental impact of potentially harmful elements in phosphogypsum is probably quite low.

Concentrations of the other potentially harmful elements in phosphate rocks (see for example Syers et al., 1986), are generally so low that application of phosphate rock or manufactured fertilizers will not substantially increase soil concentrations above natural levels. Long-term application of phosphate fertilizers increases soil U levels but does not appear to enhance U concentrations in plants, probably

because organic matter in the soils absorbs most of the U. Retention of uranium in high pH soils with low organic content would be much less, so loss of U into the aquatic environment and uptake by plants might be higher under these environmental conditions.

Sam, Ahamed, et al. (1999) carried out a radiological and chemical assessment of the Uro and Kurun phosphate deposits at Uro and Kurun in Eastern Nuba mountains in the state of Kordofan (Western Sudan). They showed that natural radionuclides in the Uro and Kurun rock fertilizers do not contribute to the mean terrestrial radiation exposure of the population although exposure rates in air 1 m above Uro and Kurun phosphate deposit areas places them among high background radiation areas. Estimates of the maximum emanation power showed that the extent of contamination that could be expected for the soil fertilized with Kurun rock is negligible compared with that of unfertilized soils in Sudan. These results confirmed earlier study that showed that the natural radionuclides contained in Uro and Kurun ground rock phosphate contribute very little to the average terrestrial radiation exposure to the population (Sam and Holm, 1995).

Erdem, Tinkilic et al. (1996) investigated the distribution of the radioactive element uranium in phosphate fertilizers in different steps of the triple superphosphate (TSP) production process. It was found that 50% of the uranium is dissolved in the acid during the production of phosphoric acid while the remainder is precipitated with phosphogypsum residue. The observations showed that in the second step, the sum of uranium in phosphate rock and phosphoric acid completely passed into TSP in the TSP manufacturing process.

There is a general paucity of readily available (published) information on concentrations of potentially harmful elements in the phosphate rocks resources of sub-Saharan Africa. This situation should be remedied so that the potential environmental impact of mobilizing these rocks can be adequately assessed.

AGRONOMIC ASSESSMENT

This sub-section of the report firstly reviews the existing or anticipated direct use of phosphate rock in agriculture and then describes some of the agronomic assessments of local rock phosphates and fertilizer products derived from them. Details of agronomic evaluations carried out in each country and of the relative economic benefits for specific phosphate rock-crop-soil-climate situations are given in the country profiles in the second section of this report.

Existing or anticipated direct use of phosphate rock in agriculture

It is difficult to obtain reliable information concerning the existing use of phosphate rock as a direct application fertilizer in sub-Saharan Africa. Data available from McClellan and Notholt (1986), Notholt (1986), World Survey of Phosphate Deposits (Savage, 1987), Van Kauwenbergh et al. (1991a; 1991b), Atkinson and Hale (1993), Gerner and Mokwunye (1995), and Appleton (1994) together with unpublished information suggest that more than 1,000 t per year of phosphate rock are, or have recently been, used as direct application fertilizer in Burkina Faso, Mali, Senegal, South Africa, Tanzania and possibly also in Nigeria (Table 14). Exclusive rights to mine the Tundulu phosphate rock (TPR) are reported to have been acquired by a Malawian fertilizer blending company, which is reported to be providing granulated mixtures of TPR and conventional chemical N and K fertilizers for agronomic field trials being carried out by the Rockefeller Foundation. In addition, unknown quantities of guano have been used for direct application in at least five countries. Further details are given in the individual country profiles. Small quantities of ground phosphate rock have also been used for agronomic experiments.

A wide range of research on phosphate rock resources and their potential for use as direct application fertilizer has been carried out by the International Fertilizer Development Centre (IFDC) in collaboration with national mineral resource and agricultural organisations. The main results are summarised by Van Kauwenbergh et al. (1991a a; 1991b b) and IFDC Annual Reports, to which the interested reader is referred for greater detail concerning areas and crops for which phosphate rock has some potential as a direct application fertilizer. The major interest has been the potential use of these phosphate rocks for basic food crops, including maize, millet and beans, but there is perhaps greater potential for the use of finely ground phosphate rock for perennial crops, especially tea, and also for forestry and agroforestry (Appleton, 1990; Appleton, 1994; Appleton et al., 1991; CGIAR, 2000; FAO, 2000a; FAO, 2000b; FAO, 2000c; ICRAF, 2000a; Sanchez et al., 1999; Sanchez and Palm, 1996; Vanlauwe et al., 1999).

It is anticipated that the future use of phosphate rocks in tropical agriculture will expand for plantation crops and pastures and especially in situations where landlocked countries have local deposits of phosphate rock. Increased use of phosphate rocks is also anticipated where more reactive rocks, such as the Tilemsi phosphate rock from Mali, can be used effectively to increase the yield of annual food crops. The use of water-soluble P-fertilizers blended or compacted with the phosphate rock might enable phosphate rocks of lower reactivity to be used (Chien and Menon, 1995a; Fernandes, 1996b; Mnkeni et al., 2000; Sale and Mokwunye, 1993).

Carbonatite phosphate resources in Africa tend to be low grade and would therefore require beneficiation prior to use as direct application P-fertilizer or as raw materials for the production of PAPR or SSP. NAC solubility data (Table 12) indicate that the Sukulu and Dorowa PRs have a lower reactivity than the Tundulu PR and would be less effective when applied directly to the soil. It may be possible to enhance the P-availability of these igneous phosphate rocks, by composting or mixing with pyrite (Anon., 1987; Lowell and Well, 1995; Lowell and Well, 1993; Wachira and Notholt, 1986). Carbonatite phosphate rocks or concentrates might be suitable for use as direct application fertilizer for tea in Burundi, coffee in Kenya, forestry, agroforestry and soil rehabilitation in many countries of Central and Eastern Africa, and possibly also for grain crops under favourable soil conditions.

The use of ground rock phosphate in sustainable agricultural practices is currently being evaluated (Bationo et al., 1998b; Bationo et al., 1996; Diouf et al., 1995; FAO, 2000b; Gerner and Mokwunye, 1995; ICRAF, 2000a; IFDC, 2000b; ILEIA, 2000; Mokwunye, 1995a; Vanlauwe et al., 1999).

Table 14 Direct use of phosphate rock for agriculture in sub-Saharan Africa

Country	PR deposit	Rock type	Amount produced	Where used	Crops	Current (C) or former(F) use	Commercial (C) or experimental (E) use
Angola	Cabinda	Sedimentary	na.	Angola	na.	?C	C
Burkina Faso	Kodjari	Sedimentary	2,207t (1994)	Burkina Faso	Sugar cane, maize, rice	C	C, E
Kenya	Chulu Hills	Guano	small	local	na.	F	C
Kenya	Suswa	Guano	small	local	na.	F	C
Malawi	Tundulu	Igneous	10 t	local	Tea	C	E
Mali	Tilemsi	Sedimentary	2,000 t/y	Mali	Cotton	F	C, E
Mauritania	Civé	Sedimentary	na.	Mauritania	na.	F	C
Namibia	Cape Cross	Guano	na.	S. Africa	na.	?C	C
Niger	Tapoa (Parc W)	Sedimentary	na.	na.	na.	na.	E
Senegal	Taiba	Sedimentary	1,200 t	Ivory Coast	na.	na.	na.
Somalia	Mait Island	Guano	na.	Saudi Arabia	na.	?C	C
South Africa	Varswater	Sedimentary	?20,000 t	South Africa	na.	C	C
Tanzania	Amboni, Tanga	Guano	na.	Tanzania	na.	na.	C
Tanzania	Zanzibar	Guano	na.	Zanzibar	na.	?C	C
Tanzania	Minjingu	Sedimentary	2,500 t (1994)	Tanzania Kenya	na.	C	C, E
Tanzania	Panda Hill	Igneous	na.	Tanzania	na.	F	E
Togo	Hahotoe	Sedimentary	? 4,100 t	Nigeria	na.	?C	?C
Uganda	Bukusu	Igneous	na.	Uganda	na.	F	C
Uganda	Sukulu	Igneous	na.	Uganda	na.	F	E
Zimbabwe	Various	Guano	na.	Zimbabwe	na.	?C	C

na. = no information readily available; ? = uncertain

Agronomic assessment of local phosphate rocks and derived phosphate fertilizer products

Most of the agro-economic studies of the direct use of indigenous rock phosphates and of phosphate fertilizer products derived from them have been carried out by the IFDC in collaboration with SADCC/ICRISAT and national agricultural research organisations (Bekunda et al., 1997; Gerner and Mokwunye, 1995; Mokwunye and Vlek, 1986; Semoka and Mnkeni, 1986; Van Kauwenbergh et al., 1991a; ZFTDC, 1991).

In the period 1975-1980, the Malian-Dutch "Primary Production Sahel (PPS)" project analysed the role of water, N and P in rangeland productivity, and compared the effect of the Tilemsi rock and TSP on the production of rangeland and rangeland species, legumes included (*Zornia*). It was concluded that TSP was 20 times more effective than Tilemsi rock in the first year of application (Krul and et al., 1982) although the Tilemsi PR became more effective with time.

Whereas P is a serious limiting factor in most of Africa, especially in humid regions, N is generally more limiting than P in semi-arid and sub-humid West Africa (Breman, 1998; Krul and et al., 1982). Even so, the absolute availability of P in Sahel still much lower than in humid West Africa. Insufficient attention has been paid to the availability of N in evaluations of the RAE of PR (Henk Breman, personal communication 22 June 2001). PR was frequently compared with P-fertiliser in situations where N was deficient. As a consequence, the response to P-fertiliser was depressed due to insufficient availability of N whereas response to PR was not depressed because N was not yet deficient. In these cases, the RAE value observed is high, often much too high (Breman, 1997). High RAE values are often linked to low yields. High absolute yield increases as well as high RAE are prerequisites (Henk Breman, personal communication, 22 June 2001).

The use of finely ground phosphate rocks as direct application P fertilizers in tropical farming systems may be a cheaper alternative to manufactured water-soluble fertilizers. However, the agro-economic effectiveness of ground phosphate rock in tropical environments depends on the extent to which the required P uptake rate of the crop plant can be maintained by the rate of phosphate rock dissolution in the soil. The agronomic effectiveness will depend on a number of factors including the chemical reactivity (solubility) of the phosphate rock; its particle size and porosity; soil characteristics including acidity (pH), Ca and P status, P-adsorption capacity; physical characteristics that control soil moisture; crop P and Ca requirements and root characteristics; climate; and soil and plant management practices (Chien, 2001a; Chien and Menon, 1995b; Mokwunye and Vlek, 1986). Although the highly weathered soils in the humid tropics provide conditions which favour adequate rates of phosphate rock dissolution, the agro-economic effectiveness of phosphate rocks is reduced as the acquisition of dissolved P by plant roots is restricted by competition from P sorption processes in soils with very high P sorption capacities. An additional economic benefit may result from the ability of phosphate rocks to provide Ca, in addition to P, because subsoil Ca deficiency is becoming more widely recognised as a production constraint in highly weathered tropical soils (Chien, 2001a; Hellums et al., 1989). The residual effects of phosphate rock are an important factor in its use (Visker et al., 1995).

Agronomic evaluation of phosphate fertilizers in tropical sub-Saharan Africa carried out in the 1980's suggested that with the exception of the Tilemsi phosphate rock from Mali, which has a relatively high reactivity (see Table 12) the west African rocks tested (Parc W (Niger), Hahotoe (Togo), Kodjari (Burkina Faso)) have lower potential for direct application, whereas partial acidulation of the phosphate rocks dramatically enhanced their agronomic effectiveness. Both PR and PAPR performed best on acid Ultisols under wet climatic conditions (Bationo et al., 1986).

Initial agronomic trials by IFDC and ICRISAT suggested that phosphorus is the most limiting nutrient in west Africa¹ although response by millet to nitrogen when moisture and P are non-limiting can be substantial (Bationo and Mokwunye, 1991). Application of 15-20 kg P/ha was usually adequate for

¹ this view is not shared by Henk Breman (personal communication 22 June 2001) because the assessment was based on a relatively small number of maize trials on sandy soils in two or three countries. For a more complete synthesis see Breman Breman, H., 1998. Soil fertility improvement in Africa, a tool for or a by-product of sustainable production? *Soil Fertility/Africa Fertilizer Market*, 11(5): 2-10.

optimum yields. Matam phosphate rock from Senegal, Tilemsi phosphate rock from Mali and Tahoua phosphate rock from Niger, were found to be suitable for direct application. Partial acidulation (50% with sulphuric acid) of the less reactive phosphate rocks resulted in products with similar agronomic effectiveness as commercial superphosphates. Tests conducted by farmers showed that millet and other crop yields can be increased by more than 250% by the use of fertilizers (Bationo and Mokwunye, 1991).

N and then P are more limiting than water in the Sahel South of the 300 mm isohyet. Even at 400 mm of annual rainfall, plants use only 10 - 15% of the available water because of lack of nutrients. Soil improvement and increased availability of nutrients can lead to a 3 to 5 times higher rangeland and crop production, in which case 50% of the rain water leaves the system through the plants. Yield increases can be higher when rainfall is higher or irrigation used (Krul and et al., 1982).

Partial acidulation of phosphate rock (PR) or compaction of PR with soluble P fertilizers (e.g. SSP or TSP) at a P ratio of approximately 50:50 represents a means of producing economically attractive P fertilizers from indigenous PR sources that may otherwise be unsuited for use as a P fertilizer (Chien, 2001b). Kpombrekou et al. (1991) demonstrated that whereas ground Togo PR is an ineffective P source for both maize and cowpeas, PAPR and compacted (PR + TSP), have relative agronomic efficiency (RAE) values with respect to SSP of 72.5% and 84.7%, respectively, for increased dry-matter yield of maize and 87.7% and 97.1%, respectively, for increased cowpea seed yield. These results were based on greenhouse trials using an acid sandy loam (Typic Albaquult) limed to pH 5.5.

Ssali (1991) reviewed the performance of alternative phosphate fertilizer materials in East and Southeast Africa based on research carried out by the East and Southeast African Fertilizer Management and Evaluation Network (ESAFMEN) established in 1987 under the auspices of the IFDC. Beneficiated and unbeneficiated phosphate rock (PR), partially acidulated phosphate rock (PAPR-25 and PAPR-50), and PR compacted with SSP and TSP and other mineral fertilizers were evaluated. Results for the period 1988-1990 indicated:

- the importance of choosing the proper test crop for nutrient trials (maize was the test crop on three sites and sorghum on the fourth);
- broadcasting and incorporation of PR prior to sowing was superior to placement application of PR;
- agronomic efficiency index (AEI) varied from 61-78% for beneficiated PR;
- reactive Minjingu PR significantly increased maize yield and was 61% as effective as SSP on one site;
- a remarkable AEI performance of 63 to 78% was recorded at two sites for the unreactive igneous Dorowa PR;
- partial acidulation to 25% did not substantially increase performance though PAPR-50 generally improved performance (AEI 73-103% relative to SSP);
- substantial residual effects were noted but these were not significantly better than the residual effects with conventional fertilizers (SSP and TSP);
- all alternative materials tested significantly increased grain yield at the four sites tested.

Ssali (1991) concluded that this demonstrates the high potential PR and PAPR have in this region and that their comparative advantage will increase when subsidies are removed from imported mineral fertilisers.

Numerous field trials conducted by IFDC in Asia, sub-Saharan Africa, and Latin America have demonstrated that PAPR at 40%-50% acidulation with H_2SO_4 or at 20% with H_3PO_4 approaches the effectiveness of SSP or TSP in certain tropical soils and crops. The agronomic effectiveness of PAPR is affected by mineralogical composition and reactivity of the PR used and by soil properties and soil reactions. If a PR has high $Fe_2O_3 + Al_2O_3$ content, it may not be suitable for PAPR processing because of the reversion of water-soluble P to water-insoluble P during the PAPR manufacturing process (Chien, 2001b).

More recently, there has been considerable interest in the incorporation of phosphate rock in agroforestry and also in rotation systems incorporating cover crops (such as *Mucuna* or *Tithonia*) and nitrogen-fixing legume crops, such as soybean. Chien, Carmona, et al. (1993) examined the effect of phosphate rock sources on biological nitrogen-fixation by soybean in a greenhouse study because very little information

was available concerning the effect of phosphate rock (PR) sources on biological nitrogen fixation (BNF) in legume crops. The effectiveness of three sources of PR (Hahotoe PR, Togo; Tilemsi PR, Mali; and Sechura PR, Peru) was compared with that of TSP in increasing soybean seed yield and the amounts of N fixed by the soybean crop. The RAE of the three PRs with respect to TSP (RAE = 100%) in terms of increasing seed yield was Hahotoe rock = 6.0%, Tilemsi rock = 45.9%, and Sechura rock = 75.2%; this trend followed the same trend as PR reactivity, i.e. Sechura rock > Tilemsi rock > Hahotoe rock. BNF was affected significantly by all the P treatments. The RAE values of the three PRs with respect to TSP in terms of influencing the amount of BNF were Hahotoe rock = 3.0%, Tilemsi rock = 43.4%, and Sechura rock = 71.2% i.e. the same as the RAE variation identified for seed yield. Of the two west African PRs tested, only the Tilemsi PR appears to have any potential for incorporation in rotations involving legume crops. Cost:benefit ratios were not evaluated by Chien, Carmona, et al. (1993).

Hoffland (1992) made a quantitative evaluation of the role of organic-acid exudation in the mobilization of rock phosphate by rape. Phosphorus-deficient rape plants appear to acidify part of their rhizosphere by exuding malic and citric acid. A simulation model was used to evaluate the effect of measured exudation rates on phosphate uptake from Mali rock phosphate. It was concluded that organic acid exudation is a highly effective strategy to increase phosphate uptake from rock phosphate, and that it is unlikely that other rhizosphere processes play an important role in rock phosphate mobilization by rape (see also Hoffland et al., 1989a; Hoffland et al., 1989b; Hoffland et al., 1992).

Omar (1998) investigated the role of rock-phosphate-solubilising fungi and vesicular-arbusular-mycorrhiza (VAM) in the growth of wheat plants fertilized with rock phosphate. The greatest positive effect on growth and phosphorus contents of wheat plants was recorded in the treatments that received rock phosphate and were inoculated with a mixed inoculum of the three microorganisms used, followed by dual inoculation treatments of *G. constrictum* plus either *Aspergillus niger* or *Penicillium citrinum*. The importance of fungi for the release of phosphorus from phosphate rock and soils have been investigated in a range of studies (Bojinova et al., 1997; Goenadi et al., 2000; ICRISAT, 2000b; Lukiwati and Simunungkalit, 2001; Mba, 1994a; Mba, 1994b; Mba, 1996; Mba, 1997; Nahas, 1996; Nahas and Deassis, 1992; Narsian and Patel, 2000; Omar, 1998; Singh and Singh, 1993; Vassilev et al., 1995; Vassilev et al., 1996a; Vassilev et al., 1997a; Vassilev et al., 1996b; Vassilev et al., 1997b; Vassilev et al., 1997c; Vassilev et al., 1998; Vassileva et al., 1998a; Vassileva et al., 1999; Vassileva et al., 2000; Vassileva et al., 1998b; Wahid and Mehana, 2000; Whitelaw, 2000)

Economic assessment of local phosphate rocks and derived phosphate fertilizer products

An assessment of the relative economic effectiveness (REE) of different phosphorus fertilizer products with respect to SSP, calculated as ratios of net benefit estimates, demonstrated that (i) if PAPR could be produced and supplied at a price that was about 20% lower than the price of SSP, it could be economically effective for the crops and soil tested; and (ii) even if ground phosphate rock was supplied at prices 70% lower than SSP, the direct application of PR was substantially less profitable than SSP, apart from the maize/beans intercropping at Kabete in Kenya (Table 15).

Table 15 Comparison of the relative economic effectiveness of ground phosphate rock (PR), PAPR (50) and TSP with respect to SSP (adapted from Baanante, 1986, Table 18)

Country (Site)	Crop	Phosphate rock (PR)	Ground PR	PAPR (50)	TSP
Nigeria (Zaria)	Maize	Togo	0.25	0.72	nd
Nigeria (Mokwa)	Maize	Togo	0.80	0.71	nd
Togo (Sarakawa)	Maize	Togo	0.57	1.69	2.32
Sierra Leone (Njala)	Maize	Togo	0.51	0.94	nd
Kenya (Kabete) 1st season	Maize -beans	Togo	1.02	0.88	nd
Kenya (Kabete) 2nd season	Maize -beans	Togo	0.63	0.72	nd
Niger (Sadore) 1982	Millet	Parc W	0	0.84	1.30
Niger (Sadore) 1984	Millet	Parc W	1.86	1.10	1.24
Niger (Sadore) 1982-84	Millet	Parc W	0.49	0.90	1.29

nd = no data

More recently, Dahoui (1995) reviewed cost determinants of phosphate rock application for sustainable agriculture in West Africa and concluded that whereas the current cost per unit of P in phosphate rock is currently about half that for P in TSP, the cost could be reduced significantly if (a) PR production was undertaken by autonomous enterprises operating on a commercial basis; (b) ground PR is used in relatively close proximity to the mine or milling sites where spoils are deficient in P; and (c) the use of PR is increased, thereby reducing fixed costs/unit P.

Gerner and Baanante (1995) discussed the economic aspects of phosphate rock application for sustainable agriculture in West Africa. They concluded that it was necessary to evaluate the use of indigenous PR resources as a capital investment by society with full account being taken of the environmental benefits and costs, together with the impact of this investment on food security and poverty alleviation. The application of PR may not be profitable currently to West African farmers growing food crops because of current crop prices and socio-economic factors including farming methods and land tenure.

Hien, Kabore, et al. (1997) used stochastic dominance analysis to determine the risk characteristics of phosphate fertilization of millet, sorghum and maize with commercial NPK fertilizer, rock phosphate and partially acidulated rock phosphate in Burkina Faso. The analysis shows that among the four treatments tested, commercial NPK fertilizer has the most desirable risk characteristics. The rock phosphate treatments have higher yields and in certain cases higher returns than the no-fertilizer control, but those benefits are less sure than for the soluble commercial fertilizer. The cash returns from rock phosphate treatments are rarely significantly different from those of the control. Rock phosphate treatments never dominate the commercial fertilizer treatment. If farmers have a choice between commercial fertilizer, rock phosphate and partially acidulated rock phosphate, at current prices most of those who use fertilizer would choose the soluble commercial product. If the availability of commercial fertilizer were limited (e.g. due to the lack of hard currency), some farmers would use rock phosphate - especially the partially acidulated product (Hien et al., 1997).

Shapiro and Sanders (1998b) reviewed fertiliser use in semi-arid West Africa with regard to profitability and supporting policy on behalf of the International Livestock Research Institute (ILRI). They concluded that under existing farming conditions in the Sudanian and Sahelo-Sudanian zones of semi-arid West Africa, *imported inorganic fertilisers are the only technically efficient and economically profitable way to overcome prevailing soil-fertility constraints*. Shapiro and Sanders (1998b) considered that *alternative*

soil fertility measures, such as organic fertilisers and natural rock phosphate, should be seen as complements to rather than substitutes for imported inorganic fertilisers, until wider experimentation makes them more successful. The model results presented by Shapiro and Sanders (1998b) support the importance of the rapid introduction of inorganic fertiliser in semi-arid West Africa. They observed that this could be strengthened by the improvement in the macro-economic environment and liberalisation of domestic economic policies currently under way in the French currency countries. West African governments can facilitate this process by making the importation of inorganic fertilisers easier for the private sector and by enabling, rather than resisting, higher domestic cereal prices for farmers to profit from fertiliser use and intensify their production (Shapiro and Sanders, 1998b).

A conceptual framework of a simple decision support system/expert system was developed by FAO/IAEA-IFDC to serve as a guideline for direct application of phosphate rocks. Simple and multiple linear regression analyses are used to identify the soil and environmental factors that most influence the agronomic effectiveness of PR. Data requirement and further investigations on PR application to tropical acid soils, under well-defined management conditions, e.g. cropping system, cultivation, fallow, and P fertilization history, were identified to further develop the decision support system (Heng, 2001).

A phosphate rock decision support system (PRDSS) for estimating initial response to phosphate rock (PR) application with respect to water-soluble phosphate (WSP) fertilizers has been developed by the IFDC based on data principally from West Africa (Singh et al., 2001). The model is designed to function for a wide range of PR sources, soil conditions, rainfall regime, and selected crops. It incorporates the effect of PR sources (PR solubility), soil pH, soil texture, organic matter, type of crop, and moisture/rainfall regime. The system predicts the relative agronomic efficiency (RAE) of PR with respect to water-soluble fertilizers. The soil/crop must be responsive to P application, as the model is not meant to be used for determining if P is limiting or the P requirement rate. In addition, other management factors such as water, nutrients, and pests must not be limiting crop performance. The model also takes into account the effect of rainfall on PR dissolution but does not consider socioeconomic aspects directly. Ultimately, it is hoped that the PRDSS also will be a useful research and extension tool to assess the agronomic and economic possibilities/liabilities of using locally available PR materials as a P source in a range of cropping systems in the tropics (Singh et al., 2001).

³²P isotopic techniques may be used for evaluating the agronomic effectiveness of natural and modified PR-products. An FAO/IAEA Co-ordinated Research Project (CRP) on "The use of nuclear and related techniques for evaluating the agronomic effectiveness of phosphatic fertilizers, in particular rock phosphates" assessed the bioavailability of P in soils amended with phosphate rock and water-soluble fertilizers, and evaluated the agronomic effectiveness of PR products (Zapata, 2001). The ³²P isotope-exchange kinetics method allowed a complete characterization of P dynamics, and provided basic information for estimating the labile pools of soil P. The ³²P techniques are powerful tools for studying the factors that affect AE. Information from field trials was used to create a database for validating a P sub-model for providing recommendations for PR application. This project provided the framework for follow-up studies such as the joint IAEA-IFDC collaborative work on developing a decision support system for PR direct application; the publication of a FAO Technical Bulletin and the initiation of a new CRP on Tropical Acid Soils. The CRP will continue research on an integrated approach to soil, water and nutrient management with the ultimate goal of being to achieve sustainable agricultural production in the savannahs of Africa and Latin America (Zapata, 2001). Zaharah (2001) outlined the applications and limitations of the ³²P isotopic techniques and the future prospects for its use in phosphate research.

STRATEGIC ROLE OF PHOSPHATE ROCK

This sub-section of the report reviews the role of phosphate rock in strategies for dealing with soil infertility in sub-Saharan Africa.

Strategies for sustainable management and rehabilitation of degraded soils

The FAO Land and Plant Nutrition Management Service has developed a *Strategy for the Management and Rehabilitation of Degraded Soils* that in some countries includes the use of local phosphate rock resources (FAO, 2000). Restoration of degraded soil calls for management and conservation measures such as contour cultivation, planting cover crops, mulches, fast growing trees, selection of proper crop rotation, as well as the application of fertilizer, soil amendments and organic manures. In Malawi, farming systems or practices that improve soil fertility include crop rotation, intercropping, improved cultivation methods and the *use of indigenous fertilizer material resources* including limestone, gypsum, and rock phosphate (FAO, 2000b; FAO, 2000c). In Tanzania, the use of Minjingu phosphate rock, Panda phosphate rock, farmyard manure crop residues, and leguminous plants either as green manure or a component of crop rotation and agroforestry are some of the options used to rectify degraded spoils. Minjingu PR is an effective source of P when applied to perennial crops grown on acid soils. In Uganda, the use of Busumbu rock phosphate is being promoted especially for growing legume crops and agroforestry species. In Zambia, the FAO supported soils team leads research in soil fertility restoration and maintenance through corrective liming, judicious fertilizer use in conjunction with organic inputs, promotion of the use of acid tolerant sunhemp as green manure, and use of *indigenous phosphate rock* as a phosphorus source. The FAO strategy document (FAO, 2000b; FAO, 2000c) notes that there is a general awareness of the need to develop sustainable agricultural systems including the use of nitrogen-fixing green manures, improved fallows using agroforestry, crop rotations, FYM and crop residue management as well as the correction of soil acidity with liming, sustaining soil P using *phosphate rock*, and ameliorating saline soils using gypsum.

DFID's *Sustainable Agriculture Strategy* DFID (1995) clearly identifies the need to increase crop yields through , amongst other things, the use of organic and, inorganic fertilisers.

Strategies for combating desertification at the desert margins

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) researches strategies for combating desertification and reducing poverty in the desert margins of Sub-Saharan Africa (ICRISAT, 2000a). In the dryland zones of Africa, over 332 million ha of once productive land are now considered degraded, due to extensive cultivation, overgrazing, population growth, and climate change. ICRISAT research on improved natural resource management strategies for combating desertification includes investigations on the source and management of phosphorus fertilizers. The following ICRISAT research results pertain to the use of phosphate rock:

- (i) Data from long-term trials showed SSP fertilizers outperformed other P sources, including TSP². SSP also had the highest phosphorus use efficiency (PUE³) value at all rates of P application, and PUE decreased as the rate of P application increased. The PUE of SSP increased with increased rainfall.
- (ii) Results indicate that phosphate rock from Tahoua, Niger outperformed phosphate rock from Kodjari, Burkina Faso in terms of effect on millet yields.

² SSP outperformed the other P sources including TSP due to the response to S in the SSP (S.H. Chien, personal communication, 8 October 2001)

³ defined as the production in kg per kg P applied

(iii) The agronomic effectiveness of partially acidulated (50%) Park W (Niger) rock phosphate was similar to that of TSP⁴. Results showed that partial acidulation of Park W rock phosphate significantly increases effectiveness.

(iv) Multi-locational trial data confirmed that the agronomic effectiveness of rock phosphate is affected by rainfall and soil acidity. Acidic soils provide an ideal environment for phosphate rock dissolution.

(v) The agronomic effectiveness of phosphate rock with cowpea was the same as the effectiveness of phosphate rock with cereal millet.

(vi) Hill placement of small quantities of P fertilizers increased PUE over broadcast P. It also increased the efficiency and effectiveness of phosphate rock fertilizers. Hill placement of 15-15-15 NPK was more effective than hill placement of SSP (ICRISAT, 2000a).

Local sources of rock phosphate have been tested and evaluated on station and on farmers' fields, in different agro-ecological zones in the savannah zone of semi-arid West Africa. Cropping systems, including millet-cowpea intercropping and cowpea-millet rotations and the incorporation of crop residues in ridges, have been identified which can significantly increase grain millet yield in a sustainable manner. A number of these technologies have been documented and are currently being extended to farmers. The integration of organic fertilizers, inorganic fertilizers, and water conservation measures appear to offer biophysical solutions to soil productivity constraints. In particular, *the concentrated application of small quantities of local rock phosphate fertilizer* in millet-cowpea rotations and the increased application of manure can significantly increase pearl millet yields, producing yields up to three times higher than traditional systems (ICRISAT, 2000a).

Soil Fertility Initiative (SFI)

The World Bank-IFA-FAO-ICRAF-IFDC *Soil Fertility Initiative for Africa* (IFA, 2000b; World Bank, 1994) is an international collaborative effort to assist African countries develop and implement strategies and actions for the rehabilitation of their land resources. The initiative will develop a number of approaches to try to resolve the problem of soil infertility. It has been proposed that there should be a stakeholders' collective and collaborative effort to stimulate demand for mineral fertilisers (IFA, 2000b). As part of the initiative, the feasibility that the negative impacts of P-deficiency on agricultural productivity could be resolved through investment in the replenishment of soil phosphorous using local phosphate rock resources is being considered (World Bank, 1994). Other donor organisations and NGOs will support a range of soil fertility projects. DFID, for example, supports some SFI activities in Nigeria whilst CIDA and DANIDA support projects in Kenya, Tanzania and Zimbabwe that are investigating opportunities for the use of phosphate rock resources.

Technologies for restoring soil fertility (Bationo et al., 1996), the role of phosphate rock as a capital investment (Mokwunye, 1995a), the investment in natural resource capital as a means of replenishing soil fertility in Africa (Sanchez et al., 1997), and a debate over who should bear the cost of an investment in phosphate rock (Teboh, 1995) are all facets of the Soil Fertility Initiative.

IFDC has been strongly involved in the Soil Fertility Initiative (SFI) from the beginning. IFDC-Africa organised in Lomé, the first African wide workshop in the framework of the initiative, leading to a framework for national soil fertility action plans (Anon., 1997). Ghana and Burkina Faso have developed national soil fertility action plans assisted by IFDC-Africa. IFDC and FAO are assisting Mali with the elaboration of an action plan, and IFDC-Africa continues to support Ghana and Burkina, trying to find ways for large-scale implementation of their plans (Henk Breman, personal communication, 22 June 2001). The integration of phosphate rock in a national soil fertility management strategy in Burkina Faso has been outlined by Diouf, Gerner, et al. (1995). Development of national soil fertility plans is a key aspect of the SFI.

Although IFDC support integrated soil fertility management that combines the use of locally available nutrient sources (like organic matter and PR) and inorganic fertilisers, IFDC-Africa does not believe that

⁴ not stated whether agronomic response to PAPER reflected enhanced sulphur content

soil amendments can be used as an alternative for fertilisers in most of Africa, or should be presented as a complement, to be used first whilst using inorganic fertilisers only if a negative nutrient balance can not be avoided using locally available resources alone. IFDC consider that such an approach is an underestimation of the difficulties of African small holders and an overestimation of the potential of locally available resources (Henk Breman, personal communication, 22 June 2001). This is because:

- The amount of available organic matter is much too limited as a consequence of the inherent very low quality of most African soils. In the Malian cotton region (the most favourable region of that country), the annually produced organic matter exploited in a sustainable way could potentially cover only one third of the requirements of crops at the level of production of the beginning of the eighties, taking the fertilizer use of that period into account (Breman and Traoré, 1987)
- Only a small fraction of the available organic matter is rich enough to be used as a simple alternative for inorganic fertiliser (again, as a consequence of the inherently poor soils). Using the organic matter decision support system developed by the Tropical Soil Biology and Fertility Institute of CIAT and others, Breman (1987) estimated that less than 3% of the organic matter in the Malian cotton zone could be used as simple fertiliser alternative (one of the four categories distinguished by TSBF). The others are only useful in combination with inorganic fertilisers.
- Only a fraction of the known forms of PR can be used as a simple alternative for P-fertiliser (Chien et al., 1999) (Henk Breman, personal communication, 22 June 2001).

IFDC-Africa (supported by the International Fund for Agricultural Development (IFAD) in cooperation with Tropical Soil Biology and Fertility Institute (TSBF) of CIAT) is developing a range of integrated soil fertility management options. The technologies are based on the integrated use of soil amendments and inorganic fertilisers, aiming at a level of soil fertility improvement that makes the use of inorganic fertilisers efficient enough to make the system economically viable. The technologies involve the use of organic matter, PR, lime etc. in order to make inorganic fertilisers more accessible for small holders and farmers on marginal land (Anon., 2002; Breman, 1998). The use of a limited amount of fertilisers, maintaining only the nutrient balance at its "natural level", results in low efficiency (caused principally by the inherently poor fertility of African soils) and high prices (caused by the scale factor). This, in turn produces very unfavourable cost-benefit ratios, which is not the way to help poor farmers (Henk Breman, personal communication, 22 June 2002).

The integrated use of soil amendments and inorganic fertilisers leads to improved soil organic matter status, improved amounts of available-P and improved soil pH, which all increase fertiliser efficiency and improved economic gains. Inorganic fertilisers contribute to their own higher efficiency. This results not only in a strong increase (of 3-5 times) in the potential cereal production capacity of the Sahel, for example, but also in the amount of straw that can be returned to the soil to improve soil organic matter content. IDFC-Africa have been able to show the positive effects of integrated soil fertility management technologies for a whole series of regions, for several crops, and different sources of organic matter (Breman and Van Reuler, 2002). PR can be part of integrated systems when the costs:benefit ratios of exploiting their P will be more favourable farmers than inorganic fertiliser-P.

According to Dr. Henk Breman, Director IFDC-Africa, mineral fertilizer use is absolutely essential in reversing the negative trend of soil nutrient depletion in sub-Saharan Africa (SSA) and arresting the degradation of natural resources. Dr Breman emphasised that *except for a few favourable regions and high-valued crops, the cost:benefit ratio of fertilizer use does not provide an incentive to farmers*. Integrated soil fertility management makes the cost:benefit ratio more attractive through higher fertilizer-use efficiency and lower environmental risk. During the initial period of adoption of integrated soil fertility management technologies, the support of governments and/or donors is vital because of the predominance of small-holder farmers and marginal lands in sub-Saharan Africa (IFDC, 2000b).

The UN's *Institute for Natural Resources in Africa* (INRA) based at the University of Ghana (Legon, near Accra), promotes innovation and collaboration among African researchers through an initiative to recapitalize Africa's soils (Harsch, 1999). With the elimination of, or drastic reduction in, government subsidies for agriculture resulting from structural adjustment programmes, many farmers cannot afford fertilizers to improve the land. One of INRA's goals is to alert African governments to the severity of the problem, and encourage them to develop national soil fertility action plans. So far, only Ghana and

Burkina Faso have drawn up such national plans, but INRA is actively disseminating those experiences to other countries in West Africa. INRA is drawing attention to the importance of minerals, especially phosphates, for agricultural output. INRA noted that phosphate rock deposits in Mali and Niger are relatively soluble and the soil's own acidity is often sufficient to facilitate dissolution, making P available for plant growth. However, many of the other phosphate rock deposits in Africa, especially those of igneous origin, are "unreactive" and require processing before it can be used as fertilizer. An INRA researcher in Togo is studying the effects on soil fertility of partially converted phosphate rock, while the institute's Mineral Resources Unit in Zambia is working on the engineering aspects of a pilot processing plant. Harsch (1999) observes that INRA is very concerned about the economic feasibility of such projects, since a key goal is to convince the private sector that investment in phosphate processing plants can be profitable.

Agroforestry is also seen to have an important role to play in the Soil Fertility Initiative. Sanchez and Palm (1996) examined the role of agroforestry in nutrient cycling in different ecosystems in smallholder maize based systems of Africa. Whereas agroforestry cannot be expected to provide additional phosphorus to most farming systems, large applications of rock phosphates or other phosphorus fertilizers could replenish the phosphorus capital of soils with a high phosphorus-fixation capacity (usually identified by their red clayey topsoil) and, after being fixed it could be gradually released by way of desorption from the oxide clay surfaces to plants during the next five to ten years. Sanchez and Palm (1996) observed that one of the problems with this approach, however, is the need to add acidifying agents to the rock phosphates in order to facilitate their dissolution in most phosphorus depleted African soils, which have pH values of about 6. The decomposition of organic inputs from agroforestry systems may produce organic acids that could help acidify rock phosphate, and this may overcome the problem.

In contrast to the general enthusiasm with the *Soil Fertility Initiative* expressed by World Bank-IFA-FAO-ICRAF-IFDC-IFPRI, Budelman and Defoer (2000) consider that the state of soil impoverishment in the African region has been exaggerated and dispute that the remedy lies primarily in the massive influx of chemical fertilizers, especially phosphorus. They consider that the use of external inputs such as mineral fertilizers should be combined with a range of other measures and agricultural technologies. A wide range of other views on the Soil Fertility Initiative have been expressed recently (New Agriculturalist, 2001).

Role of phosphate rock in nutrient cycling in agroforestry systems

Phosphorus fertility cannot be replenished by agroforestry alone, but it can be made more available through cycling. For long-term production, agroforestry systems must include the addition of phosphorus and, in many cases, of nitrogen fertilizers as well in order to reverse nutrient depletion and ensure the efficient use of resources (Sanchez and Palm, 1996). ICRAF's regional programme for the sub humid highlands of eastern and central Africa includes the use of agroforestry interventions to help mitigate the soil degradation constraint on agricultural productivity (ICRAF, 2000b). Trees can help replenish organic matter and nutrient levels in soils, as well as enhancing the release and efficiency of certain nutrients such as phosphorus. Interaction of organic matter from agroforestry trees and other nutrient sources (organic and inorganic) are being studied by ICRAF with the objective of enhancing the fertility status of soils and increase land productivity.

In areas like western Kenya, the price tag attached to soil fertility is all-important (ICRAF, 1997). Standard recommendations for commercial fertilizer applications to maize in western Kenya are 60 kg N and 50 kg P₂O₅/ha a season, costing around US\$200/ha a year for the two rainy seasons (Sanchez et al., 1999). More than 60% of farmers in the area earn less than US\$1 a day from their land so they are being advised to spend an unrealistically large part of their annual income on fertilizer. ICRAF (1997) recognises that lowering the costs of restoring soil fertility is vital to the future of agriculture in the region. Whereas improved fallows provide more than enough nitrogen for a following maize crop, the yield increases could be still higher if phosphorus deficiency could be overcome. The recommended form of phosphorus application at present is TSP, whose price is the equivalent of US\$2.20/kg of phosphorus. In contrast, reactive rock phosphate from Minjingu in Tanzania costs only the equivalent of about

US\$1.3/kg of phosphorus. ICRAF researchers are also looking at an alternative PR source in nearby Uganda, which may be cheaper due to the lower freight costs.

In highly P and N-depleted farms of Western Kenya, where farmers harvested less than 1 ton/ha of maize during a good rainy season, a combination of a recapitalization rate of 250 kg P/ha of Minjingu rock phosphate plus 1.8 ton/ha of the wild sunflower, *Tithonia diversifolia*, a common shrub planted in thousands of kilometres of farm boundaries, raised yields of maize and high-value crops such as tomatoes and beans by up to 400%. *Tithonia* is now established as a high potential shrub for soil fertility replenishment through biomass transfer; it also supplies significant quantities of nitrogen and potassium. Short-term (6-16 months) improved fallows have proven to be an effective and profitable way of adding about 100kg N/ha and recycling other nutrients in the depleted soils of Western Kenya. Even fallows as short as six months have tripled maize yields in villages where many farmers are now practising a fallow-crop rotation every year. In addition, the efficiency of the rock phosphate is enhanced by the interaction with *Tithonia*, which apparently helps solubilize phosphorus fixed by iron oxides in these Oxisols. Both the rock phosphate and the shrub are indigenous nutrient sources. In phosphorus-deficient soils, Minjingu phosphate rock from northern Tanzania is as effective and profitable as imported triple superphosphate (Sanchez et al., 1999). Farmers are applying 125-250kg P/ha as a capital investment, and expect a five-year residual effect. The potential for major increases in food production and food security is being realised by government authorities and most of the dissemination is done at the village scale as a pilot development project, involving government agencies and NGOs. It is reported that and about 4,000 farmers are trying these techniques in western Kenya. (IFA, 2000a; IFA, 2000b; Sanchez et al., 1999).

In 1996, the Royal Society (London, UK) held a scientific meeting entitled "*Land Resources: on the edge of the Malthusian precipice?*" Holderness's (1997) report on the meeting examined the topic of soil conservation and nutrient restoration with particular reference to agroforestry or 'alley cropping'. At the meeting, Dr Sanchez described ICRAF's work on restoring soil fertility using phosphate rock. Professor Syers (University of Newcastle) predicted that investment in such restoration should have a rapid payback. Where soil lacks nitrogen, both Dr Sanchez and Professor Syers proposed mostly organic means to replenish it. Many farmers in Africa cannot afford manufactured fertiliser because of the effects of "structural readjustment" policies. Holderness (1997) observed that thousands of farmers are now reported to be growing *Tithonia* shrubs, known as Mexican Sunflowers, in their hedges and using the foliage to mulch their fields. Apart from the other benefits of mulching, this allows the farmers to restore phosphorus-deficient soils using ground-up phosphate-bearing rock, which is available in many countries of SSA. Holderness (1997) reported that rock phosphate as it comes out of the ground is useful to crops only when it is applied with a mulch. Professor Vlek and Dr Kuehne reinforced the idea that the key to soil fertility is a mixture of fertiliser and organic matter. Though mulches and agroforestry sound very "organic", not one speaker at the Royal Society meeting was opposed to inorganic fertilisers or to pesticides and several stated that without them we would starve. Professor Vlek was sceptical, though, of the prospects. Producing enough food for projected populations of the developing world in 2020, for example, would mean supplying 185 Mt of added plant nutrients (nitrogen, phosphorous and potassium fertiliser) a year, compared with 62 Mt in 1990. To restore levels of plant nutrients in the soil, instead of maintaining it in its present developed state, would mean adding not 185 Mt but 251 Mt a year in 2020 (Holderness, 1997).

ICRISAT (2000b) reported a method of composting rice straw that involves the use of 0.3% nitrogen (N) and 6% rock phosphate, on dry mass basis of rice straw and activating fungus (*Aspergillus awamori*). The method permitted the conversion of rice-straw into compost in 35- 45 days, compared with the usual composting period of 60 days or more. ICRISAT (2000b) report that rice-straw has been used by some researchers as a surface mulch and significant positive effects on the yield of some crops, particularly during dry seasons, have been recorded. The rapid-composting process was investigated by ICRISAT principally to resolve the situation where farmers in Asia burn large quantities of crop residues (rice and wheat straw in particular) thereby losing an important source of soil organic matter/crop nutrients whilst adding to environmental pollution, and adversely affecting health of the local populations. The procedure may have application in west Africa. For further information on the use of composting to release phosphorous from phosphate rock see (Bellaredj, 1998; Brun et al., 1993; Legault, 1998; Mahimairaja et al., 1995; Mathur et al., 1986; Sahu and Jana, 2000).

Role of phosphate rock in integrated nutrient management involving cover crops

At the 1996 meeting on *Cover Crops for a Sustainable Agriculture in West Africa* (Cornell University, 1996) it was noted that agricultural productivity in sub-Saharan Africa (SSA) must be increased substantially during the next decades in order to avert a serious food crisis. Furthermore, any efforts to enhance food security in SSA must include measures to effectively and sustainably regenerate soil productivity. It was observed that decades of cropping without fallowing have decreased soil fertility, destroyed organic matter and acidified soils. In Southern Benin, for example, where the red ultisols of the Alada plateaux have been intensively farmed for 23 years, organic matter content has dropped from 2.6 % to 0.8 %, pH has fallen from 5.8 to 4.8, and maize yields have plummeted from an average of 1500 kg/ha to 400 kg/ha. The meeting highlighted the fact that cover cropping could help reverse this trend and that cover crops can help to maximise the benefits derived from other low cost external soil amendments, *such as rock phosphate*. Where fertilizers are expensive and their quantity is limited, cover crops along with moderate amounts of externally derived nutrients (e.g. mineral fertilizer) are a cost-effective means for increasing the nutrients available in the soil and thereby increasing its productivity. In the West African Republic of Benin, farmer supported research carried out by the RAMR project (*Recherche Appliquée en Milieu Réel*, in collaboration with IITA) resulted in a simple innovation involving the use of *Mucuna* as a cover crop to rehabilitate fields abandoned because of degraded soils or excessive spear grass infestation. *Mucuna* seeds have been distributed to about 10,000 farmers, who are now adapting it to a variety of agricultural systems. Rotations of cereals with legumes, application of organic amendments (e.g. crop residue) and P fertilizer with ridging can also substantially increase the effectiveness of P applied either as phosphate rock or as conventional mineral fertilizers.

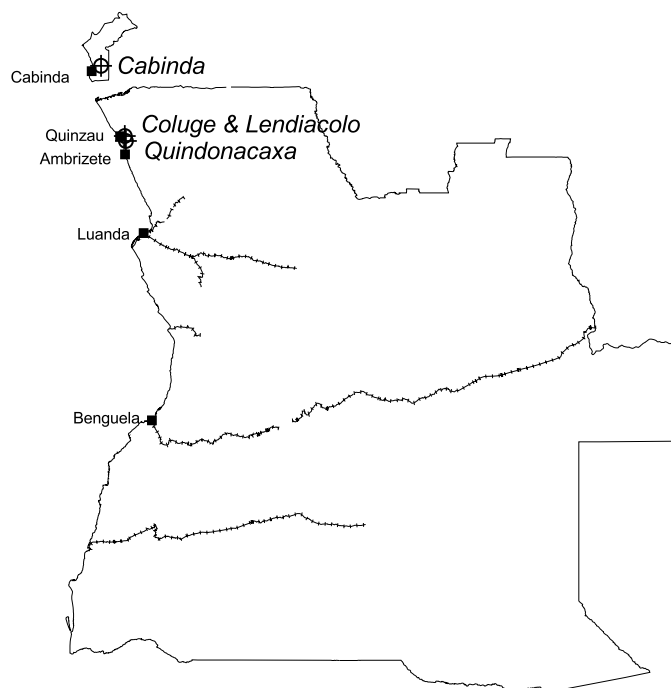
Kamh, Horst, et al. (1999) investigated the release of soil and fertilizer phosphate by cover crops. The studies tested the hypothesis that incorporation of cover crops into cropping systems may contribute to a more efficient utilisation of soil and fertilizer P by less P-efficient crops through exudation of P-mobilising compounds by the roots of P-efficient plant species. Citrate exudation from *Lupin* cluster roots was reported to be 10 times higher than that from root tips. Kamh, Horst, et al. (1999) concluded that white *Lupin* can mobilise P not only from the available and acid-soluble P, but also from the stable residual soil P fractions. Furthermore, they discovered that wheat in mixed culture and in rotation could benefit from the P mobilization capacity of white *Lupin*. Growth and P uptake of maize grown in rotation after legumes were enhanced indicating that improved P nutrition was a contributing factor.

Dominance of N deficiency over P in semi-arid and P deficiency over N in humid West Africa is illustrated by the characteristics of dominant species, in particular the trees (i.e. N-fixing legumes in Sahel and trees with strong mycorrhiza linkages in humid zones; (Breman and van Reuler, 2002)). This has consequences for the question: "when and where recommending legumes + P (or PR) as a solution for farmers problems (Henk Breman, personal communication, 22 June 2001).

IFDC-Africa is working with farmers to test the use of Togo rock (Hahotoe) in combination with *mucuna* in the southern part of Togo and in southern Benin. Tossa (2000) showed that using this combination followed by maize makes P more available for maize compared with the direct application of Togo rock on the maize crop. IFDC-Africa is using this system to make the use of NPK fertiliser economically feasible on a range of crops including maize and cassava (Anon., 2002). In addition, IFDC-Africa has been testing the system in 60 villages over the last few years in collaboration with the Institut Togolais de Recherche Agronomique (ITRA) and the IFAD funded rural development project "Programme d'Organisation et de Développement Villageois" (Henk Breman, personal communication, 22 June 2001).

COUNTRY PROFILES

Angola



Location, Quantity, Quality

Phosphate deposits occur in a sequence of marine Upper Cretaceous to Lower Eocene rocks deposited in the coastal Congo Basin, and as reworked accumulations in sediments of more recent age. The most important phosphate rock resources occur in the enclave of Cabinda, and in the Lucunga River area in northern Angola where phosphate rock resources were discovered in 1951. Commercial development has been prevented by the considerable variation in thickness and low grade of the phosphate rock beds together with a lack of adequate transport and port facilities.

In Cabinda, an estimated 16 Mt (million tonnes) of phosphate rock resources, of which 3.3 Mt are classed as proven, have been identified in five deposits (Cacata, Cambota, Chibute, Chivovo, and Mongo n'Tando) located within a 80 km coastal zone stretching from Massabe to the port of Cabinda. The phosphate rock deposits are of variable thickness and composed of extremely siliceous phosphate nodules and phosphatic limestones of variable thickness which generally contain 12-34% P_2O_5 .

Residual deposits of pelletal phosphatic nodules and phosphatic limestone occur in 0.3 to 0.6 m thick beds at three localities (Coluge, Lendiaçolo, and Quindonacaxa) in the Lucunga River area, to the east of Quinzau and about 40 km north of the port of Ambrizete. Total phosphate rock reserves in the Lucunga area are reported to be about 28 million tonnes with 25% P_2O_5 , although grades range up to 33% P_2O_5 . SiO_2 in the PR is generally greater than 15%. Overburden thickness ranges from 0.1 to 2 m.

An occurrence of phosphate rock has been recorded in an igneous complex with a central carbonatite core, located 4 km south-west of Longonjo, south-west of Huambo, but no details are readily available.

Past production (1960 onwards)

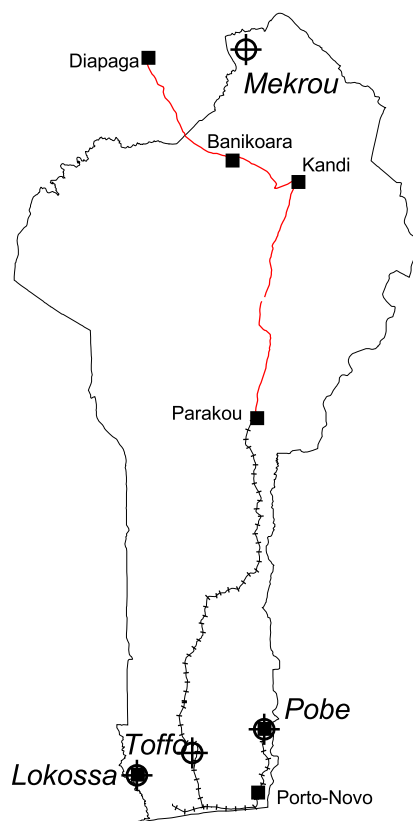
A 15,000 t/y experimental mine in the Quindonacaxa area (16 km south-east of Quinzau) was developed in collaboration with Bulgaria in 1981 to produce phosphate rock (18% P₂O₅) which was beneficiated to 29% P₂O₅. This material was transferred to Lobito from distribution to the interior of Angola by rail. The mine is reported to have closed after 1 year due to guerrilla activity (Atkinson and Hale, 1993).

Sources: (Giresse and Baloka, 1997; McClellan and Notholt, 1986; Menov, 1985; Notholt, 1999; Sustrac et al., 1990)

Agronomic testing and use

Apart from the brief period when PR concentrates from the Quindonacaxa area were used in the interior of Angola, there are no additional records of phosphate rock being used for direct application, either for agronomic trials or commercially.

Benin



Location, Quantity, Quality

Potentially important phosphate rock resources of 5 million tonnes of poorly sorted phosphorites occur over about 200 km² in the structurally and stratigraphically complex Mekrou River area, close to the northern border of Benin. The Upper-Proterozoic deposits in the Pendjari Formation were discovered in the late 1970's and represent an extension of deposits of the same general age in adjacent Burkina Faso and Niger. The phosphate deposits comprise medium to dark grey phosphatic sandstones (20 to 26% P₂O₅) separated by grey and green shales. Lenticular phosphatic sandstones in the lower sequence exceed 10 m in cumulative thickness although individual sandstones are generally only about 0.5 m thick. The UNDP proved reserves to a depth of 30 m of about 3.3 million tonnes (25% P₂O₅) underlying an area of 0.225 km². Low NAC solubility (1.9% P₂O₅) indicate low potential for use as a direct application fertiliser whereas the low Fe₂O₃ + Al₂O₃ + MgO/ P₂O₅ ratio (0.07) and low chlorine (about 50 ppm) confirm that the concentrate or ore could be used for the production of a number of manufactured phosphate fertiliser products. Mining Annual Review (2000) reported that "The future of the phosphate deposit at Mekrou and the iron ore deposit of Loumbou-Loumbou could be enhanced when a hydro-electric dam project on the river Mekrou is given the go-ahead."

Paleocene to Eocene phosphate resources have been identified at Pobe, Kpome, Toffo, and Lokossa in southern Benin. Whereas these phosphate rocks are similar to the economic deposits in Togo, their relatively low P₂O₅ concentrations (ranging up to 23%, but generally <20%), poor quality and occurrence in generally thin (<1 m) beds has meant that they have never been considered to have economic potential for fertilizer manufacturing.

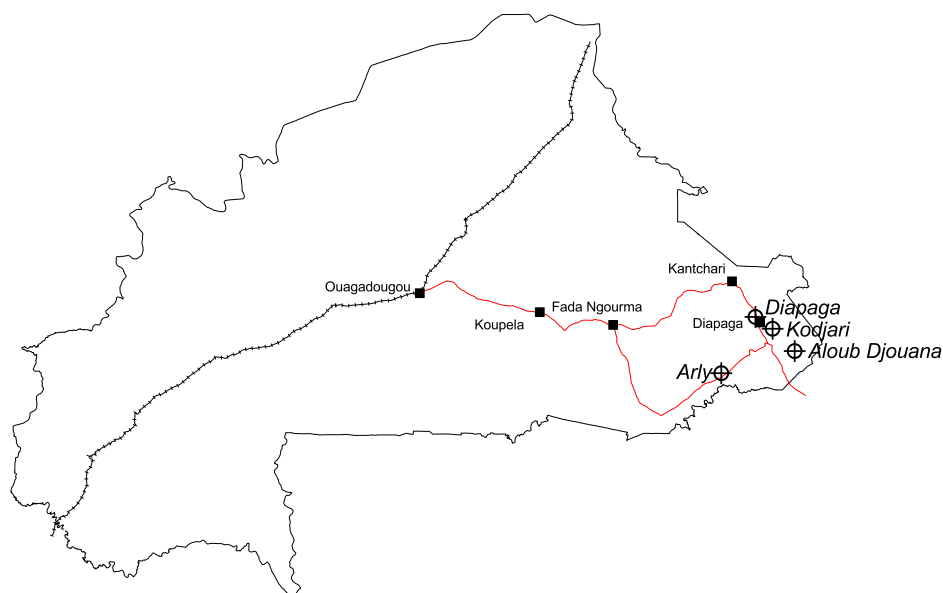
Sources: (Flicoteaux and Trompette, 1998; McClellan and Notholt, 1986; Sustrac et al., 1990; Van Kauwenbergh et al., 1991a)

Agronomic testing and use

Aïhou and Adomou (1999) tested a maize legume (cowpea and *Mucuna*) rotation system to try and overcome soil degradation caused by overexploitation and lack of credit for chemical fertilizers in Benin. Results after two years indicated that yields higher than that of the control (previous maize + 0P: 1518 kg/ha) were observed through the residual effects of cowpea or *Mucuna* treatments, which received a combination of 50% TSP and 50% Togo phosphate rock (previous *Mucuna* + TSPN: 2576 kg /ha; previous cowpea + TSPN: 2519 kg/ha). The TSPN combination gave a 27% surplus of maize grain yield as compared to the control without phosphorous application (1947 kg/ha). But, as compared to organic matter sources, cowpea and *Mucuna* residues induced respectively maize grain yields that were 41% and 35% higher than yields obtained with maize residues (1666 kg/ha). These trials emphasise the potential benefits of applying P-fertilizer in rotation systems, although the relative contributions from TSP and RP to increased yield were not examined in these trials.

Additional sources: (Aïhou and Adomou, 1999; Cornell University, 1996; Glaser and Drechsel, 1992; IITA, 1999b; IITA, 2000; Tossa, 2000; Vanlauwe et al., 1999)

Burkina Faso



Location, Quantity, Quality

Three Upper Proterozoic sedimentary phosphate rock deposits were discovered in the late-1960's – early 1970's in the *Parcs Nationaux du 'W'* area, adjacent to the Burkina Faso - Niger border, and about 135 km SSE of Niamey in Niger. 1 to 15 m thick phosphorite beds and lenses with 15 - 32 % P_2O_5 occur at Diapaga (12°8'N, 1°45'E; estimated resources 224 Mt), Kodjari (12°1'N, 1°55'E; 80 Mt) and Arly (11°35'N, 1°25'E; about 4 Mt). The best developed phosphatic beds in the Kodjari Formation range from 4 m to 16 m in thickness and display zonations resulting from weathering to a depth of 12 m. Whereas the quality of the phosphate ore (indicated by the Fe+Al+Mg/P ratio) increases with depth, generally high levels of impurities would produce problems in fertilizer products (Van Kauwenbergh et al., 1991a). NAC solubility ranges from 1.9 to 2.7%, which is rather low for use as direct application fertilizer (Van Kauwenbergh et al., 1991a). The Kodjari deposits have been worked for direct application fertilizer (see below). Although the phosphate rock beds at Arly are very siliceous (29-34% SiO_2), they are relatively high grade with 26 to 32 % P_2O_5 and only minor amounts of Al, Fe and Mg (combined $Fe_2O_3 + Al_2O_3$ is less than 2%). NAC soluble P_2O_5 is 2.8% (Van Kauwenbergh et al., 1991a). The Arly phosphorite beds are up to 1.5 m thick within a formation that varies from 0 to 15 m. The Aloub Djouana deposit, with 19 to 29% P_2O_5 , 6-7% Al_2O_3 , and 29-35% SiO_2 , is generally lower grade than the Kodjari and Arly deposits (Van Kauwenbergh et al., 1991a).

Current production

The sedimentary phosphate rock at Kodjari (27.5% P_2O_5) was reported to have been exploited with the assistance of the Federal German Agency for Technical Cooperation (*Der Bundesminister für Wirtschaftliche Zusammenarbeit* (BMZ)) at a rate of 1,000 tpy for direct application to the soil (McClellan and Notholt, 1986). The rock was transported to Diapaga for grinding and bagging. 5,462 mt of *Burkina phosphate* (in 50 kg bags) was produced during the period 1978 to 1985 of which 4,599 mt was sold to farmers, agricultural centres and other organisations within Burkina Faso (Van Kauwenbergh et al., 1991a). FAO recorded a production of 1000 t phosphate rock in 1993/94, all of which was used for direct

application. Other sources indicate production in 1994 was 2,207 t. The ground phosphate rock was promoted for a variety of crops including maize, rice and sugar cane. Sugar cane producers were buying the ground phosphate rock in 1994, but the bulk of it was being used experimentally. Phosphate fertilizer production of 300 t P₂O₅ reported for 1993/94 (Table 3) was all ground phosphate rock; no manufactured phosphate fertilizers are produced in Burkina Faso.

Sources: (Maurin et al., 1989; McClellan and Notholt, 1986; Trompette, 1989; Van Kauwenbergh et al., 1991a)

Agronomic testing and use

Van Kauwenbergh, Johnson et al. (1991a) summarised the results of agronomic trials carried out with partially acidulated Kodjari PR in Burkina Faso in the mid-1980's. PAPR (50) was 108% as effective as SSP for sorghum planted on Alfisol whereas finely ground Kodjari PR was only 62% as effective. A residual study with maize at Saria produced the following RAE data with reference to TSP: Kodjari PAPR (50) 92%, control 62%. In another trial with maize in the Soudanian savanna region, Kodjari PR and PAPR were, on average, only 84% as effective as SSP. For additional details see Van Kauwenbergh, Johnson et al. (1991, p.192-193).

Lompo, Sedogo, et al. (1995) reported the results for maize sorghum and millet trials that studied the agronomic impact of Burkina (Kodjari) phosphate rock (BPR) and dolomitic limestone. BPR applied at a rate of 400 kg/ha or 100 kg/ha followed by corrective applications of 100 kg/ha annually resulted in average yield increases of about 130 kg millet/ha, 200 kg sorghum/ha and 400 kg maize/ha. The RAE (relative to TSP) for BPR was 69% for millet, 65% for sorghum and 47% for maize. Maize yields increased in response to BPR in the high rainfall areas of South and South-west Burkina Faso whereas low crop yields resulted in the low rainfall areas. On trials with rain-fed rice, BPR was as effective or more effective than TSP in the first year of the trial whereas in the second year the effectiveness of the BPR was enhanced and higher than that for TSP at dosages less than 90 kg P₂O₅/ha. On irrigated rice, partial acidulation of the BPR was not necessary and the BPR could be used at a rate of 500 kg/ha in year one (corrective application) followed by annual top-up applications of 100 kg/ha. For sorghum production, the highest yields were obtained with TSP, especially when applied with dolomite. Yields for BPR and 50% partially acidulated BPR were almost identical with about 45% increase in yield for NK-BPR compared with the NK-0P control. P was applied at a rate of 25 kg P₂O₅/ha/year in these trials.

Bado and Hien (1998) evaluated the agronomic efficiency of Burkina Faso rock phosphate (BPR) and triple superphosphate (TSP) on upland rice crops in oxisols with four different phosphate input levels (0, 13, 26 and 39 kg/ha/year). Results showed that P deficiency is a limiting factor for upland rice production and that the application of TSP or BPR increased P absorption and rice yield. Rice uptake of P was better with TSP, probably because of its solubility. In the first year, the two phosphate sources had the same agronomic efficiency on rice yield, while BPR more efficiently increased rice yield than TSP in the second year, confirming the residual benefit of BPR. The authors of this report conclude that BPR seems well adapted and economically suitable for upland rice fertilization.

Muleba (1999) studied cowpea and sorghum grain crops, fertilized with 26 kg of phosphorus (P) per ha from either a P-soluble (SSP) or a slightly P-soluble fertilizer (Kodjari rock phosphate - KRP), and cowpea and crotalaria (*Crotalaria retusa*) green manure crops, either unfertilized or fertilized with 26 kg P/ha from KRP for their effects as preceding crop treatments for maize. The experiment was conducted in semi-arid West Africa (SAWA) at Farako-Ba in Burkina Faso in 1983-86. Nitrogen (N) and soluble P fertilized and unfertilized subtreatments, applied to maize the following year, allowed the effects of the preceding crop treatments in improving soil fertility and the direct effects of P and N fertilizers applied to the maize crop to be assessed. Maize productivity was increased both by P fertilization and by soil improvements following cowpea and *crotalaria*; N fertilization in excess of 60 kg N/ha was not beneficial. Cowpea grain crop treatments, especially when fertilized with a P-soluble source, maximized maize yields, whereas cowpea and *crotalaria* green manure treatments were either similar to the cowpea grain treatment fertilized with RP or were intermediate between the latter and the sorghum treatment fertilized with SP. Sorghum, regardless of the source of P-fertilizer used, appeared not to be a suitable preceding crop for maize in SAWA.

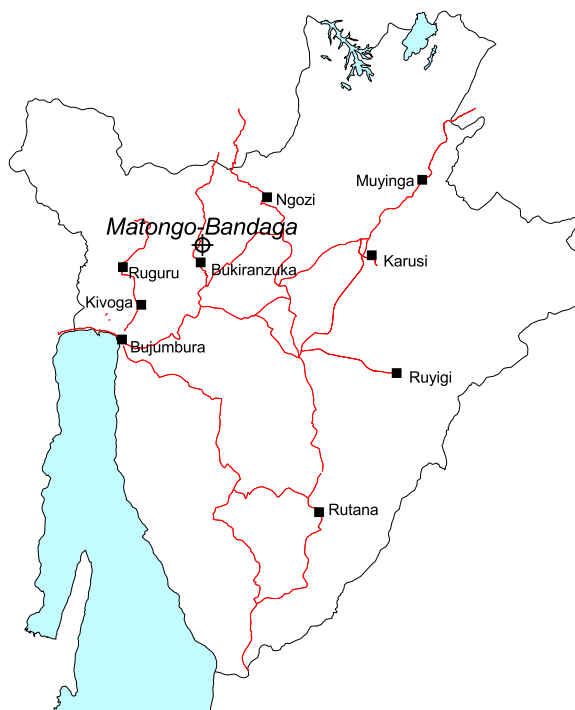
Muleba and Coulibaly (1999) studied the effects on cowpea and subsequent cereal crop productivity of sparingly soluble natural rock phosphate from Kodjari (KRP) in Burkina Faso, and a commercial single superphosphate (SSP) fertilizer at Farako-Ba in the Northern Guinea Savannah (NGS) and at Oipasse in the Sudan Savannah (SS) regions of Burkina Faso. The objectives of the research were to study the direct and residual effects of the P fertilizers on soil fertility improvement in order to boost agricultural productivity in both regions. Cowpea cultivars, in both regions, and maize and sorghum in the NGS and SS regions, respectively, responded more strongly to SSP than to RP fertilizer treatments. The optimum rate of SSP and RP source was 21.8 kg P/ha and 43.6 kg P/ha, respectively, for cowpea in both regions. The optimum rates of phosphorus fertilizer applied in the second year to maize in the NGS and to sorghum in the SS region, in addition to the optimum rate of P applied to cowpea the previous year, was 10.9 kg P/ha of SSP or 43.6 kg P/ha of RP, and 21.8 kg P/ha of SSP or 43.6 kg P/ha of RP, respectively. Both P sources had significant residual effects for up to 2 years. The agronomic effectiveness of RP relative to SSP, in the year of application of both fertilizers, was greater for cowpea than for maize in the NGS region and similar for cowpea and sorghum in the SS region; it increased markedly for the two subsequent cereal crops in both regions. Cowpea fertilization with both P sources proved, therefore, to be effective in improving the soil fertility and boosting the productivity of cereal crops in the 3-year crop sequence.

Segda and Hien (2001) reported research in Burkina Faso directed towards the promotion and development of the use of cover crops and an alternative to the traditional grazed fallow in two ecosystems: rain-fed sorghum (East) and maize based systems and upland rice (West) and lowland rice system in the two zones. In the rain-fed ecosystem in the western region of Burkina, species that performed very well were *Mucuna cochinchinensis*, *Mucuna pruriens*, and *Cajanus cajan*. Generally, these screening activities indicated that legumes offer an alternative to natural fallows in solving low soil fertility and low crop yield problems. Yields of cereal crops (sorghum, millet, and rice) planted in rotation after legume intercrop or a short legume fallow, increased as compared to yields under monoculture and after one year natural fallow. Weed infestation was lower with subsequent cereals to legume fallows. With respect to the interactions between rock phosphate and legumes, studies indicated that phosphorous (P) application improved shoot biomass, nodulation, and symbiotic nitrogen fixation of *Mucuna*, as compared to the control without phosphorous. The authors concluded, on the basis of the promising results obtained, that cover crops (notably *Mucuna*) displayed great potential in rotation and intercropping systems in the tropical savanna zone in Burkina Faso.

In Burkina Faso, PR was promoted as a cheap fertiliser that can replace inorganic chemical fertiliser in general instead of a source of P in cases where P is the limiting factor. The Dutch and Danish Embassy in Ouagadougou worked with the Burkina government on the economics of large-scale use of Burkina (NEI, 1998). The conclusions are not very favourable for a large-scale introduction of PR (Kuyvenhoven and Lanser, 1999).

Additional sources: (Bado and Hien, 1998; Bationo et al., 1992b; Bekunda et al., 1997; Cattan, 1992; Cornell University, 1996; Diouf et al., 1995; Enyong et al., 1999; Harsch, 1999; Hien et al., 1997; ICRISAT, 2000a; ILEIA, 2000; Ker, 1995; Kuyvenhoven and Lanser, 1999; Lompo, 1993; Muleba, 1999; Muleba and Coulibaly, 1999; NEI, 1998; Sanchez et al., 1997; Segda and Hien, 2001; Tomlinson et al., 1998; USAID, 1999; West Africa Rice Development Association, 1999; Zong, 1995)

Burundi



Location, Quantity, Quality

Residual apatite-rich phosphate ore occurs in a weathered mantle up to 55 m thick over the Upper Ruvubu Alkaline Complex at Matongo-Bandaga, located 40 km north-east of the capital Bujumbura. Much of the phosphate mineralization appears to be associated with either extensively altered schists or syenitic rock, with the prospective ore deposits lying at the contact between nepheline syenite and carbonatite. Some of the apatite may have been introduced into the Matongo country rocks as a result of late-stage metasomatic or hydrothermal processes. These rocks have suffered further supergene alteration including ferruginization and the formation of aluminium phosphates of the crandallite group. Feldspathic phosphatic sands, of possible eluvial origin, have been reported from near the upper surface of the carbonatite.

Investigations carried out by UNDP, the British Sulphur Corporation (1982-83) and latterly by IFDC (1987) and *Département de Géologie et des Mines* (DGM) in 1988-89 reveal that there is a large mass of relatively unconsolidated, highly phosphatic weathered material within which there are numerous zones of phosphate (apatite and crandallite) mineralization. This heterogeneous regolithic material overlies carbonatite that has been weathered to a depth of at least 130 m. Much of the mineralization lies in horizontally orientated, discontinuous, bodies, related to the general configuration of the underlying carbonatite. Exploitation of phosphate would be rendered difficult by the heterogeneous nature of the deposit in which high grade 'blocks' of phosphate rock have restricted horizontal and vertical extensions.

Reserve estimates made in 1984 indicated 40 Mt, averaging 4.6% P_2O_5 (no cut-off, no minimum thickness); and 17.3 Mt with 11% P_2O_5 (based on a cut-off grade 5%, 1.5 m minimum thickness) (Notholt, 1999). The most recent reserve estimates made in 1988-89 indicated three ore bodies with 3.17 Mt to a mineable depth of 40 m. These could yield 350,000 to 450,000 t of phosphate concentrate, depending on the recovery rate. Beneficiation tests indicate that the apatite ore can be concentrated to about 35% P_2O_5 .

A major problem with the reserve and resource estimates relates to the fact that hydrated Ca-Al phosphate (crandallite) is difficult to remove by conventional beneficiation procedures and is therefore a potentially deleterious component of the Matongo phosphate ore. Low CaO: P₂O₅ ratios reported for many of the samples indicate that much of the ore probably consists of intimate mixtures of apatite and crandallite. However, it should be remembered that sedimentary crandallitic ores in western Senegal are mined on a commercial scale and calcined to provide a fertilizer (*Phospal*) for direct application to acid soils, usually as phosphate-potash mixtures. Calcination may be applicable to some of the Matongo ores.

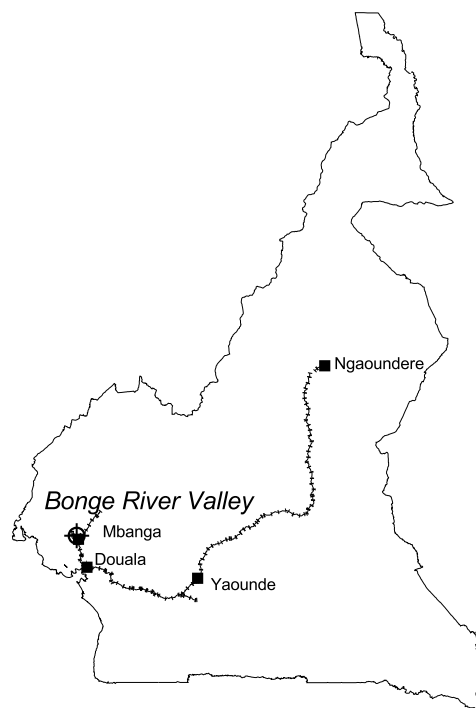
Sources: (Kurtanek and Tandy, 1989; McClellan and Notholt, 1986; Notholt, 1999; Songore, 1991; Van Kauwenbergh and Roy, 1990)

Agronomic testing and use

VandenBerghe (1996) studied the effect of Matongo (Burundi) rock phosphate and urea as compared to di-ammonium phosphate (DAP) in the composting process and on the yield of potatoes in the Mugamba region in Burundi. Trials on potatoes cultivated in Kaolisols compared (i) non-treated compost, (ii) treated compost with diammonium phosphate (DAP) and (iii) treated compost with local phosphate rock from Matongo (MPR) and urea. Fertiliser-treated composts showed better C/N ratios, and higher P and N contents than the non-treated compost. Analysis of potato yields showed a linear response to compost dose while regression analysis indicated that the response curves for non-treated compost and DAP compost were significantly different, the MPR compost occupying an intermediate position. The Relative Agronomic efficiencies of DAP- and MPR-compost are 146 and 118 respectively compared with non-treated compost. Economic analysis showed higher profits, value/cost (V/C) and better risk factors for the different doses of MPR compost used in this study, when compared to untreated compost. Application of organic matter and lime had a favourable effect on pH, exchangeable aluminium and P Bray-1 contents of the soils, MPR and DAP-composts behaving in a similar way.

Additional source: (IDRC, 1996)

Cameroon



Location, Quantity, Quality

Siliceous phosphatic nodules containing 12 to 18% P_2O_5 occur in the Bonge River Valley, near Kompina, 50 km NNW of Douala. Little information is available on these occurrences but they are probably not of economic interest even though they occur in Eocene sedimentary strata.

Source: (McClellan and Notholt, 1986)

Agronomic testing and use

No details are available on agronomic trials in the Cameroon using phosphate rock. *Additional sources* include: (Bouharmont, 1993; Ker, 1995; Menzies and Gillman, 1997; Moyersoen et al., 1998; Sustrac et al., 1990; USAID, 1999)

Central African Republic



Location, Quantity, Quality

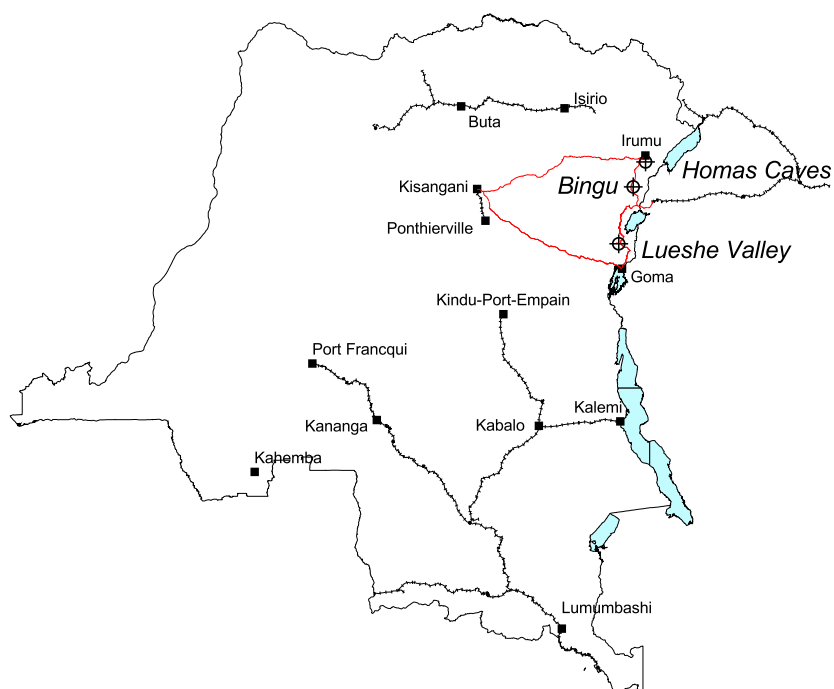
Small phosphatic lenses reaching a total thickness of 20 to 25 m occur at depths of up to 25-35 m within Eocene clays at Bakouma, close to the border with Democratic Republic of the Congo (formerly Zaire) - about 480 km north-east of Bangui and approximately 1,500 km inland from the Cameroon port of Douala. The deposits were discovered during the search for uranium in the 1960s. Grades of 9-35% P_2O_5 have been recorded together with up to 0.56% uranium (average 0.25% U_3O_8), which is much higher than uranium levels recorded in other phosphate rock deposits in sub-Saharan Africa. The phosphorites are intensely weathered to depths of 5 m or more.

Source: (McClellan and Notholt, 1986)

Agronomic testing and use

There is no record of phosphate rock being used for direct application, either for agronomic trials or commercially.

Democratic Republic of the Congo



Location, Quantity, Quality

Apatite is a potential by-product if pyrochlore was ever to be extracted from the residual ore developed over carbonatite at Lueshe, 40 km south of Lake Kivu (1°0'S, 29°8'E). The carbonatite itself contains only about 4% P_2O_5 but the grade increases to about 10% in the residual ferruginous material developed over the carbonatite. Apatite has also been reported from the Bingu carbonatite complex located 80 km north of Lake Edward but, as with Lueshe, the main economic potential of these residual deposits is for niobium, of which there is reported to be 30 Mt of resources with 1.36% Nb_2O_5 .

Total reserves of bat guano found in the Homas caves in Kibali-Ituri Province in the late 1940's were estimated at 200,000 tons, of which 170,000 tons averaging at least 12% P_2O_5 are believed to be present in 26 caves. The caves are developed in dolomite outcropping on the western flanks of Mt. Hoyo, about 12 miles south of the town of Irumu. Chemical analyses of the guano show concentrations ranging from 5 to 24% P_2O_5 . There were plans in 1948 to work the deposit in Sagasaga cave, which attains a thickness of nearly 40 ft, but no actual working appears to have taken place.

Apatite is present also in minor amounts in aplites, pegmatites and veins of pre-Cambrian age. None of the apatite and guano occurrences are of commercial interest as a source of phosphate.

Sources: (Agence Congolaise de Presse, 2000; McClellan and Notholt, 1986; Notholt, 1999)

Agronomic testing and use

No details are available on agronomic trials in Democratic Republic of the Congo⁵ using phosphate rock.

⁵ The Democratic Republic of the Congo was known as Zaire prior to May 29, 1997.

Côte d'Ivoire

Location, Quantity, Quality

There is no evidence that phosphate rock resources occur within the Côte d'Ivoire.

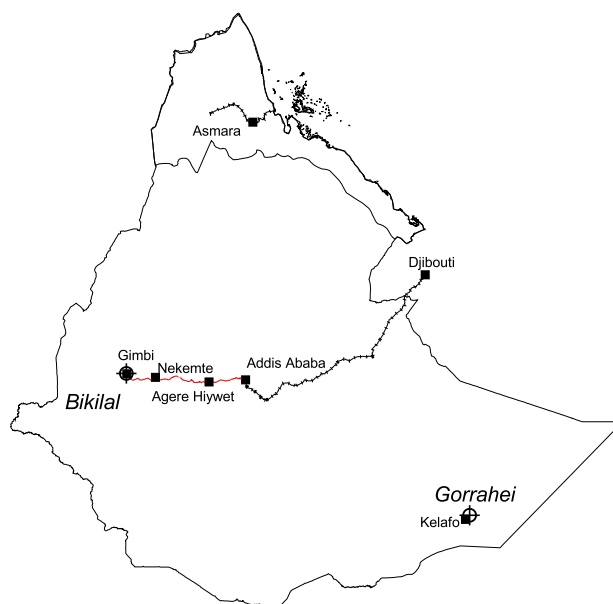
Agronomic testing and use

Bank (1997) reported that small quantities of rock phosphate are used by the "Tropical Rubber Côte d'Ivoire" company. Somado, Kuehne, et al. (2000) investigated the enhancement of biomass and nitrogen accumulation in short-duration pre-rice legume fallows by phosphate rock application in rice-based systems in humid Côte d'Ivoire

West Africa Rice Development Association (1999) reported trials with rock phosphate and TSP for upland rice in humid forest areas in the Bouaké area, Côte d'Ivoire. TSP out-yielded Burkina Faso, Mali, Niger, Senegal and Togo RP in initial trials whereas only Mali RP showed potential as a substitute for TSP. A residual effects trial at Man, Côte d'Ivoire, showed that Mali RP performed as well as TSP in the first year. In the second year (1999) all RPs gave significantly higher rice yield responses than in the first year - demonstrating the residual effect. It was concluded that rock phosphate looks increasingly like a viable alternative to TSP for rice fertilization in the humid uplands.

Additional sources: (Bekunda et al., 1997; Ker, 1995)

Ethiopia



Location, Quantity, Quality

A few phosphate rock occurrences have been recorded in sedimentary and igneous rocks at various sites in Ethiopia, but their potential is not well known. The only significant phosphate occurrence in Ethiopia is in the igneous Bikilal apatite-magnetite-ilmenite deposit located in the Welega Region, 20 km NNE of the town of Gimbi, and about 465 km W of Addis Ababa. The deposit is low grade (averaging about 4.5% P_2O_5 , (IFDC, 1988)) and the results of exploration work have not yet been published. Mining Annual Review (2000) reported that the Ethiopia Geological Survey has verified the existence over 200 Mt of phosphate resources.

The rock phosphate contains 15-20% hydroxy-fluorapatite with a low solubility (0.8% NAC P_2O_5) in a sample with 7% Total P_2O_5 (IFDC, 1988). The igneous apatite would be expected to have a relatively low solubility and therefore low potential as a direct application fertilizer. However, an apatite concentrate could be recovered relatively easily from the amphibole (approx. 50%) and magnetite-ilmenite (approx. 30%) gangue and this could be processed to produce a water soluble phosphate fertilizer (IFDC, 1988). A high $Fe_2O_3+Al_2O_3+MgO/P_2O_5$ ratio of 5.4 for one sample with 7% P_2O_5 compares unfavourably the ratio of 0.1 found in most commercial concentrates. This would lead to problems during the manufacture of phosphoric acid, SSP or partially acidulated PR (IFDC, 1988).

Geological comparisons with neighbouring countries suggest that sedimentary phosphate rock is likely to be present in Ethiopia. Sedimentary sequences of Late Cretaceous-Lower Eocene age are the most promising exploration targets, in view of the widespread distribution of phosphate in rocks of comparable age in neighbouring countries such as Egypt and Jordan. The depositional characteristics of the Upper Palaeocene-Lower Eocene Auradu Series, restricted to the eastern Ogaden, suggest that this formation provides the most appropriate target for phosphate exploration. Whereas a number of sedimentary strata have potential for the occurrence of sedimentary phosphate resources, prospecting activities by the Ethiopia Institute of Geological Surveys have not so far identified any significant occurrences (Assefa, 1991; IFDC, 1988) although some very minor phosphate mineralization is reported to have been observed in outcrop. In addition, fragments of phosphorite and phosphatised fossils have been encountered in Cretaceous sedimentary rocks intersected at a depth of about 800 m in a borehole drilled

during exploration for oil in the south eastern Ogaden desert. Unfortunately, no strata of this age crop out at the surface as thick Palaeogene sediments bury them.

The phosphate exploration programme carried out by the Geological Survey has been a major component of Ethiopia's recent attempts to develop the fertiliser industry in order to boost its agricultural productivity (Mining Annual Review, 2000).

Sources: (Assefa, 1991; IFDC, 1988; McClellan and Notholt, 1986; Notholt, 1999)

Agronomic testing and use

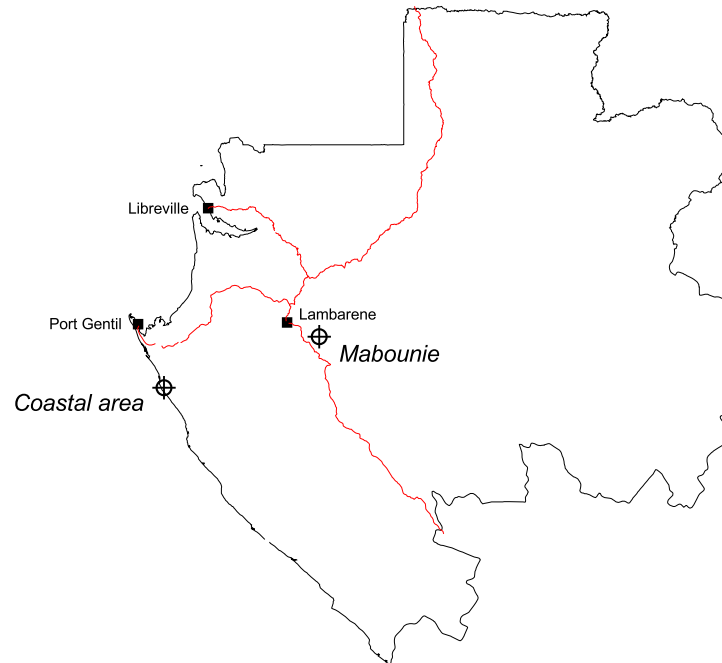
Bekele and Hofner (1993a) evaluated the effectiveness of six different phosphate fertilizers on the yield of barley and rape seed on reddish brown soils of the Ethiopian Highlands. The fertilizer sources include: basic slag (BS), bone meal (BM), Ethiopian (Bikilal) rock phosphate (ERP), Gafsa rock phosphate (GRP), triple superphosphate (TSP) and a mixture of TSP and GRP in the ratio 1:4. The highest agronomic effectiveness relative to TSP (RAE) for both crops was obtained with basic slag. Rape was found to utilize P not only from the reactive rock phosphate (GRP) but also from the unreactive one (ERP), which had a total P content of only 3% and 0.4% ammonium citrate soluble P. Barley, on the contrary, could not utilize P from this magmatic rock phosphate and failed to grow. This confirms reports from elsewhere that rape can make effective use of RP whereas cereal crops such as barley are generally much less responsive.

Haque, Lupwayi, et al. (1999b) discovered that unacidulated and partially acidulated Minjingu rock phosphates applied during cultivation of *Stylosanthes guianensis* (grass) in the Ethiopian Highlands was as agronomically effective as TSP. Yields increased from 3 t/ha without phosphate up to 5 t/ha. Haque, Lupwayi, et al. (1999b) also investigated the agronomic effectiveness of unacidulated and partially acidulated Minjingu and Chilembwe phosphate rocks for clover production in Ethiopia. The fertilizers were applied once at 0-80 kg P ha⁻¹. Over four consecutive clover crops, Minjingu PR was 114%, PAPR(25) was 113% and PAPR(50) was 107% as effective as TSP in increasing clover herbage yields. In the Chilembwe phosphate rock experiment, PR was 27%, PAPR(25) was 57% and PAPR(50) was 73% as effective as TSP in increasing clover herbage yields, over all the five crops. It was concluded that raw Minjingu phosphate rock is highly effective on clover in these vertisols and partial acidulation is not necessary, but raw Chilembwe phosphate rock is ineffective and 50% partial acidulation is recommended.

Haque and Lupwayi (1998a) evaluated the effectiveness and residual effects of Egyptian phosphate rock (EPR) and Togo phosphate rock (TPR) relative to triple superphosphate (TSP) applied at 0, 20, 40, 80, and 160 kg P ha⁻¹ to annual *Trifolium* (clover) species grown in a P-deficient Vertisol. Over all the seven crops, EPR was 82% as effective as TSP in increasing clover DM and 83% as effective in increasing P uptake. For TPR, the relative responses were 54% and 52% for DM yield and P uptake, respectively, and the corresponding substitution rates were 29% and 27%. Mixing these phosphate rocks with triple superphosphate (TSP) in various proportions (at 60 kg P ha⁻¹) revealed that the highest response was observed with TSP applied alone, but the phosphate rocks applied alone also significantly increased yields compared with the controls without applied P. Mixtures of TPR and TSP increased yields only slightly over pure TPR, and mixtures of EPR and TSP had no effect on yields compared with pure EPR, presumably because EPR is more reactive than TPR. It was concluded that EPR is highly effective in these soils, but the effectiveness of TPR is low, reflecting the low NAC solubility of the TPR (3% P₂O₅) compared with EPR. The highly reactive EPR could be used to elevate the P status of the P-deficient Vertisols and increase feed availability and livestock productivity in the Ethiopian highlands. Mixing of these phosphate rocks with TSP was not recommended (Haque and Lupwayi, 1998a; Haque and Lupwayi, 1998b).

Additional sources: (Ayele and Mamo, 1995; Bekele and Hofner, 1992; Bekele and Hofner, 1993a; Bekele and Hofner, 1993b; Belete et al., 1992; DANIDA, 2000; Duffera and Robarge, 1999; Ghizaw et al., 1999; Haque and Lupwayi, 1998b; Haque et al., 1999b; IDRC, 1996; IFA, 2000a; Nnadi and Haque, 1988; Shapiro and Sanders, 1998a; Soltan et al., 1993; Ssali, 1990; Vagen et al., 1999)

Gabon



Location, Quantity, Quality

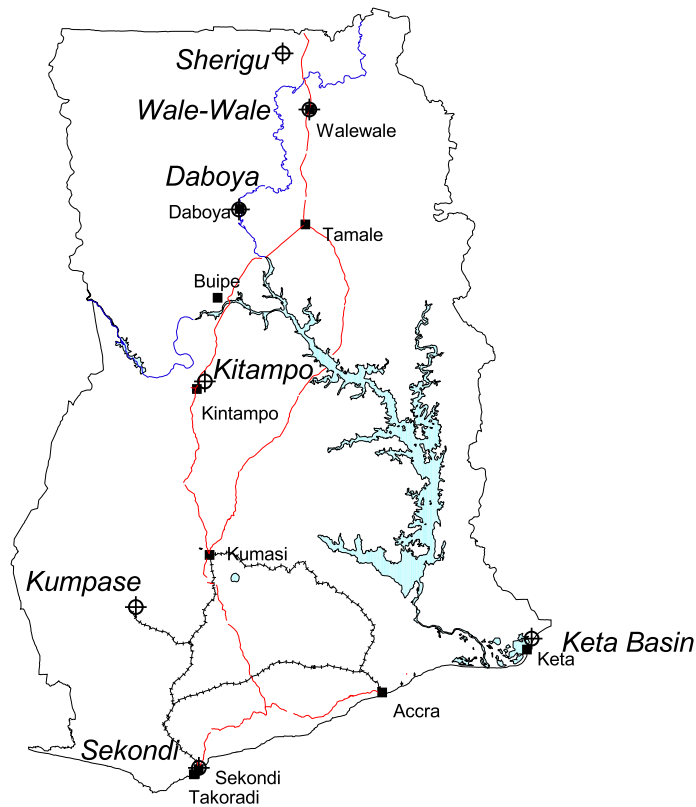
Highly silicified nodular phosphate rocks occur in Cretaceous strata in the coastal zone of Gabon, SSE of Port Gentil. Grades range from 8-32% P_2O_5 but the phosphate is probably of little economic interest as a source of raw material for fertilizers. Phosphate resources were discovered recently associated with the Late Proterozoic Mabounié carbonatite complex, located in central Gabon about 40 km ESE of Lamberéné and less than 10 km from river transport. Intense weathering over the carbonatite has resulted in the development of a 40 m thick lateritic zone comprising an upper 15 m thick indurated phosphatic layer containing magnetite and secondary apatite, overlain by a 15 m thick 'mottled' layer containing magnetite, hematite and crandallite, and a 8 m surface layer containing hematite, goethite, crandallite, quartz and kaolinite. Accessory mineral phases of possible economic significance include pyrochlore (niobium) and baddeleyite (zirconium). Geological resources of 140 Mt containing 24% P_2O_5 were discovered following a regional mineral reconnaissance and the Gabon Government sought foreign technical and financial assistance to develop the deposits through the *Société Minière du Moyen Ogooué* consortium, of which the Government owned 62%. Production of 2 million metric tons per year of phosphate concentrate containing about 39% P_2O_5 could be obtained over at least 20 years. A slurry pipeline from Mabounié to Lambaréné and then river transport to Port Gentil is the most likely route for transporting phosphate concentrates to exterior markets. Recovery of a niobium co-product also was under study (Direction des Relations Economiques Extérieures de France, 2000; Jones, 1996). A detailed evaluation of the phosphate deposit was carried out in 1998 (Anon., 1998b).

Sources: (Anon., 1998b; Barusseau et al., 1988; Giresse and Baloka, 1997; Hourcq, 1966; McClellan and Notholt, 1986; Sustrac et al., 1990)

Agronomic testing and use

No details are available on agronomic trials in the Gabon using phosphate rock

Ghana



Location, Quantity, Quality

Sedimentary phosphate rock occurrences of Eocene to Cretaceous age occur in the Keta Basin, and at Sekondi, 180 km SW of Accra, where phosphatic nodules with about 15% P_2O_5 occur in shales exposed in the coastal cliffs near Sekondi. Little is known about the quantity of resources although they are believed to be very small. In the Keta Basin, P_2O_5 concentrations were generally below 2.3% with a few samples in the range 10 to 25%. Limited reconnaissance exploration has been carried out so there is still potential for the discovery of a phosphate deposit in the Keta Basin that is similar in size and quality to the Hahotoe-Kpogame deposits in neighbouring Togo. Van Kauwenberg (1991, Figure 3.3.5) records thirteen phosphate deposits in Ghana of which only Keta and Sekondi are considered to be of any significance.

Sources: (McClellan and Notholt, 1986; Van Kauwenbergh et al., 1991a)

Agronomic testing and use

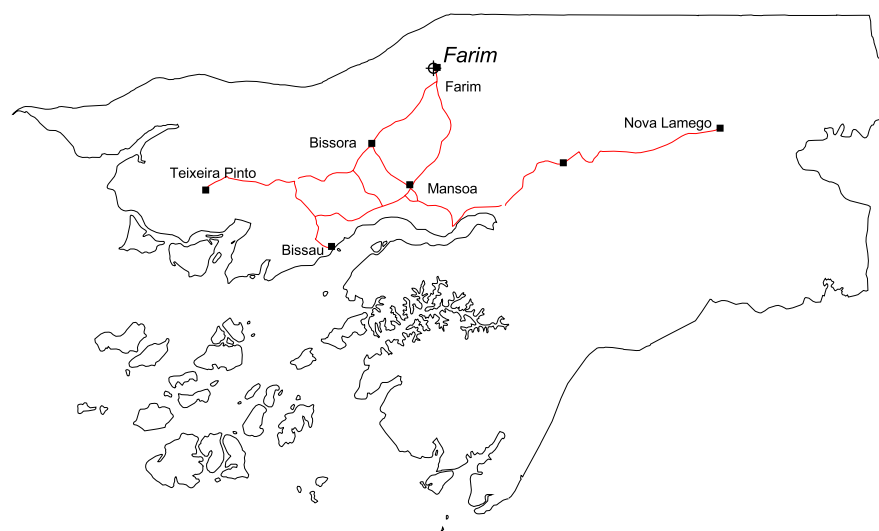
Laboratory and greenhouse trials with sorghum carried out by Abekoe and Tiessen (1998) indicate that Togo RP is not effective in alfisols of northern Ghana, probably due to high base saturation and moderate P adsorption capacity of these soils. The relative agronomic effectiveness of the PAPR was 63% of SSP.

OwusuBennoah and Acquaye (1996) carried out a greenhouse evaluation of the agronomic potential of different sources of phosphate fertilizer in a typical concretionary soil of northern Ghana, which is near neutral with respect to pH and which comprise mostly lateritic ferruginous nodules with high P-sorption capacity. The objective was to evaluate the effectiveness of freshly-applied SSP, Togo PR and Togo PAPR-50, and the effectiveness of the residues of these fertilizers in a glasshouse pot study using maize

to measure fertilizer effectiveness. One level of P was applied for each fertilizer (26.4 kg P ha⁻¹). Increases in dry matter yield of shoot and total P uptake followed the trend SSP > PAPR-50 > PR > control. The relative agronomic efficiency (RAE) of PAPR-50 was 58% that of commercial SSP in increasing growth of the crop, while that of PR was only 23%. The residual effect of either PAPR-50 or PR on dry matter yield and total P uptake was found to be negligible compared with SSP, suggesting that apatitic P was poorly effective relative to SSP in the neutral pH soils. This would be expected as PR is generally ineffective in neutral/alkaline soils. Relative to SSP, the P from residues of PAPR-50 and PR was poorly effective for sustainable plant production in the soils studied.

Additional sources; (Abekoe, 1996; Ankomah et al., 1995; Chesworth et al., 1983; DFID, 1995; Hardter and Horst, 1991; Hardter et al., 1991; Harsch, 1999; Horst and Hardter, 1994; IFA, 2000a; ILEIA, 2000; Kato et al., 1995; OwusuBennoah et al., 1997; Tiessen et al., 1993; Tiessen et al., 1991)

Guinea Bissau



Location, Quantity, Quality

More than 100 Mt of phosphate rock resources averaging 30% P_2O_5 occur near Farim in the coastal zone of Guinea Bissau (McClellan and Notholt, 1986). They are similar in age to the Eocene deposits, which are exploited commercially in Senegal. The phosphorite beds range from 1 m to 6 m in thickness but the relatively thick (26-50 m) overburden would increase the cost of mining these deposits. Al and Si increase upwards as the phosphate grade decreases; Fe_2O_3 averages approximately 6%, which is much higher than in the Senegal phosphate rock (1% Fe_2O_3).

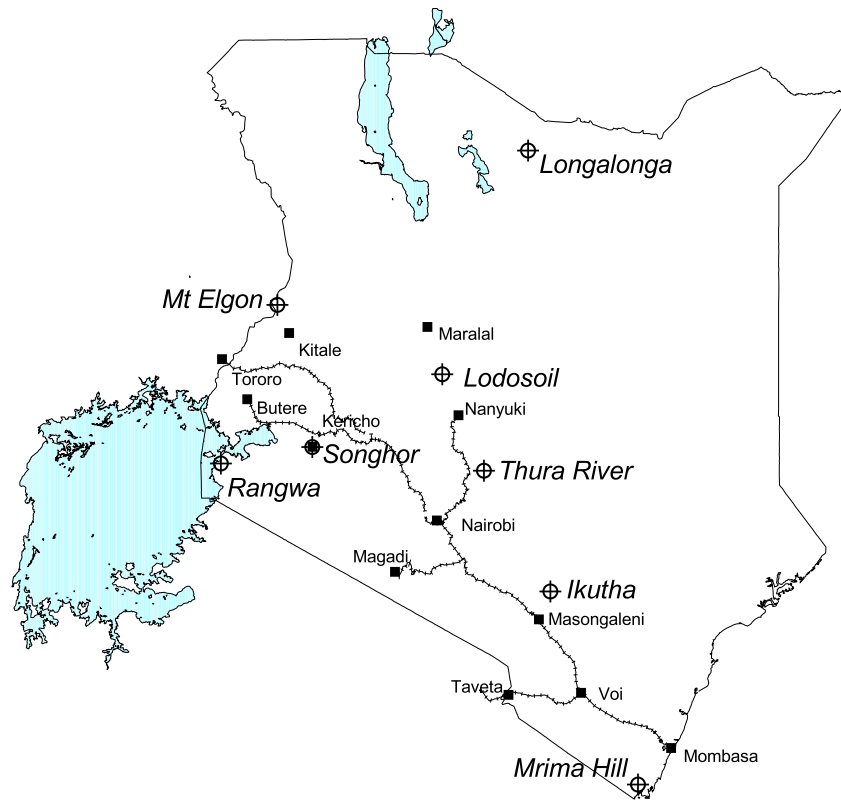
Detailed evaluation of the phosphate deposit is reported to have been carried out in 1998 (Mining Annual Review, 1998). Champion Resources of Vancouver, Canada continued evaluation of the Farim deposits where drilling has proven a resource of at least 166 Mt, grading 29.1% P_2O_5 . It is possible to upgrade this phosphate rock to a low impurity concentrate with 36% P_2O_5 that has a very low Cd concentration and is very suitable for phosphoric acid production. The planned production rate is 1.5 million tonnes of phosphate rock concentrate per annum over a 25 year period. Potential consumers and investors are being sought. Mine construction, if approved, would take about 2 years (Mining Annual Review, 2000).

Sources: (Boujo et al., 1988; Champion Resources, 2000; McClellan and Notholt, 1986; Prian, 1989; Prian et al., 1987; Sustrac et al., 1990)

Agronomic testing and use

Gaspar, Monteiro, et al. (1995) published a note on the direct application of Farim rock phosphate, but no details of the study were readily available.

Kenya



Location, Quantity, Quality

Deposits of igneous phosphate occur at four localities in Kenya. Apatite is enriched to average levels of 3 to 4% P_2O_5 in residual soils overlying carbonatite at Mrima Hill, 65 km SW of Mombasa. Most of the apatite has been altered to aluminium phosphates of the crandallite group of minerals. Apatite concentrations are also found in carbonatite and alkaline rocks at Mount Elgon (1-4% P_2O_5) and Rangwa (0.5-5.8% P_2O_5) and in magnetite veins (0.1-9% P_2O_5) at Ikutha, 250 km SE of Nairobi. A sample of Rangwa phosphate rock with an unusually high proportion of carbonate-fluorapatite (73%) and only 20% calcite had a NAC solubility of 3.6% P_2O_5 . Whereas this indicates some potential for its use as a direct application fertilizer if resources of an adequate size could be identified, this is unlikely as the Rangwa carbonatite ore is relatively low grade (about 5% P_2O_5) and has low NAC soluble P_2O_5 (0.5-1% IFDC, 1988).

Cave deposits of phosphatic bat guano, containing 11% P_2O_5 and 13% N, has been reported in caves in the Chulu Hills, Machakos District, south east of Nairobi; in the Suswa area in the Rift Valley; near Mombasa, Coast Province; and in western Kenya near Kisumu in Nyanza Province. These deposits are generally too small to be commercially workable, but small quantities of guano were obtained from Chulu Hills. Some occurrences of bat guano (9-10% P_2O_5) in large limestone caves at Vipingo, 25 miles north of Mombasa were investigated periodically since 1966 as a possible source of phosphate for fertilizer purposes. Many of the guano deposits have been exploited in the past on a very small scale.

Apatite has also been reported from kyanite-graphite schists near Longalonga in the Taveta area; in alluvial gravels at Songhor in the Kericho area; in lenses associated with an altered basic intrusion 16 km west of Lodosoit in the Nanyuki-Maralal area; and in a pegmatite near the Thura River, southeast of Embu (IFDC, 1988).

Past production

A few thousand tons of a fused phosphatic fertilizer known as "sodaphosphate" was produced annually between about 1951 and 1961 at Turbo, in the Rift Valley Province about 20 miles WNW of Eldoret. Soda from Lake Magadi south-west of Nairobi and low grade phosphate rock from the Busumbu mine in south-eastern Uganda were fused following a modified Rhenania process that was developed shortly after the Second World War by the East African Industrial Research Board, Nairobi. The product, sold under the trade name of 'Kenphos', contained an average of 28% P₂O₅. Approximately 26,100 tons of sodaphosphate (equivalent to 7,320 tons P₂O₅) were produced during the period 1951 to 1961 (Notholt, 1999).

Sources: (Coetzee and Edwards, 1959; Gaciri, 1991; Idman and Mulaha, 1991; IFDC, 1988; Kuivasaari, 1991; Lucas, 1992; McClellan and Notholt, 1986; MMAJ, 1992; Notholt, 1999; Schlueter, 1995; Van Straaten, 1999)

Agronomic testing and use

The earliest recorded PR agronomic study in Kenya was one that examined the effects of ground rock phosphate and elemental sulphur on the yield and P uptake of maize in western Kenya (Bromfield et al., 1981).

Nziguheba, Palm, et al. (1998) studied the effect of organic and inorganic sources of phosphorus (P) on soil P fractions and P adsorption in a field without plant growth on a Kandiudalf in western Kenya. A high-quality organic source, *Tithonia* leaves, and a low-quality source, maize stover, were applied alone or in combination with triple superphosphate (TSP). Integration of inorganic P (TSP) with organic materials had little added benefit compared to sole application of TSP, except that combination of *tithonia* with TSP increased microbial biomass. The results indicate that a high quality organic input can be comparable to or more effective than inorganic P in increasing P availability in the soil. These results are partially in conflict with results reported by ICRAF (see below).

Sanchez et al. (1999) reported the results of ICRAF's work with its partners in Kenya which have shown that two-year leguminous fallows accumulate about 200kg N/ha in their leaves and roots. When these are incorporated into the soil, maize yields double and sometimes quadruple. The greatest impact of this work has been in southern Africa where more than 10,000 farmers are now using a 2-year fallow, 2 to 3-year maize rotation. An equivalent amount of mineral fertilizer would cost US\$ 240/ha in that region, an unrealistic amount to farmers who make less than 1 US dollar per day (Sanchez et al., 1999).

In many areas of East Africa, smallholder farms need both nitrogen and phosphorus, necessitating the combined use of organic and mineral sources of nutrients. Short-term (6-16 months) improved fallows have proven to be an effective and profitable way of adding about 100kg N/ha and recycling other nutrients in the depleted soils of Western Kenya. Even fallows as short as six months have tripled maize yields in villages where many farmers are now practicing a fallow-crop rotation every year. ICRAF studies have demonstrated that in phosphorus-deficient soils, Minjingu phosphate rock from northern Tanzania is as effective and profitable as imported triple superphosphate. Farmers are applying 125-250kg P/ha as a capital investment, and expect a five-year residual effect. According to Legault (1998), ICRAF report that conventional, phosphorus-rich fertilizer costs about 130 shillings (US\$2) a kilo whereas phosphate rock is sold at a lower price (55 shillings per kilo). *Even so, it is still too expensive for the majority of subsistence farmers.* Biomass transfers from hedges of the wild sunflower, *tithonia*, have increased yields of maize and high-value crops such as tomatoes and beans in western Kenya, where about 4,000 farmers are trying these techniques. Most of the dissemination of this farming system is done at the village scale as a pilot development project, involving government agencies and NGOs.

Van Straaten (1998) reported results of agronomic trials with phosphate rock fertilizers in western Kenya and Uganda where phosphate deficiency is one of the principal factors limiting crop production. About 80 % of the soil samples in Western Kenya are below the critical level of extractable P (i.e. 5 mg EDTA bicarbonate extractable P/kg). Sedimentary rock phosphates from Minjingu in Tanzania (MPR) and igneous rock phosphate from Busumbu in Uganda (BPR), are being tested in field experiments at several

sites in western Kenya. Treatments include the application of beneficiated and concentrated rock phosphates from Busumbu and Minjingu together with Busumbu rock phosphate blended with TSP (70 % beneficiated BPR, 30 % TSP) and agglomerated in a locally produced disc pelletizer. The application rate for field tests is 30 kg P/ha, 60kg N/ha and 60 kg K/ha. A RAE for the BPR blends of 70 % was recorded for the initial trials from the short rains (Nov/Dec. 98). *As expected, the yield response for the directly applied igneous BPR was low due to its low reactivity.* On-going field tests use various rock phosphates and blends as well as a mixture of locally available biomass (*Tithonia diversifolia*) with rock phosphates.

Mineralogical and chemical characterization showed that the Bududa and Butiriku phosphates are largely made up of francolite resulting from weathering of apatite bearing carbonatites. Agronomic testing confirmed their suitability as simple straight P-fertilizers on P-deficient highly leached soils in Western Kenya (Van Straaten, 1999). In contrast, the phosphates rocks used for these studies are composed of mainly fluorapatites with varying amounts of secondary francolites and Fe-phosphates. This observation is in contrast to previous reports (IFDC, 1988; Notholt, 1999) that much of the near-surface phosphate rock at Busumbu was composed of more reactive francolite. Trials with Busumbu fluorapatite PR indicated a very limited agronomic response, reflecting the low reactivity of the BPR. Igneous fluorapatite rocks are generally not suitable as direct application phosphate fertilizers because of their mineralogical and chemical characteristics. Van Straaten (1999) reported that several innovative modification techniques using appropriate technology approaches with Busumbu phosphate rock mixed and pelletized with soluble N and P fertilizers were tested on researcher-designed and farmer-managed fields in Uganda and Kenya during the long rains in 1999. Results of field testing in Western Kenya confirmed that the Busumbu blends (75 % Busumbu Rock Phosphate and 25 % TSP) had a relative agronomic effectiveness of 70-80 % compared with TSP alone. These much cheaper products and techniques are currently being refined and tested to produce a low-cost fertilizer for millions of small holder farmers in East Africa. Research is continuing with efforts to utilize locally available organic residues (including plant residues and wastes from the sugar industry) and microbial activity to enhance solubilization of phosphate rock. The ultimate aim is to develop agronomically effective, low-cost P-fertilizers utilizing local resources for smallholder farmers in East Africa (Van Straaten, 1999).

Mutuo, Smithson, et al. (1999) conducted a field study with corn for three growing seasons (18 months) on a P-deficient, acid soil in Kenya to compare a soluble P source (TSP) and relatively reactive sedimentary Minjingu PR from Tanzania. In the 18 months following application of 250 kg P ha⁻¹, P_i extracted with a mixed anion-cation resin was comparable for TSP and PR. Minjingu PR was an effective source of P for corn. Corn yields were comparable for TSP and PR, and the relative agronomic effectiveness of PR averaged 107% in the first season and 79% in the third.

A particular challenge in replenishment of fertility of degraded soils is to develop products formulated for the needs of smallholder farmers. The Phosphate Rock Evaluation Project (PREP) at Moi University, Kenya, formulated and field-tested a product, the PREP-PAC, which is an inexpensive product that combines fertilizer, legume seed and rhizobial inoculant techniques. PREP-PAC is specifically targeted at low soil fertility common in the smallholder farming systems operating on highly weathered and leached acrisols (ultisols) and ferralsols (oxisols) of western Kenya. PREP-PAC contains 2 kg of the reactive/biogenic locally available Minjingu (Tanzania) rock phosphate (PR), 0.2kg imported urea, 0.13 kg seed of a N-fixing food legume, rhizobial inoculant (Biofix), seed adhesive (gum arabic), lime pellets and instruction sheet for use in English, Kiswahili and other local languages. The pack is assembled at US \$ 0.58 per unit and is intended to ameliorate plots of 25m². The product is particularly effective in acid (pH<5.5) and low P (<10mgPkg⁻¹) soils. The principle is to apply enough slowly available PR for several cropping seasons with readily available nitrogen fertilizer (urea) and to intercrop with a legume that provides residual fixed-nitrogen and organic inputs to the soil.

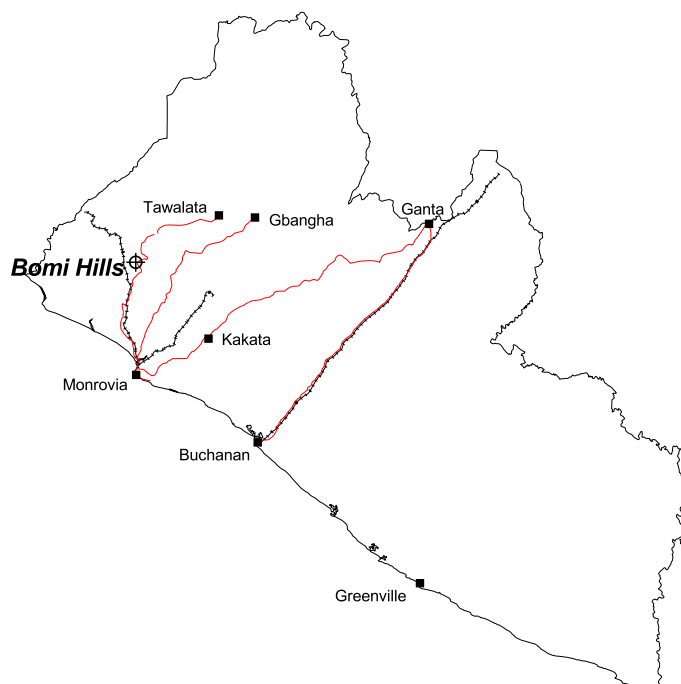
On-farm experiments of PREP-PAC were carried out using maize-bean intercrops. Yields increased to 4.1 kg maize and 1.1 kg bean (p<0.001) for both crops and the improvement in bean yield during the first cropping season nearly offset PREP-PAC's investment costs. Interactions between PREP-PAC components in a maize-soybean intercrop on nutrient-depleted soils were also evaluated. The total value of the intercrops ranged between \$ 0.83 in the un-amended plots and \$ 2.44 in those treated with PREP-PAC. Significant positive effects were observed with the addition of PR (p<0.001), urea (p=0.04) and

inoculant ($p=0.01$) and in interactions between PR and urea ($p=0.02$) or inoculant ($p=0.07$). The return ratio to PREP-PAC investment was 2.6 in the sandy soil and 3.7 in the loamy soil. The responses of dry bean and soybean to rhizobial inoculants with tolerance to acidity were tested in three acid and low fertility soils. Significant treatment effects were found for both legumes. PREP-PAC is currently being field-tested by five developmental organizations and test-marketed by several retailers of agricultural supplies. Methods of lowering the cost of PREP-PAC production by 30% (to \$ 0.41 per unit) are being evaluated, primarily through bulk purchase and reduced packaging and transportation costs (Okalebo et al., 2001).

Phosphorus deficiency affects around 80% of the acid soils of western Kenya, but fertilizer use is limited due to high prices. Smithson et al. (2001) studied two contrasting phosphate rocks (PRs) for their agronomic performance in western Kenya maize production. Minjingu PR (MPR, Tanzania) with about 13% total P and 3% neutral ammonium citrate (NAC) soluble P and Busumbu PR (BPR, Uganda) with about 14% total P and 0.3% NAC-soluble P in the weathered "soft rock" fraction of BPR, after removal of magnetic Fe oxides. A five-year trial at one site showed MPR to be as effective as triple superphosphate (TSP, 20% P) at equal P rates. In further trials at over 25 sites, MPR averaged 70 to 80% as effective as TSP. MPR remains rather expensive relative to TSP due to high transport costs. MPR, BPR and BPR:TSP mixtures were compared with against TSP in test strips on 42 smallholder farms in 7 locations in western Kenya and 2 locations in eastern Uganda. In Kenya (26 farms), BPR gave significant maize yield increases relative to no-P control (average 1.3 t ha^{-1} yield increase, $p = 0.07$ to 0.01). In Kenya, BPR averaged 48% as effective as TSP (range 20-77%). At the same sites, MPR averaged 74% as effective as TSP (range 41-113%). In Uganda (16 farms), there was no response to applied P in any form. Minjingu PR is reasonably effective at many sites, and the question of its suitability is now primarily one of economics. Performance of BPR is poorer, though its lower cost and location near to P-deficient areas make it attractive in some situations (Smithson et al., 2001).

Additional sources: (Addison, 1999; Baobab-News, 2000; Bashir et al., 1997; Bationo et al., 1992b; Bekunda et al., 1997; CGIAR, 2000; DFID, 1995; Gladwin et al., 2000; Gladwin and Thomson, 2000; Holderness, 1997; ICRAF, 1997; ICRAF, 2000b; ICRISAT, 2000b; IDRC, 2000; IFA, 2000a; Ker, 1995; Keter and Fiskell, 1982; Okalebo et al., 2001; Okalebo et al., 1994; Recke et al., 1997; Sanchez and Palm, 1996; Sanchez et al., 1997; Smithson et al., 2001; Warren, 1994)

Liberia



Location, Quantity, Quality

Secondary phosphate deposits at Bomi Hill and near Bambuta, north of the port of Monrovia in western Liberia are associated with iron ores. Although 1 million tonnes of phosphate rock grading 32% P_2O_5 have been identified, these ferruginous and aluminous phosphate deposits have low potential as a raw material for fertilizer manufacture due to their complex mineralogy and unfavourable chemistry.

Source: (McClellan and Notholt, 1986)

Agronomic testing and use

No details are available on agronomic trials in Liberia using phosphate rock

Madagascar



Location, Quantity, Quality

In the Majunga Basin of northern Madagascar, phosphatic nodule beds containing less than 20% P_2O_5 occur in (i) marls of Lower Cretaceous age occur near Ambato-Boeni; (ii) in Upper Cretaceous sediments near Marovoay; and (iii) in rocks of comparable age south of Soalala and near Sitampiky. Phosphatic beds occur also at the base of the Palaeocene on Antonibe peninsula. Phosphorite may also occur in the Rovuma Basin, as this area is geologically similar to the adjacent Majunga Basin in Madagascar. Weakly phosphatic grits are found in the lacustrine beds of Lake Alaotra, and phosphate has been recorded also from Pliocene marls at Antanifotsy (Notholt, 1994a).

Whereas these thin, nodular phosphorites appear to be of limited extent, they of interest as indicators of phosphogenesis in the Cretaceous, Palaeogene and Neogene-Quaternary sediments of southeastern Africa. The phosphate potential of Madagascar has not been fully investigated and the presence of more extensive beds of phosphate rock cannot be discounted.

Source: (Notholt, 1994a)

Agronomic testing and use

Pichot, Truong et al. (1982) reported a study of the influence of soil liming on the solubilization and performance of rock tricalcium phosphates from West-Africa on a ferrallitic soil from Madagascar, but no details are readily available.

Malawi



Location, Quantity, Quality

Apatite in igneous rock is found at several localities in southern Malawi. Phosphate deposits of potential economic importance are associated with the Tundulu carbonatite in Mlanje District, southeast of Lake Chilwa where there are also notable concentrations of pyrochlore, barytes and several rare-earth fluorocarbonate minerals, which could possibly be recovered as by-products in the treatment of apatite. However, the remoteness of the deposits and the lack of local demand for phosphatic fertiliser have so far prevented their exploitation. Small deposits of apatite also occur on Chilwa Island and at Mlindi in Blantyre District. In northern Malawi, uraniferous phosphate rock has been recorded at a depth of over 180 m from a borehole at Livingstonia, Rumpi District.

The Tundulu, Chilwa Island and Kangankunde carbonatite complexes in southern Malawi all contain hard rock phosphate concentrations. Of these, only the Tundulu apatite rock has any economic potential as a fertilizer raw material. Resources of about 0.8 Mt grading $>20\%$ P_2O_5 have been identified and higher grade rock (28-30% P_2O_5) could be selectively mined and crushed. More recently, reserves of 2 Mt of rock phosphate with 17% P_2O_5 have been reported (Mining Annual Review, 1999). Whereas the quantity of phosphate rock and the demand for phosphate fertilizers are probably too small to justify the establishment of a fertilizer manufacturing plant, agronomic trials are being carried out to assess the potential use of ground Tundulu phosphate rock as a direct application fertilizer for tea (Appleton, 1994). The ground phosphate rock is probably not reactive enough for use with annual crops. Met-Chem Canada Inc. evaluated the economic potential of the Tundulu Phosphate resources for the Malawi Development Corporation and

concluded that the recovery of niobium and rare earth resources from the carbonatite could contribute to lowering the P_2O_5 cut-off grade and increase the phosphate reserve figure (Mining Annual Review, 1999).

Apatite occurs in biotite-pyroxenite in the centre of the Basement Complex Mlindi ring structure. Alluvial black soil overlying the pyroxenite near Ligowe contains an average of 8% apatite and slightly weathered biotite-pyroxenite near Butao, about one mile south of Ligowe, contains about 12% apatite (Bulletin No.12, Geological Survey Nyasaland, 1959, p.35). Notholt (1999) reports that a local prospector made a fertilizer consisting of 40% finely ground biotite-apatite rock and weathered material from the pyroxenite, 20% finely ground, hand picked apatite and 40% ground dolomitic marble, also obtained nearby. The fertiliser was distributed to various Government experimental stations and to private coffee and tobacco estates for testing.

Sources: (Appleton, 1988; Appleton, 1994; Briggs and Mitchell, 1990; Garson, 1965; ITC, 1998; Malawi Development Corporation, 1999; McClellan and Notholt, 1986; MMAJ, 1988; Notholt, 1986; Notholt, 1999; SADC-EU Mining Investment Forum, 2000)

Agronomic testing and use

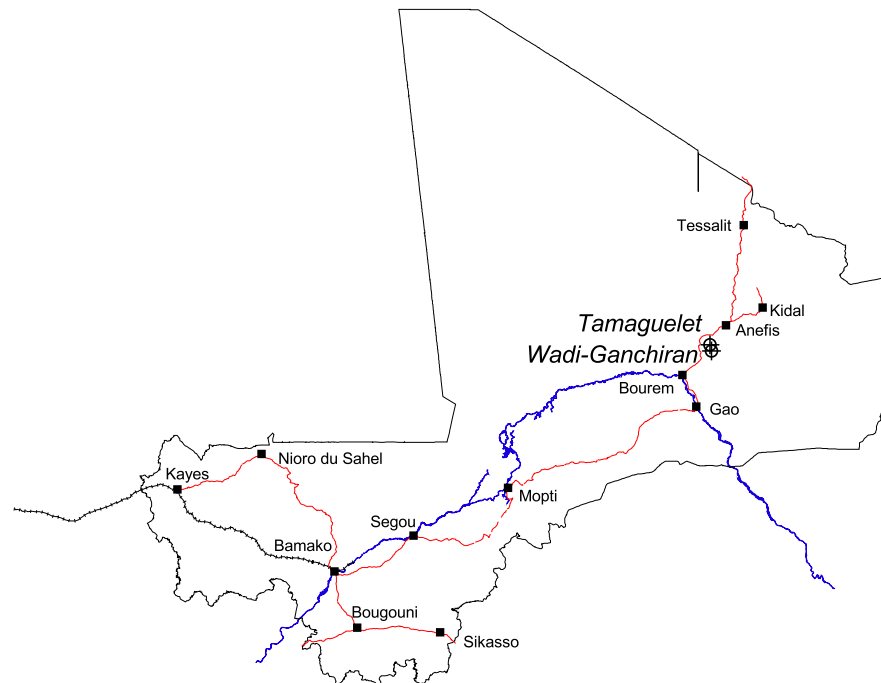
An evaluation of the agronomic potential of using phosphate rock from the Tundulu carbonatite as direct application fertilizer for tea included (i) laboratory investigations of the rate and extent of dissolution of phosphate rock in soils in closed incubation and open leaching systems in order to identify the rate and extent of dissolution and the soil factors which influence dissolution (Riggs and Syers, 1991) and (ii) tea plant field trials to study the growth response and P-uptake at different P application rates. The substantial dissolution of the Tundulu phosphate rock (TPR) recorded in both the incubation and leaching systems confirm the potential agronomic effectiveness of this relatively unreactive PR in the acid, P-deficient soils found in the tea growing area of Malawi. Field trials to assess the response of tea plants grown on acid P-deficient soils to TPR at different application rates are being carried out in the Thyolo-Mulange area of eastern Malawi by the Tea Research Foundation of Central Africa. The trials were scheduled to last 5 years and the results for the first two years were reported by Appleton (1994). Although the results should be viewed with caution, a progressive increase in yield with TPR application rate has been recorded amounting to 3.6% at the 60 kg P_2O_5 ha⁻¹ application rate. This response is not dissimilar to responses of 4-6% in southern India experiments where PR application rates were 34 to 78 kg P_2O_5 ha⁻¹ (Ling et al., 1990). In the Malawi tea trial, average leaf P concentrations increased with the amount of P applied both as TPR and TSP so there was clearly an increase in P uptake by the tea plants from both P sources. The results for the first two years of the Malawi tea trial are, therefore, reasonably positive although it will not be possible to make a full evaluation until the trial has run at least five years. Economic advantages of using TPR include (a) the low cost per unit P (estimated to be 8 times cheaper than imported TSP); (b) savings in foreign exchange; (c) low capital investment for mining and grinding equipment; (d) low energy requirements; (e) reduced loss of P through complex beneficiation. It is estimated that substitution of phosphate rock for imported TSP by the Malawi tea industry would reduce annual fertilizer costs by approximately US\$ 600,000 (Appleton, 1994).

Wendt and Jones (1997) evaluated the extent of phosphorus deficiencies in Malawi as related to maize production, and assessed the value of Malawi Tundulu phosphate rock (TPR) in supplying P for maize production. Comparison of the effects of TPR, a low-reactivity P source, and triple superphosphate (TSP) on maize yields was carried out at 4 locations testing low to medium in soil P and employing three P rates (8.8, 17.5, and 35 kg P ha⁻¹), two placement methods (point placement and banding), and three N fertilizers of different acidulating abilities (calcium ammonium nitrate (CAN), urea, and ammonium sulphate (SA)). Both TSP and TPR were more effective when band applied, compared to the traditional point application. Response to banded TPR was site-specific, and was related to P sorption capacity, with best responses occurring on low P-sorbing soils. Rates of P above 8.8 kg ha⁻¹ did not generally improve yields the first season, but did result in increased residual response. While the most acidifying N source, SA, did not improve yields significantly over the least acidifying, CAN, yields using both SA and CAN were significantly better than yields under urea. This is probably due to higher ammonia volatilization losses using urea. A further trial implemented at 2 sites in 1992/93 indicated that broadcasting PR gave greater yields than did banding. Wendt and Jones (1997) concluded that *Tundulu PR, applied as a band*

or broadcast, has potential for replacing conventional P fertilizers on some soils in Malawi and that lower P rates than the currently recommended 17.5 kg ha⁻¹ may be equally effective and more economical for either P source.

Additional sources: (Appleton, 1988; Appleton, 1994; FAO, 2000b; FAO, 2000c; IDRC, 1996; ITC, 1998; Le Mare, 1986; Lowell and Well, 1995; Lowell and Well, 1993; Maida, 1980; Maida, 1985; Mathur et al., 1986; Semoka and Mnkeni, 1986; Snapp, 1998; Wendt and Jones, 1997)

Mali



Location, Quantity, Quality

Upper Cretaceous to Tertiary sedimentary phosphate rock deposits have been recorded at six localities in eastern Mali of which Tamaguelet (17°38'N, 0°15'E) in the Tilemsi Valley, 150 Km N of Gao and 105 km NE of Bourem, and Ganchiran (17°30'N, 0°17'E), located 135 km north of Gao, are the most important. Other Tilemsi Valley deposits occur at Chanamaguel, Tin Hina and Anderakoyene (or Andarakoyene). The phosphorite beds are 1-2 m thick and are overlain by 2-9 m of lateritised sediments. 20 to 25 Mt of phosphate rock resources with 27% P₂O₅ have been identified in the Tilemsi area of which 15Mt with 17-31.5% P₂O₅ are in the Tamaguelet deposits (Van Kauwenbergh et al., 1991a). The Ganchiran deposit is very similar but has a relatively high manganese content. The Chanamaguel deposit has phosphorite beds up to a maximum of 1 m thick that average 28% P₂O₅; Tin Hina has beds of 0.2 to 1.6 m with an average of 21.6% P₂O₅. Anderakoyene, 76 km to the SW of Tin Hina comprises 4 or 5 phosphorite beds with P₂O₅ ranging from 4 to >25%, but Fe₂O₃ ranges from 16 to 20% and MnO₂ is generally 2%, rising to 12% in the weathered surficial material.

More recently, total phosphate rock resources in the Tilemsi valley have been reported as follows: Tamaguelet 11.4 Mt, Chanamaguel 1.0-1.6 Mt, Tin Hina 3-5 Mt, and Anderakoyene 2-4 Mt (Van Kauwenbergh et al., 1991a).

20 to 40% upgrading of P₂O₅ content may be attained by simple screening, attrition scrubbing and/or washing (Van Kauwenbergh et al., 1991a). High combined R₂O₃ (Fe₂O₃+Al₂O₃; Fe₂O₃ averages about 8%) and a R₂O₃/P₂O₅ ratio of 0.1 to 0.13 means that the phosphate rock is relatively poor quality for the production of SSP, phosphoric acid and DAP. It is reported that partially acidulated products have been produced from the Tilemsi ore at 15% and 30% acidulation levels (Van Kauwenbergh et al., 1991a).

Whereas Precambrian (infra-Cambrian) rocks similar to those associated with phosphorites in neighbouring Senegal are also located in the Kayes area of western Mali, phosphate rock has not yet been discovered (Van Kauwenbergh et al., 1991a).

Past production (1960 onwards)

The Tamaguelet deposit is reported to have been worked at a rate of 2,000 to 8,000 tpy from 1976 to 1989 and converted into ground rock for direct application using a 30,000 tpy capacity mill constructed in Bourem by the GTZ (McClellan and Notholt, 1986; Van Kauwenbergh et al., 1991a). Production costs were \$108/ton ex-mill whilst farmers paid \$189/ton at the distribution centres. The ground phosphate rock was transported via the Niger River to Mopti, Segou and Bamako, although this was possible only during the period August to December. A change in Government policy in 1989 regarding credit payments eliminated the demand for local ground phosphate rock resources, which had been sold primarily to commercial cotton farmers but had also been used for agronomic research by the IFDC. As far as is known, no phosphate rock is being produced in Mali at present.

A Chinese-Malian consortium is planning to build a P-fertilizer plant in Mali using Tilemsi rock (Henk Breman, personal communication, 22 June 2001).

Sources: (McClellan and Notholt, 1986; Pascal and Diene, 1987; Pascal and Traore, 1989; Van Kauwenbergh et al., 1991a)

Agronomic testing and use

In the period 1975-1980, the Malian-Dutch "Primary Production Sahel (PPS)" project analysed the role of water, N and P in rangeland productivity, and compared the effect of the Tilemsi rock and TSP on the production of rangeland and rangeland species, legumes included (Zornia). It concluded that TSP was 20 times more effective than Tilemsi rock in the first year of application (Krul and et al., 1982) although the Tilemsi PR became more effective with time.

Kagbo (1991) carried out on-farm trials in the Operation Haute Vallee project, Mali, to assess the possibility of replacing, partially or entirely, imported cotton fertilizer with natural rock phosphate from a local source, and to assess the residual effect on maize and sorghum grown after cotton. The maize/cotton sequence, although not normally used by Malian farmers, was more profitable than either pure cotton grown alone or a cotton/maize sequence when local rock phosphate was used instead of imported fertilizer.

Van Kauwenbergh, Johnson et al. (1991a) summarised the agronomic results of a programme that covered the entire agroecological range in Mali. The main results were:

- Tilemsi phosphate rock (TPR) was, on average, 78% as effective as TSP and PAPR;
- broadcasting and incorporating TPR before planting produces 20-25% higher yields than when the TPR was banded in soils with pH of 5 or higher in the humid and subhumid areas;
- on very acid soils with pH <5, banding of phosphate prior to planting gave higher yields for millet, sorghum and groundnuts;
- rice yield increased by 20% when TPR was broadcast and incorporated rather than banded;
- TRP, although producing lower yields than TSP in the first year, had a residual impact such that yields in the subsequent years for TSP and TPR were similar in the humid and subhumid areas;
- the RAE of the PAPR increased with the degree of acidulation;
- results for on-farm trials indicated that TPR applied with urea and K-sulphate performed as well as complex fertilisers being used by Malian farmers.
- economic results indicated that TPR can result in net returns and value:cost ratios similar to those for TSP;
- no consistent economic advantage was observed for PAPR compared with TSP or TPR.

For further details, see p.97-98 in Van Kauwenbergh, Johnson et al. (1991a).

An agro-economic evaluation in Mali using the reactive Tilemsi rock for maize-cotton intercropping indicates that ground phosphate rock compares favourably with TSP in net benefit and value/cost ratio (Table 16). IFDC concluded that Mali would benefit from the use of directly applied indigenous ground phosphate rock, which would lead to foreign exchange savings, reduce dependence on foreign suppliers and generate local employment (IFDC Annual Report 1992).

Table 16 Comparison of the relative economic benefits of ground Tilemsi phosphate rock (PR) and TSP in Mali (adapted from IFDC, Annual Report, 1992)

Crop rotation	Fertilizer	Net benefit (US \$/ha)	Value/Cost ratio
M-C-M-C ¹	Tilemsi PR	225	3.5
M-C-M-C	TSP	196	3.3
C-M-C-M	Tilemsi PR	324	4.0
C-M-C-M	TSP	295	4.3

¹ M = maize, C = cotton

Doumbia, Hossner, et al. (1993) defined the soil chemical properties associated with poor early growth of sorghum in acid soils of Mali in subhumid West-Africa. Application of P alone or any treatment combination containing P resulted in improved sorghum growth and yield. Amending the soil with Tilemsi rock phosphate or Diamou lime significantly increased exchangeable soil Ca²⁺ and Mg²⁺. Each of these amendments significantly reduced the concentrations of exchangeable soil Al³⁺. Phosphorus deficiency is one of the major factors limiting sorghum growth and yield in these Paleustalfs in which P deficiency is more critical than the need for N. An application as low as 2.5 mg P kg⁻¹ of soil not only prevented symptoms of poor early growth but also produced a significant dry matter increase in the greenhouse. In a second study, Doumbia, Hossner, et al. (1998) conclude that P deficiency and Al toxicity may be associated with reduced sorghum growth in these soils. *Short-term sorghum response to amendments and fertilizers suggests that the simple technology of liming may be an inadequate prescription for managing these acid soils.*

Bationo (1994) presented results on the agronomic efficiency of the Tilemsi (Mali) and Tahoua (Niger) PRs as well as PAPR derived from these PRs. Bationo et al., (1986), found that Tahoua and Parc-W (Niger) have an agronomic efficiency of 76% and 48% compared with SSP. The PAPRs had a much high RAE as shown in Table 17.

Table 17: RAE of PAPRs in different agro-ecological zones of West Africa

Treatment	Soil order	Crop	RAE (% compared to SSP)
Togo PAPR 50	Alfisol	maize	90.0
Togo PAPR 50	Ultisol	maize	66.7
Togo PAPR 50	Oxisol	maize	108.9
Kodjari PAPR 50	Alfisol	maize	84.1
Kodjari PAPR 50	Alfisol	sorghum	81.3
Kodjari PAPR 50	Alfisol	mil	108.9
Parc-W PAPR 50	Entisol	mil	93.4

Ballo (1995) summaries information on the location and characteristics of the Tilemsi phosphate rock (TiPR) deposits; the agroecological factors that favour its use; the proportion of total cropped area in southern Mali that received TiPR during the period 1989-1994; amounts of TiPR supplied; the application methods; the agronomic benefits and the constraints to the use of TiPR. Bagayoko and Coulibaly (1995) dealt with the conditions for promoting TiPR; analysed the constraints on the adoption of TiPR and discussed the prospects for improving the acceptability of TiPR by increasing its solubility, improving its physical characteristics and developing a fertilizer scheme.

Bationo, Ayuk, et al. (1995) carried out an agronomic and economic evaluation of Tilemsi phosphate rock in different agroecological zones of Mali where phosphorus deficiency is known as one of the major constraints to crop production. Farmer-managed trials were conducted in three agroecological zones of Mali to evaluate the profitability of Tilemsi phosphate rock (TiPR) in different crop-rotation systems in comparison with conventional water-soluble fertilizers. Results show that crop yields using TPR are comparable to those for imported fertilizers recommended for cotton and cereals. The economic evaluation also clearly indicated that direct application of TiPR is relatively profitable in comparison with recommended imported fertilizers and that good management enhances the profitability of fertilizers in general.

Henao and Baanante's report on "An Evaluation of the Strategies to Use Indigenous and Imported Sources of Phosphorus to Improve Soil Fertility and Land Productivity in Mali" (1999) states that phosphate fertilizers are needed in Mali for the production of food and cash crops and that *Tilemsi phosphate rock is a suitable indigenous source of phosphorus for the sustainable production of important cropping systems in Mali*. Estimates of private and environmental benefits show that investments in the application of Tilemsi phosphate fertilizer can be profitable for farmers even when rates of discount are as high as 30%. However, poor rainfall in some semiarid areas and the sudden decline in prices of crop output could make this investment unprofitable to farmers. The important magnitude of environmental and social benefits associated with the use of Tilemsi phosphate rock shows that investing in the application of the fertilizer is highly profitable at the community and country levels. These results show that such an investment will, in the long run, improve the welfare of farmers and the conservation of natural resources. In the short run, however, drastic fluctuation in prices and climatic conditions can result in short-term financial losses for farmers. Therefore, in areas with greater uncertainty about rainfall and in crops with low price stability, it is more difficult (risky) for farmers to invest in the phosphate rock or any other source of phosphorus. Henao and Baanante (1999) consider that investment in phosphate fertilizer is necessary and a crucial factor in the restoration, maintenance, and enhancement of soil fertility and the conservation of natural resources in Mali. Parallel investments in complementary technologies for erosion control, water conservation, and use of organic fertilizers should be considered as part of investment packages for soil fertility restoration and conservation. Given the long-term nature of investments in the exploitation of phosphate rock deposits and the benefits that phosphate rock can provide to the farmers, credit and price policies should be established and maintained for several years as part of any program to promote the sustained use of Tilemsi phosphate rock in Mali. The report (Henao and Baanante, 1999) recommends that provisions should be made in fertilizer strategies regarding the effects that adverse fluctuations in climate and market prices may have on profitability and farm income. This is particularly important for investments in phosphate fertilizers because the effects of phosphate fertilizers on soil fertility and crop production take place during several years.

Norsk Hydro studied with *La Compagnie malienne de développement des textiles* (CMDT) the option to replace inorganic P in the cotton fertiliser with ground Tilemsi rock (Henk Breman, personal communication, 22 June 2001) but the results do not appear to have been published.

Additional sources: (Bagayoko and Coulibaly, 1995; Ballo, 1995; Bationo, 1994; Bationo et al., 1997; Bationo et al., 1992b; Bationo et al., 1998a; Bationo et al., 1998b; Bationo and Mokwunye, 1991; Bationo et al., 1996; Bationo et al., 1999; Chien et al., 1993; Cornell University, 1996; Doumbia et al., 1993; Enyong et al., 1999; Harsch, 1999; Henao and Baanante, 1999; Hoffland, 1992; Hoffland et al., 1992; IFA, 2000a; IFDC, 2000a; Kagbo, 1991; Kébé et al., 1999; Ker, 1995; Thibout et al., 1980; Van Kauwenbergh et al., 1991a; West Africa Rice Development Association, 1999)

Mauritania



Location, Quantity, Quality

Eocene sedimentary phosphate beds located near Bofal and Loubboira, to the west of Kaedi and immediately north of the Senegalese border, are the most important phosphate deposits in Mauritania. These shallow dipping, relatively undisturbed phosphorite beds are highly siliceous and vary in thickness from 5.1 m in the west to 0.4 m in the east, although they are generally 1.7 to 2 m thick. Approximately 5 m of clays and sandstones overlie the phosphate rock. The deposits have been worked on a small scale to provide ground phosphate rock, with P_2O_5 concentrations ranging from 26 to 34%, for agronomic trials. Low carbonate substitution in the francolite results in low NAC soluble P_2O_5 ranging from 2.3 to 3.4%. This suggests that the ground phosphate rock may not be suitable for direct application.

Reserves at Bofal are 106 Mt with an average thickness of 1.7 m, an average grade of 21% P_2O_5 and an average overburden of 8 m. In comparison, Loubboira has 29 Mt reserves with an average thickness of 2 m, an average grade of 19% P_2O_5 and an average overburden of 7 m. The relatively thick overburden and hardness of the cap-rock is likely to constrain the utilization of these deposits. Additional 1.5 to 2 m thick phosphate rock beds are reported in a 60 km² area near Aleg, Tamourt and Beira, about 30km NW of Bofal.

Resources of about 150,000 t have been identified at Civé (Sive), near Kaédi on the north bank of the Senegal River, where phosphate rock beds average 1 m in thickness and 26 – 28% P_2O_5 . These deposits have some potential for use as a direct application fertilizer and it is reported that local farmers are extracting PR for this purpose (p. 124 in Vanlauwe et al., 1999).

Beneficiation of the Boufal- Loubboira phosphate rock by a combination of attrition scrubbing, screening and froth floatation results in a very high quality concentrate with about 36% P_2O_5 , low Cd (5-12 mg/kg) and very low $Fe_2O_3 + Al_2O_3 / P_2O_5$ of 0.025 which is well below the permitted ratio for commercial ore (0.10). Quality characteristics are given in Table 3.5.5 of Vanlauwe (1999).

A pre-feasibility study of a 2 million ton concentrate/year operation was carried out in 1983/84. This concluded that transportation costs (by road, Senegal River, railway or pipeline) would be too high to make exploitation economically viable. A planned feasibility study that would have assessed the viability of a 1.2 million ton / year phosphoric acid plant (for export) and production of TSP for local use has not been carried out. The Mining Annual Review (2000) reported that a mining licence for phosphate had been issued to SIPIA.

Phosphatic nodules with 23-32% P₂O₅ occur in Palaeozoic sediments at the remote location of Zemmour et Akhdhar near Bir Mauritanie in northern Mauritania (25°10'N, 11°35'E). The beds are relatively thin and of limited extent, so the potential for utilization is relatively low.

Silurian iron-phosphate deposits were discovered in the Adrar area on the western part of the Taoudeni Basin (Vanlauwe et al., 1999) where the Oued Chig Formation contain phosphatic pebbles with 17-22% P₂O₅. In addition, Precambrian phosphate bearing formations have been reported from the Idjibitene region but little appears to be known about these (Vanlauwe et al., 1999).

Low grade (7-10% P₂O₅) Precambrian phosphorites are also reported from the Nouedgué-Bou Naga area, Idjibitene, SW of Iriji in NW Mauritania (Vanlauwe et al., 1999). Low carbonate substitution in the metamorphosed fluor-apatite bearing rocks indicate very low potential for direct application, especially as Mauritania has plentiful resources of reactive PR in the Bofal area.

Two phosphate rock occurrences are recorded between Atar and Ouadane, and another to the east of Akjoujt, but no further information on these is readily available (Van Kauwenbergh et al., 1991a).

Sources: (Boujo et al., 1988; Boujo and Jiddou, 1989; McClellan and Notholt, 1986; McClellan and Saavedra, 1986; Notholt, 1991; Slansky, 1986; Van Kauwenbergh et al., 1991a)

Agronomic testing and use

No details are available on agronomic trials in Mauritania using phosphate rock.

Mozambique



Location, Quantity, Quality

Exploration for rock phosphate led to the discovery of a number of low grade apatite-magnetite deposits of possible Proterozoic age. An apatite-magnetite rock forms part of an alkaline igneous complex located northeast of the town of Muande, some 30 km NW of Tete in western Mozambique. Combined total reserves of 4,150,000 tonnes P_2O_5 , at an average P_2O_5 grade of 5% have been reported for the hard rock and eluvial deposits down to a depth of 140 m. The deposit was evaluated as a source of magnetite ore for a proposed iron and steel plant, but it is possible that apatite concentrates may be produced as a by-product if the magnetite iron ore is mined.

The largest known phosphate resource in Mozambique is the Evate apatite magnetite deposit, located to the NW of Monapo and 100 km north-east of Nampula, close to the port of Nacala. The steeply dipping, elongate deposit is reported to be 3 km long and up to 800 m wide. Phosphate mineralised zones are 5 m to 100 m wide and the deposit is reported to contain reserves of 155.5 Mt grading 9% P_2O_5 . 9 Mt of residual apatite enriched material have also been delineated. The deposit is composed of apatite, magnetite, forsterite, phlogopite and graphite.

Deposits of around 22,000 tonnes of phosphatic bat guano containing 9 to 11% P_2O_5 occur in Tertiary limestone caves in the coastal area of Mozambique, 96 km NW of Vilanculos. The deposits were investigated in 1952 by the *Servicos de Geologia e Minas*, when reserves were estimated at 14,000 cubic metres (approximately 146,000 long tons). Similar deposits occur at Govuro and Buzi.

Slightly phosphatic, calcareous sandstones occur on the left bank of the River Inkomati near Sabie, 29 km WNW of Maputo but these appear to have low potential. The sandstones contain glauconite and the potential for using the rock as a fertilizer has been investigated in the past. This occurrence is of interest

as a potential indicator of phosphogenesis of Cretaceous and Palaeogene age in southeastern Africa. The occurrence of more extensive beds of rock phosphate in the area cannot be ruled out entirely as the area has not been explored systematically. Glauconitic sandstones with 0.3 to 3.1% P_2O_5 are reported from the Magude area (Manhica, 1991).

Production

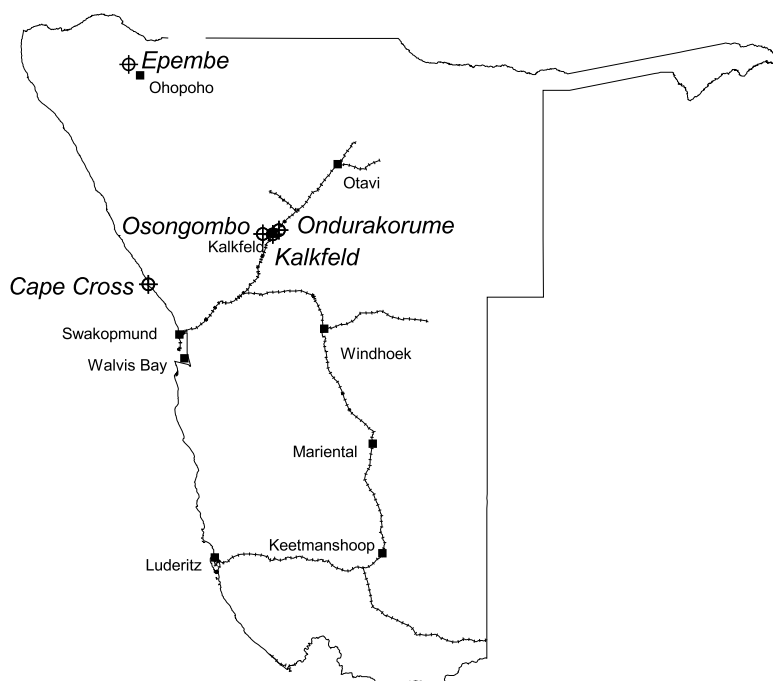
Production from Vilanculos was recorded for the period 1955 and 1960 and totalled 2,732 tons - the maximum annual output having reached 1,856 tons in 1956. It is reported that the sole producing company was Companhia Colonial do Buzi, Beira (Notholt, 1999).

Sources: (Manhica, 1991; McClellan and Notholt, 1986; Notholt, 1994a; Notholt, 1999)

Agronomic testing and use

No details are available on agronomic trials in Mozambique using phosphate rock.
Additional source: (IDRC, 1996)

Namibia



Location, Quantity, Quality

Phosphate occurrences have been recorded from the Kalkfeld, Osongombo and Ondurakorume carbonatite complexes located to the NE of Cape Cross and also at Epembe, 30 km NW of Ohopoho (Chopoho) and SW of Swartbooisdrif on the Cunene River. Average grades are only 3.6 to 7% P_2O_5 and the deposits are probably too small and remote to be of commercial interest. The Ondurakorume carbonatite, located about 13 km north-east of Kalkfeld appears to be the most promising of the known carbonatite complexes as a possible source of phosphate.

Glauconitic sediments containing 4% P_2O_5 have been recorded on the continental shelf at depths of 230 to 300 m.

Phosphatic guano containing 9 to 12% P_2O_5 occurs on islands located between Cape Cross and the Orange River.

Production

Deposits of phosphatic guano occurring about 12 miles south-east of Cape Cross Bay were worked by the Damaraland Guano Company for some years after 1895, and were probably extensive since 6,000 to 8,500 tons are stated to have been exported annually for use as fertilizer by farmers in the Cape Province of South Africa. The remaining deposits estimated to contain approximately 4000 tons of guano averaging about 22% P_2O_5 , were acquired by the South African Department of Agriculture around 1919, shipments of guano to South Africa apparently continuing until at least the early 1930s. Ten commercial consignments of guano received at Table Bay, Cape Town, contained 20.15 to 23.75% P_2O_5 (Notholt, 1999). Bat guano was produced in Namibia (South-West Africa) in 1938 and 1939, when recorded output was 751 and 631 short tons respectively. About 500 tons were shipped to South Africa during this period. There appears to be some confusion over the reported grade of the guano as Notholt (1999) states that " Production of phosphatic guano generally containing between 20 and 25% BPL (9 to 12% P_2O_5) for the period 1959-66 ranged from 400 to 1800 long tons, much of which was exported." It is not known if production continues.

Sources: (Birch, 1979; Bremner and Rogers, 1990; Fransolet et al., 1983; Fransolet et al., 1986; Hendey and Dingle, 1989; Keller and Vonknorring, 1985; McClellan and Notholt, 1986; McManus and Schneider, 1994; Notholt, 1999; Pirajno, 1994; Rao and Rao, 1996; Zabel et al., 1998)

Agronomic testing and use

No details are available on agronomic trials in Namibia using phosphate rock.

Niger



Location, Quantity, Quality

The Late Precambrian Tapoa deposit is situated near the border with Benin (12°29'N, 2°25'E), some 135 km SSE of Niamey. These deposits were discovered during the late-1960s in the *Parcs Nationaux du 'W'* area, astride the Burkina Faso -Niger border and are the largest PR resources in west Africa. No development is currently permitted within the park boundaries. The phosphate rock beds are sub-horizontal and covered by up to 60 m thick sandstones. Estimated total resources of 1,250 Mt and reserves of 100-500 Mt, averaging 27 % P₂O₅, have been delineated. These resources are the stratigraphical equivalent of the Late Precambrian Kodjari and Penjari Groups in Burkina Faso and Benin. Beneficiation studies by the IFDC indicate that concentrates with 34% P₂O₅ can be produced at a recovery rate of 70% of the P₂O₅. Whereas a NAC solubility of 1.4 - 2.8% P₂O₅ implies relatively low suitability for use as direct application fertilizer, agronomic trials have indicated significant improvements in yield can be obtained through the use of ground PR (Van Kauwenbergh et al., 1991a).

Approximately 7.5 Mt of Palaeocene to Eocene, flat lying, sedimentary phosphate rock resources grading 23% P₂O₅ have been delineated at Tahoua, located 375 km northeast of Niamey (Van Kauwenbergh et al., 1991a). The deposit comprises phosphate nodules up to 75 cm in diameter in a clay matrix. Fe₂O₃ is in the range 5.7 to 10.3% and SiO₂ 8.5-25.8%. NAC soluble P₂O₅ ranges from 2.6-3.3% so the PR would not be expected to be very effective as a direct application fertilizer.

A similar deposit located at Akkar (also known as Annekeur, Innakeur, In Akker, Annekeur and Anneker), 63 km NNW of Tahoua, was worked for direct application fertilizer (see below) although the quantity of resources has not been determined. This is one of a group of poorly known deposits in the Ader Douchi area, the other being Gaoy (or Gaoye, Gaweye) , 65 km north of Tahoua.

Past production (1960 onwards)

The Tahoua deposit is reported to have produced approximately 1,000 t per year of finely ground phosphate rock during the period 1979-84 (Van Kauwenbergh et al., 1991a). It is assumed that most of this rock was used for agronomic trials organised by the IFDC. The potential output from the processing plant is reported to be 10,000 t/y (Notholt, 1994a).

Sources: (Boujo et al., 1988; McClellan et al., 1985; McClellan and Notholt, 1986; Notholt, 1994a; Trompette, 1989; Van Kauwenbergh et al., 1991a)

Agronomic testing and use

Roesch and Pichot (1985) described the use of Tahoua rock phosphate as an initial basal dressing and for maintenance applications on the sandy soils of Niger.

IFDC and ICRISAT have demonstrated that phosphorus is the most limiting nutrient in west Africa although response by millet to nitrogen when moisture and P are non-limiting can be substantial. Application of 15-20 kg P/ha was usually adequate for optimum yields. Matam phosphate rock from Senegal, Tilemsi phosphate rock from Mali and Tahoua phosphate rock from Niger, both of which are medium reactive, were found to be suitable for direct application. Partial acidulation (50% with sulphuric acid) of the less reactive phosphate rocks resulted in products with similar agronomic effectiveness as commercial superphosphates. Tests conducted by farmers showed that millet yields can be increased by more than 250% by the use of fertilizers (Bationo et al., 1995).

The relative economic benefits of different P fertilizers applied to millet in Niger is demonstrated in Table 18 which clearly shows that TSP was the most profitable source of P followed, as would be predicted, by SSP, PAPR(50) and PR.

Table 18 Comparison of the relative economic benefits of ground Parc W phosphate rock (PR), PAPR (40 or 50), SSP and TSP for millet in Niger.

Site	Fertilizer	Net benefit (US \$/ha)	Value/Cost ratio
Sadore	Parc W PR	14.68	3.8
	PAPR (50)	26.77	3.0
	SSP	29.88	2.8
	TSP	38.67	5.4
Mai Gamji	Parc W PR	32.35	5.1
	PAPR (40)	60.34	4.2
	SSP	75.70	4.0
	TSP	84.28	7.4

Source: (adapted from Baanante, 1986, Table 17)

The agronomic effectiveness of (i) finely ground Tahoua and Parc W ground phosphate rocks from Niger, (ii) phosphate rock partially acidulated with sulphuric acid at 50% acidulation level (PAPR50), (iii) single superphosphate (SSP), and (iv) triple superphosphate (TSP) for millet was assessed in a field study on a sandy soil in Niger. Application rates were 0, 6.5, 13.0, and 19.5 kg P ha⁻¹ for each of the P fertilizers. A significant millet response to P was observed in all the trials. The major findings of this study were: (i) finely ground Tahoua phosphate rock was more effective than Parc W phosphate rock because of its higher reactivity and was 82 to 91% as effective as SSP for millet production in both the initial and two subsequent seasons; (ii) partial acidulation of Parc W PR can significantly increase its agronomic effectiveness in the first year, but not in terms of residual effect; (iii) partial acidulation was not a desirable technology for increasing the effectiveness of Tahoua PR, because its high Fe₂O₃ plus Al₂O₃ content resulted in a product containing relatively low amounts of water-soluble P; and (iv) over a period of 3 years, one initial application of a large dose of P fertilizer was found to be more effective than three small annual applications in terms of total grain production (Bationo et al., 1990).

A farm-level evaluation of nitrogen and SSP-PAPR phosphorus-fertilizer use and planting density for pearl-millet production in Niger demonstrated that although phosphate alone increased yields significantly at all densities, there was little response to fertilizer N at densities below 6,000 pockets ha⁻¹. Depending on fertilizer and grain prices, analysis showed that fertilizer use must be combined with high plant density or no economic benefit from fertilizer use will be realised (Bationo et al., 1992a).

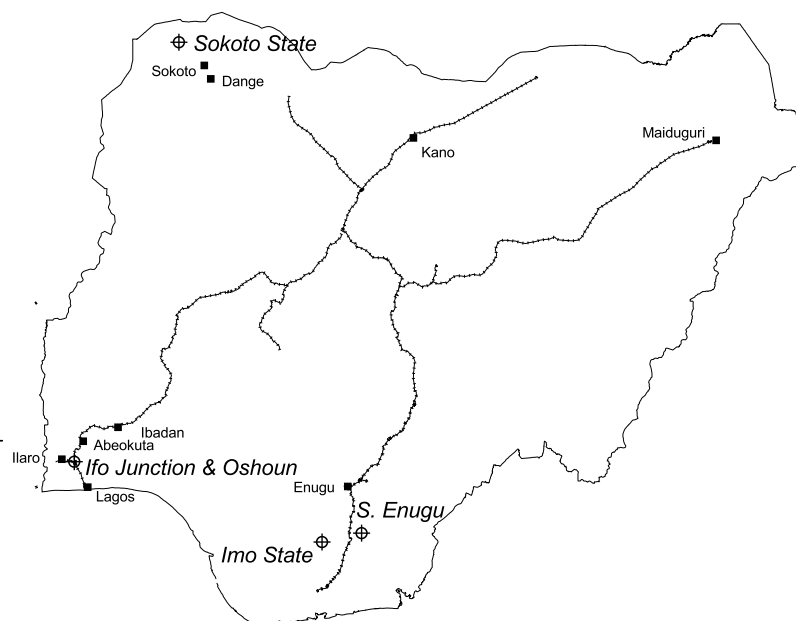
Bationo, Koala, et al. (1998b) evaluated the effectiveness of natural rock phosphates for cereal production in the Sahelo-sudanian zone of Niger where there is low erratic rainfall, high soil and air temperatures, soils with poor natural fertility, surface crusting and low water-holding capacity. Present farming systems are unsustainable, relatively unproductive, detrimental to the environment and characterised by negative plant nutrient balances in many cropping systems. Low plant-nutrient levels limit land productivity more than rainfall and phosphorus is one of the major constraints to crop production in West Africa. Farm trials carried out in Mali demonstrated that net production gains obtained after the application of Tilemsi phosphate rock were almost as good as after application of imported water-soluble P fertilizers. In Niger, once soil fertility was restored subsequent to the application of Tahoua phosphate rock, an additional pocket application of 3 kg P/ha of simple superphosphate gave higher benefits than conventional applications of 13 kg P/ha superphosphate. Bationo, Ayuk & Mokwunye (1995) present the results of a long-term evaluation of Parc-W phosphate rock (from the Tapoa are in Niger), with and without acidulation, as compared with SSP and TSP. They also studied the effect of different phosphorus management strategies.

On-farm research trials and demonstrations in soil/water conservation, use of inorganic fertilizers and rock phosphate, integrated soil management, and improved sorghum/peanut variety trials were conducted in Niger as part of the West Africa Natural Resource Management (NRM) InterCRSP Project sponsored by the Africa Bureau of USAID (USAID, 1999). Yield responses of two peanut varieties to Tahoua natural rock phosphate in a researcher-managed trial indicated that while inorganic fertilizers (SSP) did not produce any significant increase in grain and biomass yields of peanut, 200 kg/ha of Tahoua rock phosphate increased grain and biomass yields by almost 70%. This was true for both local and improved varieties of peanut. Further trials directed towards soil fertility enhancement are in progress including studies of (i) the use of rock phosphate in peanut production; (ii) the combined use of natural rock phosphate and manure; and (iii) the combined use of rock phosphate and inorganic fertilizer.

On-farm evaluation of different soil fertility management options in different agro-ecological zones of Niger by ICRISAT (2000a) revealed a high degree of yield variability between sites, farmers, years, treatments, and planting densities. The application of (i) crop residues, NPK 15-15-15 and calcium ammonium nitrate (CAN) fertilizer produced the greatest pearl millet grain yield, in a millet-cowpea rotation, followed by (ii) crop residue application combined with SSP and CAN, (iii) crop residues combined with 15-15-15, (iv) manure application alone, and (v) Tahoua Rock Phosphate. The treatments that provided the highest yields to farmers were not necessarily the ones that generated the highest benefit:cost ratio or net gains relative to the control. For example, in one area crop rotation plus hill applications of 15-15-15 and CAN fertilizers produced the highest pearl millet grain yield (1696 kg ha⁻¹), but hill placement applications of *Tahoua phosphate rock plus SSP produced a much higher benefit:cost ratio* relative to the control (but only 672 kg ha⁻¹ of pearl millet grain). The systems with the highest benefit : cost ratio tested by ICRISAT (2000a) were (i) Tahoua rock phosphate + rotations, followed by (ii) hill placement of Tahoua rock phosphate + SSP, (iii) manure application, (iv) crop residue application + 15-15-15 NPK CAN fertilizer, and (v) crop residues + 15-15-15 NPK fertilizer. The cheapest technology tested was Tahoua rock phosphate + crop rotation (approximately US\$ 5 per ha), which also produced a yield three times higher than the control.

Additional sources: (Bationo, 1994; Bationo et al., 1995; Bationo et al., 1991; Bationo et al., 1990; Bationo et al., 1992a; Bationo et al., 1998a; Bationo et al., 1998b; Bationo and Mokwunye, 1991; Bationo et al., 1999; Buerkert et al., 1997; Enyong et al., 1999; Fyfe and Kronberg, 1984; Harsch, 1999; ICRISAT, 2000a; Ker, 1995; Mahamane et al., 1997; Roesch and Pichot, 1985; Sivakumar and Salaam, 1999; USAID, 1999; Van Kauwenbergh et al., 1991a; West Africa Rice Development Association, 1999)

Nigeria



Location, Quantity, Quality

Although approximately 1 Mt of phosphorite resources have been identified in Lower Eocene strata of the Oshosun-Balogun-Ifo Junction area of Abeokuta Province in SW Nigeria (50 km from Lagos), it is reported that only about 20,000 tonnes of phosphate rock grading 27.5% P_2O_5 occur in a 1 m thick phosphorite bed with less than 3 m of overburden. The remainder of the resources are covered by up to 15 m of overburden. Beneficiation trials indicate that the phosphate rock, which contains high Fe_2O_3 (up to 11%) and Al_2O_3 (> 20%) may be upgraded by gravity separation. This deposit is equivalent in age to the mined phosphate rock deposits in Senegal and Togo.

Little information is available on Eocene phosphate rock occurrences reported in Sokoto State, but the most recent studies indicate a reserve of 5 Mt of phosphate nodules up to a depth of 10 m with an average overburden of 3.5 m. The nodules occur in shales interbedded with yellow limestones (Van Kauwenbergh et al., 1991a).

Phosphate nodules with average compositions of 32% P_2O_5 have been reported from shales and siltstones in Imo State. Evaluation of reserves was in progress in 1991 (Van Kauwenbergh et al., 1991a). The phosphate resources are thought to be the same age as those in the Oshosun area.

Sources: (Jones, 1964; McClellan and Notholt, 1986; Notholt, 1999; Sustrac et al., 1990; Van Kauwenbergh et al., 1991a)

Agronomic testing and use

Uyovbisere and Lombim (1991) reported the results of five years of collaborative field trials at Samaru, Nigeria on nitrogen, phosphorus, sulphur and potassium fertilizers. These showed that all these nutrients are needed in the soils and that whilst confirming the widespread deficiencies of N and P, the trials also showed that only moderate amounts of N and P are required to overcome these deficiencies and satisfy crop needs. *Partial acidulation of Togo phosphate rock at 50% produced a product that was agronomically as effective as commercial superphosphate.*

Results of experiments carried out on comparisons of P sources, urea placement methods and interaction of N, P, K, S fertilizers in the Ultisols of Southeastern Nigeria show that single superphosphate was superior to Togo phosphate rock, partially acidulated Togo phosphate rock, and diammonium phosphate for the production of maize (Maduakor, 1991). There was no significant interaction of N, P, K, S in the Ultisol but S was limiting. An application of a minimum of 45 kg N/ha appears to be the threshold for positive response to P by maize stover.

The relative agronomic effectiveness (RAE) of phosphate rock (PR) and its 50% partially acidulated form (PAPR) relative to single superphosphate (SSP) and diammonium phosphate (DAP) was studied in a two year field trial with maize grown on an acid Ultisol in the forest zone of southeastern Nigeria (Maduakor, 1994). All the P sources increased yields over the control. The RAE of PR relative to SSP was lower in the first year (25 and 38% for dry matter (DM) and grain yield (GY) respectively) compared to the second (64 and 58% for DM and GY respectively). Partial acidulation increased the yields by 17 and 7% for DM and GY, respectively, in the first year but not in the second. The RAE of PR and PAPR relative to DAP followed the same trend.

Adediran, Oguntoyinbo, et al. (1998) evaluated indigenous Sokoto rock phosphate (SRP), imported Togo rock phosphate (TRP), and conventional single superphosphate (SSP) in incubation and greenhouse studies using maize. The three P-fertilizers were applied on Oxisol, Ultisol, and Alfisol at rates ranging from 0-800 mg P kg⁻¹ soil. Evaluation of direct application of SSP and SRP on an oxic paleudult was carried out in the field for three years. The results of incubation studies revealed in general, that P availability increased as fertilizer rates increased. As would be expected, the P availability was greater when SSP was applied on the Alfisol compared with the Oxisol and Ultisol whilst the rock phosphates were more efficient on acid soils than on soils neutral in pH. Optimum P availability from the fertilizers was observed to occur predominantly between four and eight weeks of incubation. In the greenhouse study, SSP gave the highest cumulative P uptake, at an optimum rate of application was 200 mg P kg⁻¹ soil, while the optimum rate for rock phosphate was 400 mg P kg⁻¹ soil.

Agronomic effectiveness (EA) for the rock phosphates was about 40% relative to SSP on the Alfisol. The EA, however, for TRP and SRP was 120% and 160%, respectively, on the Oxisol, while on the Ultisol, SRP was equally effective as SSP and TRP had 65% effectiveness. The results of the field trial indicated that the SRP had 54%, 83%, and 107% agronomic effectiveness of SSP, respectively, in the first, second, and third year of cropping. Optimum rates for SSP and SRP application were considered to be 50 and 75 kg P₂O₅ ha⁻¹, respectively.

Adediran and Sobulo (1998) evaluated phosphorus fertilizers developed from Sokoto rock phosphate (SRP) in Nigeria (including PAPR). The fertilizers were applied in the greenhouse at 0-400 mg/kg soil on the Oyo Arenic Haplustalf and Alagba Kandiudult soil. Field trials were carried out at four locations:- at Ikenne in the humid, Samaru in the subhumid; and Gumi and Gusau in the semi-arid zones of Nigeria. The fertilizers were applied at 0-150 kg P₂O₅ ha⁻¹ in the humid zone and 0-100 kg P₂O₅ ha⁻¹ in the subhumid and semi-arid zones. Maize was used as test crop in most sites except at Samaru where sorghum was planted. The results of the greenhouse study showed that on the Haplustalf, PAPR, and NPK gave almost a similar relative agronomic effectiveness (~70%) as SSP, which was followed by SRP (with an RAE of between 50 and 60%). On the Kandiudult, the RAE of the fertilizers increased significantly. The PAPR and NPK were highly effective (RAE about 90% relative to SSP). *The field trial results indicated that ground SRP was suitable for direct application on slightly acid soil in the humid zone with annual rainfall >1,200 mm. Its efficiency was fairly moderate in the subhumid and quite low in the semi-arid zones (annual rainfall <900 mm).* The PAPR gave higher RAE than SRP and was comparable to SSP in the humid and subhumid zones and was fairly comparable to the latter in the semi-arid zone. This suggests that PAPR may be suitable for humid and subhumid zones. *Application of SRP on soils in the semi-arid zones of low rainfall gave relatively low yields, which could be due to inadequate moisture availability required to enhance P solubilization.*

Akande, Aduayi, et al. (1998) compared the agronomic efficiency of Sokoto Rock Phosphate (SRP) and water-soluble SSP as phosphorus (P) fertilizer sources for maize on Iwo Soil Series (Oxic Tropudalf) in the field in SW Nigeria. The effectiveness of the different rates of SRP in increasing maize grain yields in the initial experiment followed the order of SRP25 > SRP50 > SRP100 > SRP200 while the residual effect after one year on yield was as follows: SRP50 > SRP100 = SRP200 > SRP25. The optimum grain

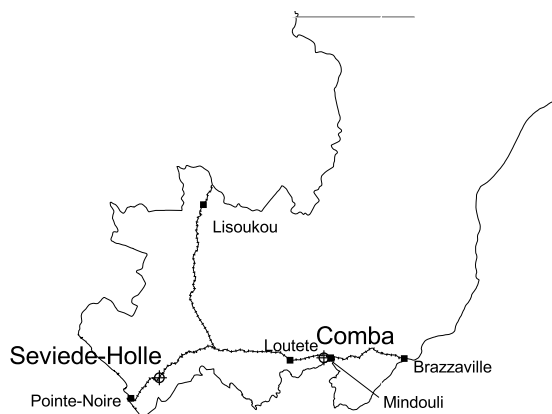
yields of 5.9 and 5.1 tonnes ha⁻¹ were obtained with SSP at the rate of 50 and 100 kg ha⁻¹ in the initial (1989) and residual (1990), respectively. The optimum grain yield could not be ascertained in the initial (1989) experiment for SRP because the yield declined as the rates of SRP increased. But in the residual effects trial (1990 season), it was 4.9 tonnes ha⁻¹ at the rate of 50 kg ha⁻¹. The relative agronomic efficiency values ranged from minus 500% to 0% and 150% to 100% in the initial and residual effects trials, respectively. *This indicates that Sokoto Rock Phosphate was more effective in supplying P for maize growth in the second than the first year of the experiment.*

IITA scientists, working with colleagues in the national programs of Benin, Côte d'Ivoire, and Nigeria in collaboration with the Belgian Government are investigating the possibility of breeding food crops like soybeans and cowpea and cover crops like *Mucuna* that could release the P chained up in savanna soils. Trials in Nigeria have shown that cover crop legumes like *Mucuna* can break down the rock phosphate, use it to grow luxuriantly themselves, and leave available P in the soil. Maize crops grown the following year yield far more grain than crops grown after a previous crop of maize. In the rhizosphere zone, legume roots interact with soil fungi and bacteria that can act as catalysts to the reaction with P probably because legume roots exude the organic acids that dissolve rock phosphate. IITA (1999b) reported that growing legumes with added rock phosphate will increase the organic matter in the soil. If only half the amount of fertilizer P that is usually applied to a maize crop to obtain its optimum yield were to be used on a maize crop following the rock phosphate-treated legume, the maize yields would be optimised. An IITA research project has indicated that site- and species-specific responses of *Mucuna* and *Lablab* to the addition of Togo rock phosphate (RP) were observed for a series of trials on a toposequence representative of the northern Guinea savanna (NGS). *Mucuna* significantly enhanced the release of P from RP and increased grain yields of the following maize crop (IITA, 1999b).

Vanlauwe, Aihou et al. (1999) examined the role of legumes in N and P nutrition of maize in the moist savanna zone of West Africa as part of a study of the use of cover crops in West Africa, in particular, evaluating whether (i) the combination of N fertilizers with organic matter may improve N-use efficiency of the former, and (ii) interactions between low reactivity rock phosphate and the rhizosphere of legumes may improve the immediate availability of rock phosphate (RP). The research activities are targeted on the derived savanna (DS) and the northern Guinea savanna (NGS) benchmarks in southern Benin and northern Nigeria, respectively. The N and P status of the soils in selected villages in the DS and NGS benchmarks was generally poor with an average of 80% and 65% of the soils responded to fertilizer N and P, respectively. Although most of the farmers in both benchmarks use inorganic fertilizer, the applications rates are low on average (40 kg N/ha) in the NGS villages. A series of experiments was established on a representative toposequence (3 fields) in the NGS of northern Nigeria to address the second hypothesis on rock phosphate (RP)–legume (*Mucuna* and *Lablab*) interactions. Vanlauwe, Aihou et al. (1999) concluded that although most of the symbiotic properties were enhanced after RP addition, this enhancement did not consistently lead to improvements in above-ground biomass production, partly caused by bacterial and/or viral diseases of *Lablab* on 2 of the 3 fields. Moreover, nearly all legume residues had disappeared from the soil surface at the time the subsequent maize crop was planted. Maize grain yields increased from 1250 to 2642 kg/ha following *Mucuna* and from 1582 to 2557 kg/ha following *Lablab* in the treatments where the legumes were treated with 90 kg RP-P/ha compared to the treatments without RP addition. *These improvements in maize yield are most likely caused by an improvement in the general P status of the soil caused by an enhancement of the soil microbiological properties* (IITA, 1999b; Vanlauwe et al., 1999).

Additional sources: (Adediran et al., 1998; Adediran and Sobulo, 1998; Adepoju, 1993; Adetunji, 1995; Adetunji, 1997; Agbenin, 1996; Agbenin, 1998; Agbenin and Tiessen, 1994; Akande et al., 1998; Bekunda et al., 1997; Cornell University, 1996; Doumbia et al., 1998; Eze and Loganathan, 1990; Fyfe and Kronberg, 1984; Hughes and Gilkes, 1986; IFA, 2000a; IITA, 1999b; Kadeba, 1990; Kamh et al., 1999; Ker, 1995; Kronberg et al., 1986; Le Mare, 1982; Le Mare and Hughes, 1982; Maduakor, 1991; Maduakor, 1994; Mba, 1994a; Mba, 1996; Mba, 1997; Mokwunye and Chien, 1980; Mokwunye, 1975; Ogunkunle and Chikezie, 1992; Okusami et al., 1997; Osodeke et al., 1993; Ouyang et al., 1999; Uyovbisere and Lombim, 1991; Vanlauwe et al., 1999)

Republic of the Congo



Location, Quantity, Quality

15 million tonnes of Upper Cretaceous to Eocene sedimentary phosphate rock resources have been delineated at Holle, situated close to the railway line, 50 km from the deep water port of Pointe Noire. The resources are generally low grade (21-25% P_2O_5) and their highly siliceous nature makes beneficiation impractical due to the high cost of flotation. The smaller (0.3 Mt, 21% P_2O_5) Sintou-Kola deposits represent a southern extension of the Holle phosphate rock deposit. A phosphate rock occurrence with 28-35% P_2O_5 has been recorded in Precambrian strata near Comba, 110 km west of Brazzaville, although its economic potential does not appear to have been assessed.

Phosphorite deposits of unknown significance have been identified in Miocene and Quaternary sediments at a depth of 40 m near Pointe Noire, off the coast of Congo and Gabon.

Sources:(Barusseau et al., 1988; Giresse and Baloka, 1997; Hourcq, 1966; McClellan and Notholt, 1986; Notholt, 1999; Sustrac et al., 1990; Woolsey and Bargerion, 1986)

Agronomic testing and use

No details are available on agronomic trials in the Republic of the Congo⁶ using phosphate rock

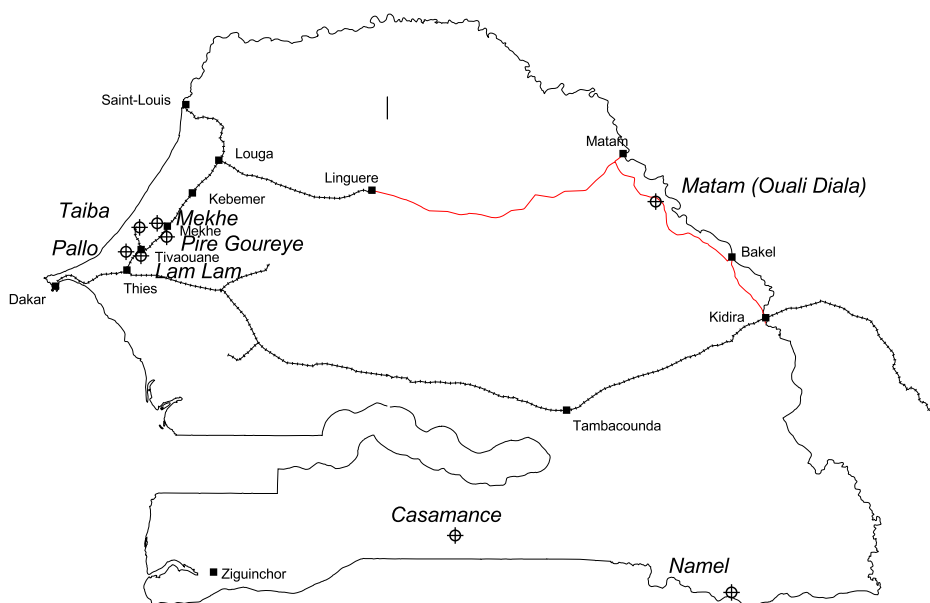
⁶ Congo-Brazzaville

Rwanda

Agronomic testing and use

No details are available on agronomic trials in Rwanda using phosphate rock apart from a brief reference in Bekunda, Bationo et al. (1997).

Senegal



Location, Quantity, Quality

The commercially exploited Taiba and Pallo phosphate rock deposits are located close to the coast, 113 and 80 km by rail from Dakar. Sedimentary rock phosphate of Lower Eocene age has been worked since 1960 near Taiba on the Thiès Plateau of western Senegal. The deposits occur at the south-west end of a large phosphate-rich sedimentary basin, approximately 22 km long and 10 km wide. Mining of the Taiba deposit has, to date, been confined almost entirely to the Keur Mor Fall on the western margin of the basin, where a bed of poorly consolidated phosphatic sandstone with an average thickness of 5.7 m contains 24 to 25% P_2O_5 . Reserves in the mining area are estimated to be 20 Mt of high-grade marketable concentrate (37.5% P_2O_5 , 82% BPL), with a further 50 Mt in the Tobène sector further to the south-east, where the rock phosphate occurs under a thicker overburden. It has been estimated that there is also a resource of about 20 Mt of $<40 \mu m$ material with 26% P_2O_5 that is currently discarded as waste. Cadmium (Cd) is high in the Taiba phosphate rock (range 60-115 mg/kg, average 87 mg/kg).

The Pallo aluminium-calcium phosphate ores worked near Thiès since 1949 were formed as the result of the lateritization of Eocene phosphatic sediments during the Pliocene and Quaternary. Resources of 90 Mt averaging 28% P_2O_5 , 6-10% Fe_2O_3 , 27-32% Al_2O_3 and 8-10% CaO have been reported (Notholt, 1994a). The ore zone varies from 3 m to 30 m in thickness, and covers an area of more than 490 km².

Phosphate rock resources have also been identified at Matam (40 Mt, 29% P_2O_5) in NE Senegal and Lam Lam (4 Mt, 33% P_2O_5), 16 km NE of Thiès. The Matam deposit is not expected to be exploited under

current phosphate market conditions. The Lam Lam phosphate rock was worked in 1952-53 but the 14-19 m thick overburden of aluminium phosphate and ferruginous laterite made the deposit economically unattractive compared to the Taiba and Pallo deposits, even though the concentrations of Fe, Al and Si in the Lam Lam phosphate rock are relatively low.

Minor occurrences of Late Proterozoic age have been described also from the Namel area of eastern Senegal.

Current production

The Taiba phosphate deposits came into commercial production in the early 1960s and are notable for the high grade (36% P₂O₅) of the phosphate concentrates obtained. Also exploited on a smaller scale are the Pallo aluminium phosphate deposits situated near Thies, although the annual marketable production from Pallo has declined from about 480,000 t in the 1980's to around 50,000 in the late 1990's. Most of the aluminium phosphate is calcined to give a product with 34% P₂O₅.

The phosphates production sector currently dominates the mining industry in Senegal even though phosphate rock production has declined about 30% during the period 1992 to 1999 (Table 19). Phosphate production accounts for more than 15% of total export earnings. A relatively small proportion of the total phosphate rock production is exported - most being converted to phosphoric acid and calcium phosphate-based fertiliser within Senegal, mainly for export. Of the phosphate rock exported in 1993, most went to Australia (120,000 t), Canada (198,000 t), China (74,000t), India (59,000 t), and Mexico (162,000 t) with minor quantities to Japan, New Zealand and Venezuela. 1,200 t was exported to the Ivory Coast where it may be used as a direct application fertilizer or used for the manufacture of phosphate fertilizers. It is reported that farmers in Senegal use none of the phosphate rock produced for direct application although a small quantity is used for agronomic experiments.

The Taiba deposit was mined by the *Compagnie Sénégalaise des Phosphates de Taiba* (CSPT) in which the Government had a 50% shareholder whereas the aluminium phosphate was mined by the *Société Sénégalaise des Phosphates de Thies* (SSPT) owned jointly by the Government and Rhône Poulenc (Mining Annual Review, 1995). In 1996 there was a merger between CSPT and the *Industries Chimiquiest du Senegal* (ICS), which operated a fertilizer complex producing sulphuric acid and phosphoric acid. A new phosphoric acid plant will be completed in 2001 and by 2003 mining will have moved to the new Tobuene sector which will probably provide sufficient capacity to permit an increase in the amount of rock phosphate exported (Mining Annual Review, 2000). In the last decade, exports of phosphate rock have been restricted as a result of an increase in the domestic production of phosphoric acid for export.

Sources: (Boujo et al., 1988; Boujo and Jiddou, 1989; Capdecombe, 1953; Chapellier et al., 1991; Flicoteaux and Hameh, 1989; Flicoteaux and Trompette, 1998; McClellan and Notholt, 1986; McClellan and Saavedra, 1986; Notholt, 1980; Notholt, 1994a; Pascal and Cheikh, 1989; Pascal and Diene, 1987; Pascal et al., 1989; Slansky, 1986; Sustrac et al., 1990; Van Kauwenbergh et al., 1991a)

Table 19 Production and export of calcium phosphate rock, aluminium phosphate, fertilizers and phosphoric acid in Senegal

	1992	1993	1994	1995	1996	1997	1998	1999
<i>Production of PR ('000t)</i>								
Calcium phosphate rock	2,284	1,667	1,587	1,544	1,377	1,584	1,519	1,797
Aluminium phosphate	93	40	23	40	78	9	21	64
<i>Export of PR ('000t)</i>								
	1187	1200	530	846	725	617	410	na
<i>Production ('000t P₂O₅)</i>								
Calcium-phosphate based fertilizers	na	160	160	160	160	160	na	na
Phosphoric acid	na	274	274	274	300	300	na	na
Aluminium phosphate, dehydrated	54	21	21	na	na	na	na	na

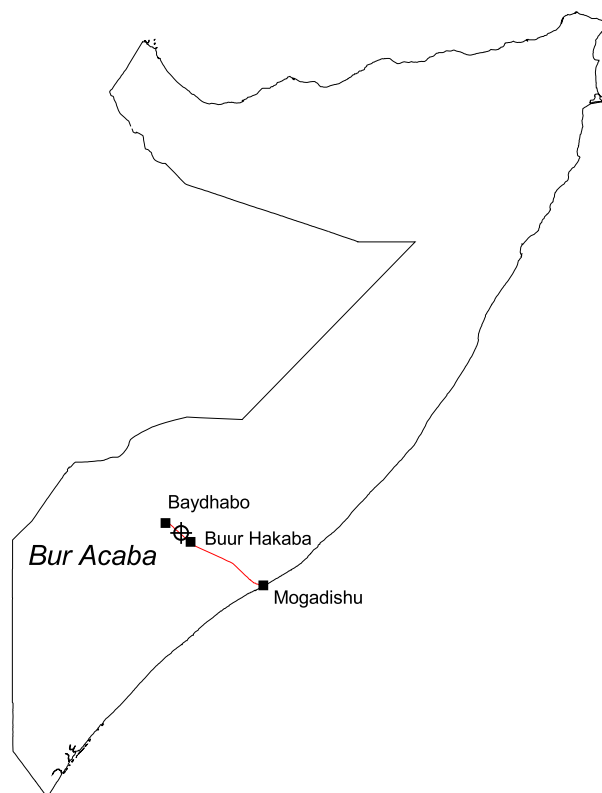
Sources: BGS World Mineral Statistics, 2001; U.S. Geological Survey - Minerals Information - 1997; FAO Fertilizer Yearbook, 1998; na = data not available.

Agronomic testing and use

USAID's *Rural and Agricultural Incomes with a Sustainable Environment* programme on *Integrated crop/livestock systems* reports that in the Thies region, it is evident that manure is most beneficial when used in combination with natural rock phosphate (at an application rate of 30 kg/hectare, roughly equivalent to 30 lb/acre) (USAID, 2001). This is true for millet crops as well as millet/cowpea intercropping. Peanut yields indicate that combined treatments of manure and natural rock phosphate, showing an increase on average of 40-60 % compared to the traditional applications of manure alone (2 tons/ha). Since 1996, the government of Senegal has been encouraging the wider use of rock phosphate to help regenerate soils within the peanut production basin (USAID, 2001).

Additional sources: (Ba et al., 2000; Bationo et al., 1992b; Bationo and Mkwunye, 1991; Bekunda et al., 1997; Cornell University, 1996; Ker, 1995; Narsian and Patel, 2000; USAID, 2001; Van Kauwenbergh et al., 1991a; West Africa Rice Development Association, 1999)

Somalia



Location, Quantity, Quality

Precambrian silicified phosphatic marbles containing 24% P_2O_5 occur at Modu Mode in southern Somalia, 25 km NW of Bur Acaba (Buur Hakaba). No resource data are available for this occurrence.

It is reported that small deposits of bird guano (10-28% P_2O_5) were worked intermittently on Mait Island, located about 54 km NE of the port of Heis and some 7 miles from the mainland near Cape Humbeis. The guano is reported to cover the island to a depth of only 5 to 8 cm, but also fills holes and crevices in the underlying bedrock. Reserves are negligible but the supply of guano is constantly renewed by the numerous colonies of sea birds that nest on the island.

Production (pre-1960)

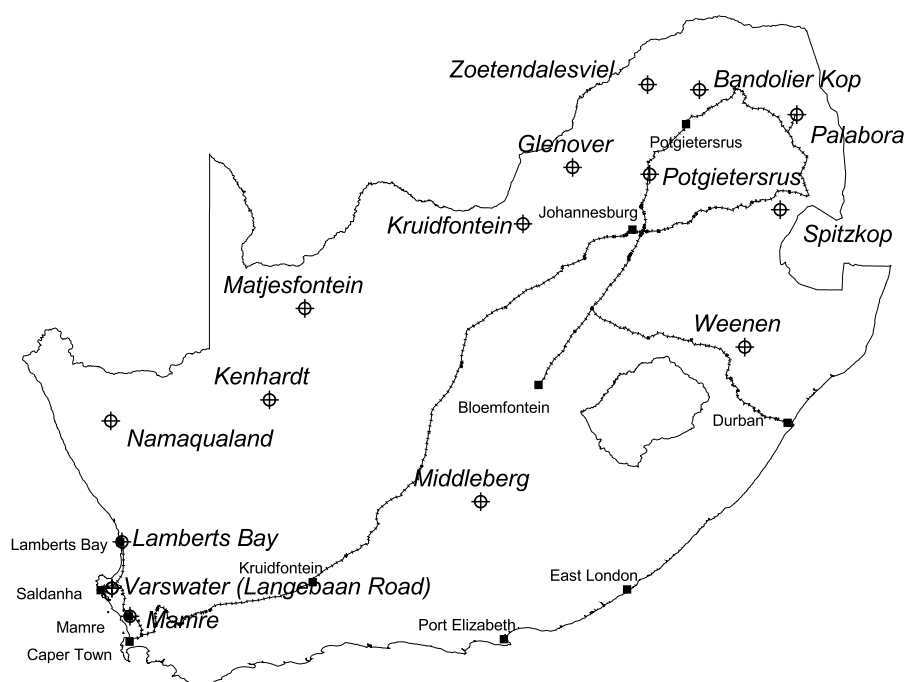
Annual exports were small but variable, reaching a maximum of 680 tons in 1951. The deposits were worked on behalf of Cowasjee, Dinshaw and Brothers, Aden, but there is no recorded output since 1960, when 339 tons was produced. The guano was exported to Saudi Arabia for use on the tobacco crops of the Hadhramut Province.

Sources: (McClellan and Notholt, 1986; Notholt, 1999)

Agronomic testing and use

No details are available on agronomic trials in Somalia using phosphate rock.

South Africa



Location, Quantity, Quality

The locations, grades and production data for the major igneous phosphate deposits of Palabora and Glenover, together with the sedimentary Varwater (Langebaan Road) deposit in the Saldanha Bay area of Cape Province are described below in the section on current production. The Palabora complex is composed of approximately 95% pyroxenite, 3% phoscorite (or foskorite; an apatite-magnetite-olivine-phlogopite rock) and 2% carbonatite. Minor igneous phosphate occurrences are located at Kruidfontein, Spitzkop and also at Bandolier Kop in the Transvaal where 0.1 Mt of resources grading 10-26% P_2O_5 have been identified at a site located 15 km ENE of the Bandolier Kop Station, in northern Transvaal. The Scheil phoscorite and apatite pyroxenite deposit, located about 70 km E of Louis Trichard, has estimated reserves of 36 Mt grading 5% P_2O_5 . Secondary phosphate occurs at five localities in the Saldanha Bay area, NNW of Cape Town. Of these, Varwater is a current producer and the other four (Sandheuwel, Paternoster, Duyker Eiland, and Constable Hill) have resources of 0.3 to 23.6 Mt grading 5 to 27.5% P_2O_5 . Of the other phosphate rock occurrences in South Africa, only the Mamre sedimentary deposit in Cape Province (0.05 Mt, 21-27% P_2O_5) and the Zoetendaalsviel guano deposit (0.04 Mt, 24 % P_2O_5) have resource estimates available.

Past production (1960 onwards)

Phosphate rock production at the Glenover Mine in northwestern Transvaal ceased in 1982. Concentrates grading 29% P_2O_5 were unsuitable for acid-process fertilizer manufacture so they were fused with serpentine to produce "Calmafos", a fused calcium magnesium phosphate fertilizer which was used locally in South Africa. The plant closed in 1983 possibly because high grade reserves had become exhausted.

Current production

South Africa has been a major producer of phosphate rock since the early 1960s with production of marketable apatite, sedimentary phosphate rock and aluminium phosphate increasing from about 1.3 Mt

in 1967 to 2.9 Mt in 1999. Nearly 3400 tons of guano was produced in 1967 but production has now ceased.

Phosphate has been extracted since about 1930 from a number of mines in the Palabora area in the Transvaal. Early production was a ground phosphate rock concentrate which was not a commercial success (Atkinson and Hale, 1993). During the period 1955-64, phosphate rock concentrates were used for SSP production. Since 1965, the Palabora Mining Company (PMC), a subsidiary of RTZ, has carried out mining. Apatite is extracted together with copper and other minerals from the Palabora ore deposit by PMC which sells the treated high grade phosphate concentrates (36.5 to 40.5% P_2O_5) to the state owned FOSKOR for subsequent treatment. The plant commissioned in 1955 has a design capacity of 50,000 t/y phosphate and the output from the plant has increased steadily from 0.5 to 3 Mt/y of phosphate rock concentrate. This is derived from about 16 Mt/yr of ore extracted by Foskor's mining and about 10 Mt/y phosphate rich tailings derived from Palabora's copper mining operation. A new beneficiation plant, costing \$US 810 million (R 3 billion) is planned for development if its commercial viability can be proven. The plant was planned to come into full production by 2000 to provide concentrates for export to international markets.

In 1993-94, 767,000 t concentrates from Palabora were used for the manufacture of phosphoric acid and a range of phosphate fertilizers in plants at Palabora, Vereenigen, Richard's Bay and Somerset West. 209,000 t of concentrates were used for manufacturing non-fertilizer products (Mining Annual Review 1995). FOSKOR manufactures phosphoric acid and a range of phosphate fertilizers, most of which is used within South Africa (Table 3). Mining Annual Review (2000) reported that a new phosphoric acid plant was being constructed in South Africa and would use local phosphate rock concentrates.

Of the 1,197,000 t of phosphate rock concentrates exported in 1993, the majority went to Belgium (560,000 t), Netherlands (119,000 t), Spain (77,000 t) and Japan (229,000) with lesser quantities to Denmark, Germany, Norway, Eastern Europe, Zimbabwe (6,000 t), the Philippines, and Australia.

High-grade rock (39% P_2O_5) from Palabora was exported to Europe for use by nitrophosphate producers and for the manufacture of industrial phosphate products in Japan.

The Palabora phosphate rock is not used for direct application, mainly due to its low reactivity.

The Varswater mine near Saldanha Bay, to the north west of Cape Town, was reported have an annual production of 20,000 t P_2O_5 , compared with about 1,100,000 t P_2O_5 from the Palabora area (Atkinson and Hale, 1993). The 10% P_2O_5 rock was upgraded to a concentrate containing 29% P_2O_5 and marketed under the brand name of "Langfos" as a direct application fertilizer or blended with DSP, MAP and sylvite. Some of the coarse concentrate was finely ground and marketed as "Langfos powder" which is a more reactive direct application fertilizer. Relatively cheap, lower grade direct application fertilizers with 18-22% P_2O_5 was marketed as "Kalfos" and supplied in bulk both locally in Cape Province but also transported to many other parts of South Africa and exported to the Far East (Atkinson and Hale, 1993). Investment was being sought in 1999 for the further development of the Langebaan and adjacent phosphate rock resources together with the erection of a phosphoric acid plant (US Department of State, 1999).

Sources: (Anon., 1989; Anon., 1998c; Atkinson and Hale, 1993; Birch, 1990; Birch, 1979; De Jager, 1989; Fourie and De, 1986; Frankel, 1943; Frankel, 1948; Hagenguth and Volk, 1986; Hendey and Dingle, 1989; Lawver et al., 1978; Notholt, 1991; Notholt, 1999; Rahden et al., 1968; Roux et al., 1989; Strydom, 1950; US Department of State, 1999; Woebking, 1986)

Table 20 Production, consumption and export of phosphate rock and phosphate fertilizers in South Africa

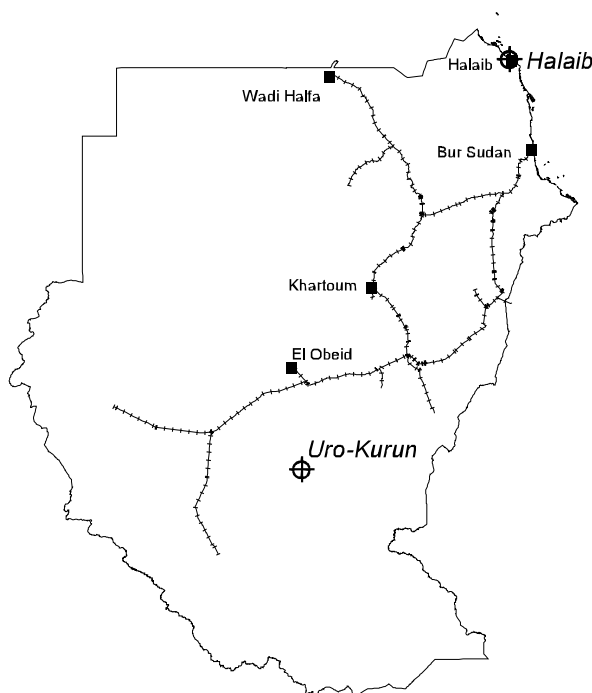
	1983	1985	1987	1989	1991	1993	1995	1997	1999
Production of phosphate rock (apatite) ('000t)	2742	2484	2623	2963	3180	3000	2790	2717	2940
Export of phosphate rock (apatite) ('000t)	303	687	1061	1094	1166	1300	1408	903	na
Phosphate Fertilizers ('000t P ₂ O ₅)									
<i>Production</i>	420	455	330	375	339	340	373	378	378
<i>Consumption</i>	388	363	275	273	257	301	240	225	218
<i>Export</i>	65	82	35	100	90	74	109	118	116

Sources: BGS World Mineral Statistics, 2001; U.S. Geological Survey - Minerals Information - 1997; FAO Fertilizer Yearbook, 1994); na = data not available

Agronomic testing and use

No details are readily available on agronomic trials in South Africa using phosphate rock apart from three papers on the use of Langebaan phosphate rock by Thibaud et al., (1992; 1993; 1994) and indirect references in the following sources: Roux, De et al. (1989); Bornman, Bornman et al. (1998); Dodor, Oya et al. (1999). In South Africa it will be very difficult, if not impossible, to improve rural development in the former "home-lands" if the Government will not invest in soil improvement (liming and increasing P-availability) like it did in the past for the white commercial farmers (Henk Breman, personal communication, 22 June 2001)

Sudan



Location, Quantity, Quality

A sedimentary phosphate rock occurrence is reported on the Red Sea coast in the Halaib district, 300 km NNW of Port Sudan. It is associated with clastic sediments and thick evaporites, which generally do not favour the occurrence of major phosphate rock deposits. Apatite is reported to occur in small quantities in pegmatites that cut schists and slates of the Basement Complex at the railway station of Shereik, close to the River Nile in the Northern Province of Sudan and about 80 miles NNW of Atbara. More recently, rock phosphates have been reported to occur at Uro and Kurun in the Eastern Nuba mountains in the state of Kordofan (Western Sudan), about 330 km south of El Obeid (10°12'N, 30°28'E) (Sam et al., 1999; Sam and Holm, 1995). The deposit at Jebel Kurun is reported to have resources of 336,000 tons. These deposits may be a potential source of raw material for ground rock phosphate fertilizer.

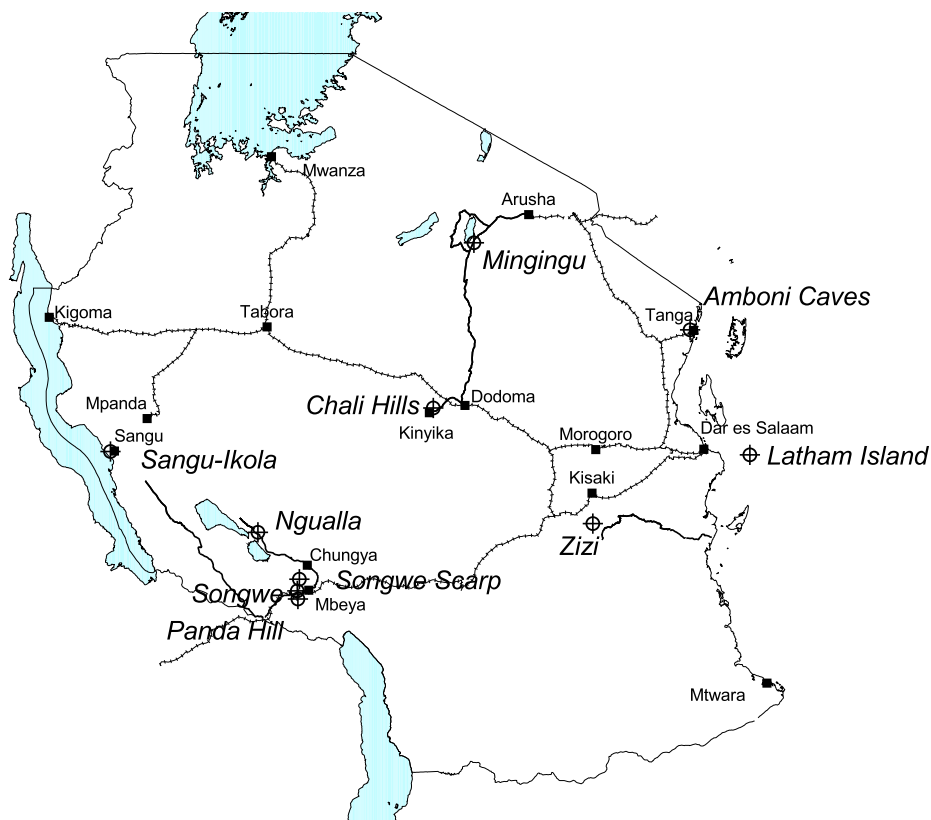
There is currently no phosphate production in Sudan and the country's limited fertilizer requirements are met by imports.

Sources: (McClellan and Notholt, 1986; Notholt, 1999; Sam et al., 1999; Sam and Holm, 1995) (<http://www.sudani.co.za/mineral.htm>)

Agronomic testing and use

No details are available on agronomic trials in the Sudan using phosphate rock.

Tanzania



Location, Quantity, Quality

Tanzania has sedimentary and igneous phosphate deposits, although only the Mingingu deposit has been exploited as a source of phosphate rock for fertilizer manufacture.

The Mingingu phosphate rock deposit is located near Lake Manyara, 112 km SW of the rail terminal at Arusha in northern Tanzania, and 550 km from the phosphate fertilizer plant located at the coastal port of Tanga. This unusual Neogene-Quaternary lacustrine phosphate deposit comprises individual phosphate beds that range from about 1 m to 3 m in thickness and thin away from the centre of the deposit at Mingingu Kopje. Total geological resources to a depth of about 60 m are reported to be 10 Mt containing an average of 20% P_2O_5 (Notholt, 1994a) whereas the proven reserves are only about 2 Mt (IFDC, 1988). Fine grained friable phosphate rock contains about 18.5% P_2O_5 and the hard siliceous phosphate rock averages 21.4% P_2O_5 . Whereas the soft ore and concentrates have only 25 and 29% total P_2O_5 , they contain very high levels of NAC soluble P_2O_5 (6%) so appear to have good potential for use as direct application phosphate fertilizer. Detailed agronomic evaluation of the Mingingu PR is required. An $Fe_2O_3+Al_2O_3+MgO/P_2O_5$ ratio of 0.24 recorded for one sample of Mingingu ore (IFDC, 1988) is well above the value (0.11) usually considered acceptable for commercial ores. Trial beneficiation reduced the ratio to 0.18, but this ore could still not produce a commercially acceptable SSP product (IFDC, 1988).

Extensive use of ground rock phosphate, and phosphate fertilizers derived from the Mingingu phosphate deposit has been assessed in relation to the radiological implications to the farmers (Makweba and Holm, 1993). The external radiation arising from the use of phosphate fertilizers in agricultural fields was found to be less than 2% of normal background radiation (50 nGy h^{-1}). There are potential environmental

impacts of using ground Minjingu phosphate rock as a direct application fertilizer (Makweba and Holm, 1993; Semu and Singh, 1996).

Deposits similar to Minjingu include those at the Pyramids, 10 km to the south of Minjingu, the Chali Hills to the west of Dodoma and Chamoto Hill, adjacent to the Iringa-Mbeya road.

Small quantities of apatite occur in 21 carbonatite complexes in Tanzania, but Panda Hill, located 20 km SW of Mbeya is the only one with much potential. Weathering has enhanced P_2O_5 concentrations in residual soils to 14-30%. It is reported that the soils may be beneficiated by washing and that the apatite concentrates have been used successfully as direct application fertilizer. P_2O_5 concentrations of about 5% in hard rock rising to 10-13% in residual soils are associated with the Ngualla, Nachendezwaya, Sangu-Ikola and Zizi carbonatites. The low grade and unfavourable mineralogy of the Songwe Scarp phosphate rock suggest that its beneficiation would be sub-economic. No NAC soluble P_2O_5 data are available for these igneous apatites, but they would not be expected to be suitable for direct application under most soil and climatic conditions.

Table 21. Phosphate concentrations and resources for carbonatites in Tanzania.

Name of carbonatite	P_2O_5 concentration	Notes
Panda Hill (Mbeya District)	6%; 17-25% in residual soils	125Mt resources
Mbalizi (Mbeya District)	5-8%	apatite in sövite;
Nachendezwaya (Ilege District)	2-6%	apatite in sövite; 6.1×10^6 tons resources
Ngualla	<1-7.4% in rock and 0.5-7.4% in soils	
Songwe Scarp	carbonatite 3-10%; weathered material >17%	
Sangu-Ikola	>10% in residual soil	16-35% apatite in carbonatite
Zizi	4.5-10.5% (average 7%) in carbonatite	concentrates with up to 25% have been produced

Phosphate resources of 2 Mt grading 3.1 to 10.6% P_2O_5 have been delineated to a depth of 30 m in a lens of weathered apatite marble located near the Great Ruaha River, 48 km SSW of Kisaki and about 112 km south of Morogoro.

Bat guano deposits in limestone caves on the Songwe River, 20 km W of Mbeya, at Amboni, 10 km N of Tanga, and on Latham Island off the southern end of Zanzibar where resources of about 3,500 tons have been reported to occur in thicknesses averaging about 0.3 m.

Production

The Tanzanian State Mining Company (STAMINCO) developed the Minjingu phosphate rock deposit in 1983 with technical cooperation from the Finnish company Kone Corporation. Initial production of about 20,000 t/y was used by the phosphoric acid/TSP plant at Tanga until it closed in the early 1990's. Of the 2,500 t production recorded in 1994, approximately 1,800 to 2,000t was exported to Kenya where it is used for direct application and for SSP production at the Thika plant, while 500 to 700 tons was sold for direct application in northern Tanzania. It is not known to which crops the phosphate rock was applied. Although it has been reported (Mining Annual Review, 1995) that the Minjingu phosphate plant is shut-down, it is understood from other sources that the mine and processing plant continue to operate on a very limited

basis. Phosphate mineral exports with a value of 0.07, 0.02 and 0.23 US\$million are reported for 1997, 1998 and 1999 (Mining Annual Review, 2000). Phosphate rock (apatite) production figures are shown in Table 22 below:

Bat guano deposits in limestone caves on the Songwe River, 20 km W of Mbeya, were worked on a small scale until 1957. About 3,000 tons of guano was extracted for use as a direct application fertilizer in the period 1934-1957 (IFDC, 1988).

Table 22 Production, consumption and export of phosphate rock and phosphate fertilizers in Tanzania.

	1991	1992	1993	1994	1995	1996	1997	1998	1999
Production of phosphate rock (apatite) '000t	4	na	na	na	21	28	3	2	2

Sources: BGS World Mineral Statistics, 2001; U.S. Geological Survey - Minerals Information - 1997; FAO Fertilizer Yearbook, 1998. na = data not available

Sources: (Aswathanarayana and Makweba, 1990; Chesworth et al., 1989; DANIDA, 2000; IDRC, 1996; IFDC, 1988; Makweba and Holm, 1993; McClellan and Notholt, 1986; Mchihyo, 1991; Mwalyosi, 1988; Mwambete, 1991; Notholt, 1999; Romney, 1987; Schlueter, 1993; Schlueter, 1995; Schlüter et al., 2001; Van Straaten, 1986; Van Straaten, 1995; Van Straaten, 1998; Van Straaten and Fernandes, 1995; Van Straaten and Pride, 1993; Van Straaten et al., 1992; Vanvuuren and Hamilton, 1992)

Agronomic testing and use

Mnkeni, Semoka, et al. (1994) evaluated the effectiveness of Mapogoro phillipsite (a zeolitic cation exchanger) to enhance the chemical breakdown of apatite in two phosphate rocks of igneous and sedimentary origin from Tanzania in a greenhouse study using an acidic P-deficient soil from Mbimba, Mbeya region. The treatments tested were 40 mg P kg⁻¹ of triple superphosphate (TSP), Panda PR (igneous), and Minjingu PR (sedimentary) applied singly and in combination with Mapogoro phillipsite at ratios of 1:1, 1:10, and 1:100. The TSP increased dry matter (DM) yield of maize fivefold indicating that the soil used required supplemental P. Application of the igneous Panda PR alone had no significant effect on yield due to low solubility and reactivity. Fourfold yield increases due to the sedimentary Minjingu PR compared to the control indicate that it was relatively more reactive than the Panda PR. Mapogoro phillipsite had no effect on the solubilization of Panda PR. However, it enhanced the breakdown of Minjingu PR substantially, especially at the PR:zeolite ratio of 1:100. This was reflected in significantly higher available P in the soil, P uptake, and DM yield. Mnkeni, Semoka, et al. (1994) concluded that it is doubtful whether application of PR-zeolite mixtures at a ratio of 1:100 would be an economic proposition for smallholder farmers.

Mnkeni and Chien (reported in IFDC, 1997) evaluated the relative agronomic effectiveness of fertilizer products derived from the low reactive Panda Hills phosphate rock of Tanzania. IFDC prepared four products aimed at improving the agronomic effectiveness of Panda Hills phosphate rock: (i) concentrated Panda PR, (ii) partially acidulated Panda PR (PAPR) with sulphuric acid at 50% acidulation level, (iii) ground Panda PR mixed with TSP, and (iv) a compacted mixture of raw Panda PR with TSP at P₂O₅ ratio equivalent to 50:50. Incubation results showed that phosphorus release was a function of the water-soluble phosphorus content of the phosphate source. The agronomic effectiveness of the materials was evaluated in greenhouse studies using three U.S. soils and four test crops – wheat, canola (rape), maize, and soybean. The results of the wheat, maize, and soybean experiments indicated that the modified Panda PR products improved the yields of these crops in two acid soils. Due to the very low reactivity of Panda PR, the crops responded only to water-soluble phosphorus in the modified products. Results of the canola study showed that in acid soils, canola (unlike the other test crops) used phosphorus from Panda PR in

the modified products as effectively as that from TSP. When tested on an alkaline soil, Panda PR was found to be about 50% as effective as TSP as a source of P for canola. These results indicate that canola is capable of utilizing P even from unreactive igneous PRs in acid and alkaline soils. When tested under the same conditions, Panda PR compacted with TSP, was found to be almost as effective as TSP in improving canola yields. Panda PAPR was intermediate in its effectiveness. Mnkeni and Chien (IFDC, 2000) concluded that Panda PR and other unreactive igneous PRs of its type could be modified and used as effectively as water-soluble phosphorus on canola when cropped on such soils.

The Minjingu Phosphate Rock Utilization Project (DANIDA, 2000) is managed collaboratively by Department of Soil Science of Sokoine University of Agriculture in Morogoro, Tanzania Ministry of Agriculture and Cooperatives, and the Chemistry Department of the Royal Veterinary and Agricultural University in Copenhagen, Denmark and will run for the period 1998-2003. The overall development objectives of the project include (i) alleviation of phosphorus nutritional constraints in Tanzanian crop production by direct application of natural indigenous phosphorus sources; (ii) reduction of Tanzania's dependence on imported soluble phosphorus fertilizers and (iii) secure the most efficient use of the limited phosphorus resources. The main field activities in connection with the Minjingu Phosphate Rock Project include evaluation of both granulated and non-granulated Minjingu Phosphate Rock as phosphorus source for maize.

Mnkeni, Chien, et al. (2000) used greenhouse experiments to evaluate the agronomic effectiveness of Panda Hills phosphate rock (PPR) from southwest Tanzania, its mixture with triple superphosphate (TSP), and a compacted mixture of Panda PR and TSP (PPR+TSP) for wheat, rape, maize, and soybean on two United States soils (Hiwassee and Windthorst). The performance of the P sources as reflected by yield, P uptake and relative agronomic effectiveness (RAE) followed the order TSP>>(PPR+TSP)>(PPR)+(TSP)>>PPR for wheat, rape, maize, and soybean on Hiwassee soil. Panda PR was very ineffective in increasing grain or dry-matter yields of the test crops on this soil. The mixture of Panda PR and TSP as well as the compacted product increased wheat, maize, and soybean yields and P uptake significantly. The increases in yields were, however, largely attributed to the TSP component of the (PPR)+(TSP) mixture or its compacted product with little or no contribution from PPR. On the alkaline Windthorst soil, the performance of the P sources as reflected by rapeseed yield and RAE followed the order TSP congruent to (PPR+TSP)>(PPR)+(TSP)>PPR. Mnkeni, Chien, et al. (2000) observed that it was remarkable that compacted PPR and TSP was at a par with TSP while PPR alone was 50% as effective as TSP in increasing rapeseed yield. Addition of lime drastically reduced the effectiveness of Panda PR, but it had little or no effect on the agronomic effectiveness of the (PPR)+(TSP) mixture or its compacted product.

Using two acid soils Acrisols and Andosols, two experiments were carried out to evaluate effect of Minjingu Phosphate Rock (Minjingu PR) on growth of four (4) agroforestry multipurpose trees, *Leucaena leucocephala*, *Senna siamea*, *Grevillea robusta*, and *Eucalyptus grandis*. In the first experiment, one month old seedlings received Minjingu PR at 0 (PR0), 52 (PR1) and 77 (PR2) Kg P ha⁻¹ in 2 Kg soil. In the second experiment the Minjingu PR rates of the first experiment were maintained, *G. robusta* and *L. leucocephala* were the test crops and only Acrisol was used (Karanja et al., 2001). There was a slower response to Minjingu PR fertilizer application in Andosols as compared to Acrisols. At 19 weeks after transplanting (21 WAT), PR2 had caused a significant ($p < 0.05$) height increase over PR0 for *L. leucocephala* and the heights where PR was added differed significantly ($p < 0.05$) from PR0 in root collar diameter (rcd) for *G. robusta* in Acrisols soils. Addition of PR2 had a negative effect on height of *C. siamea* whereas *E. grandis* did not respond to PR additions. In the second study, there were significant increases of up to 121% in height ($p < 0.001$) and root collar diameter ($p < 0.05$) and 4.5 times biomass over the controls where *L. leucocephala* seedlings received rock phosphates alone and PR+mycorrhizae at 12 months after planting. Nodulation of *L. leucocephala* was significantly affected by P application and/or A-mycorrhizae inoculation but was variable within any similar treatments except for controls. Species x treatments interactions were significant, $p < 0.05$ and $p < 0.001$ for shoot and root dry weight respectively. PR and mycorrhizae inoculation have the potential to improve legume performance in these acidic soils (Karanja et al., 2001).

Zimbabwe's smallholder farming areas are facing serious soil fertility decline caused by the fragile nature of the soil and the lack of financial resources to purchase fertilizers. Dorowa phosphate rock which is

being evaluated as a potential low cost fertilizer for the smallholder sector (Tagwira, 2001). Preliminary results show that the Dorowa igneous PR is not suitable for direct application without some form of beneficiation. Compacted and pelletized phosphate rock mixed with SSP and manure was observed to increase P dissolution to about 30% of total rock P. Relative agronomic effectiveness for maize shoot yield of 62 to 70% and grain yield of 51 to 61% for a typic rhodulstalf and typic haplustox soil respectively was recorded. Composting of phosphate rock in cattle kraals gave a percentage increase in net benefit of 83% over the farmer's practice. The rock is a potential source of P for farmers if it can be compacted with SSP, partially acidulated or composted in cattle kraals with manure. Tagwira (2001) concluded that the composting technology is probably the most promising.

Additional sources: (Addison, 1999; Bekunda et al., 1997; Chesworth et al., 1989; DANIDA, 2000; FAO, 2000b; FAO, 2000c; Gladwin et al., 2000; Gladwin and Thomson, 2000; Haque et al., 1999a; Hartemink, 1997; ICRAF, 1997; IDRC, 1996; IFA, 2000a; IFDC, 1988; IFDC, 1997; Karanja et al., 2001; Ker, 1995; Legault, 1998; Lowell and Well, 1995; Lowell and Well, 1993; Mnkeni et al., 2000; Mnkeni et al., 1994; Mkwunye et al., 1986; Mkwunye and Vlek, 1986; Mutuo et al., 1999; New Agriculturalist, 2001; Sagoe et al., 1998b; Sanchez et al., 1999; Semu and Singh, 1996; Singh et al., 1980; Tagwira, 2001; Van Straaten, 1998; Van Straaten and Fernandes, 1995; Van Straaten et al., 1992; Vanvuuren and Hamilton, 1992)

Togo



Location, Quantity, Quality

The commercial Hahotoé-Akoumapé deposits are located about 25 km by rail from Kpeme and 35 km from Lome in a NE-SW trending, 35 km long, 1-2 km wide phosphate enriched zone in Lower Eocene sediments. The phosphate rock beds vary in thickness from 2 to 6 m, and occur within the shallow dipping clays and shales of the *Série de la Lama*. Phosphate rock ore is scrubbed, wet screened and hydrocycloned to remove clay, which constitutes up to 40% of the feed to the beneficiation plant. The resulting high-grade phosphate rock contains 36% P_2O_5 and relatively low Al_2O_3 (1.0%) and Fe_2O_3 (1.5%). Cadmium (Cd) concentrations in Hahotoe phosphate rock are high, ranging from range 48 to 67 mg/kg (average 58 mg/kg). The planned development of new rock phosphate deposits at Dagbati had not commenced in 1998.

Phosphate rock occurrences have also been reported from Bassar (Pascal and Aregba, 1989), close to the northern border of Togo, but little information is readily available.

Current production

Phosphate rock is produced by the state owned *Office Togolaise de Phosphates* (OTP) from the Hahotoé and Akoumapé phosphate deposits, located 25 km inland from the rock treatment plant and the export port of Kpeme. The treatment plant has a capacity of 3.5 Mt of phosphate concentrate, but production in the mid-1990's was considerably less than the plant capacity, being only 2.1 Mt in 1994 and 2.2 Mt in 1997 (Table 23).

All the phosphate rock is exported as Togo is one of the few major rock phosphate producers that lacks downstream chemical processing facilities. Most of the 1,567,000 t of phosphate rock exported in 1993 went to Canada (561,000 t), the Philippines (330,000 t) and South Africa (430,000 t) with smaller quantities to Greece, Spain, Poland, Mexico, Uruguay, India and China. 4,100 t of Togo rock was exported to Nigeria. It is reported that the only phosphate rock consuming facility in Nigeria, the Kaduna SSP plant, was closed a number of years ago so it is assumed that rock exported to Nigeria was used as direct application fertilizer. Togo phosphate rock has been used in agronomic trials but is not used routinely as a direct application fertilizer by the local farmers.

The relatively high Cd concentration in the Togo phosphate rock is a serious problem due to the limits imposed by some western European countries. In the mid-1990's, phosphates continued to find a market in Canada, Philippines, Spain, Nigeria and India even though the Cd content is high (Mining Annual Review, 1998). However, more recently the high Cd has led to a decline in exports to these countries, which were formerly the traditional markets for Togo phosphate rock.

Phosphate rock production operations have been running at a loss since 1991 (Mining Annual Review, 1995). In 1998, Mining Annual Review reported that studies were underway with two Indian companies one of which is considering the establishment of a 330,000 t/y phosphoric acid unit and a 400,000 t/y DAP plant at Kpeme, whilst the other was studying the possibility of a 400,000 t/y phosphoric acid and associated fertiliser unit.

Phosphate mining is a major contributor to the national economy of Togo to which it contributed about 10% of GDP and 40 % of exports. Phosphate production decreased from 2.26 Mt in 1998 to only 1.7 Mt in 1999, mainly because of the loss of the 1 Mt/y contract with Agrium, Canada. Production was also constrained by an increase of the stripping ratio and related technical problems. The planned transfer to the private sector of a 40% stake in the state company, *Office Togolais des Phosphates* (OTP) was unsuccessful, and this has reduced the opportunities for the company to revamp its operations and develop downstream chemical processing facilities (Mining Annual Review, 2000). At least two South African fertiliser producers are reported to have a potential interest in using Togo rock for in-country P-fertiliser production (Henk Breman, person communication, 22 June 2001).

Sources: (Arocena et al., 1995; Boujo et al., 1988; Castaing, 1989; Johnson, 1995; Johnson et al., 1989; McClellan and Notholt, 1986; Notholt, 1980; Notholt, 1994a; Pascal and Aregba, 1989; Slansky, 1989; Sustrac et al., 1990; Van Kauwenbergh et al., 1991a; Van Kauwenbergh and McClellan, 1990)

Table 24 Production and export of phosphate rock for Togo

	1991	1992	1993	1994	1995	1996	1997	1998	1999
Production '000t	2965	2083	1794	2149	2569	2731	2631	2263	1715
Export '000t	3074	2086	2000	2234	2652	2686	2687	2243	1624

Sources: BGS World Mineral Statistics, 2001; FAO Fertilizer Yearbook, 1998)

Kpomblekou, Chien, et al. (1991) carried out a greenhouse evaluation of phosphate fertilizers produced from Togo phosphate rock by comparing agronomic effectiveness using a RAE index for the following P fertilizer sources: (i) ground Togo PR; (ii) partially acidulated phosphate rock (PAPR) at 50% acidulation with H₂SO₄; (iii) PR compacted with triple superphosphate (TSP), urea, and KCl at a P ratio of PR:TSP = 50:50; and (iv) commercial-grade single superphosphate (SSP). The results showed that *ground Togo PR was an ineffective P source for both maize and cowpeas when applied to an acid Bladen sandy loam (Typic Albaquult) limed to pH 5.5 and with P application rates 0, 50, 100, 150, and 200 mg P/kg. The RAE values were not significantly different from those for the control (no P added). For the PAPR and compacted (PR + TSP), however, the RAE values with respect to SSP were 72.5% and 84.7%, respectively, for increased dry-matter yield of maize and 87.7% and 97.1%, respectively, for increased cowpea seed yield.*

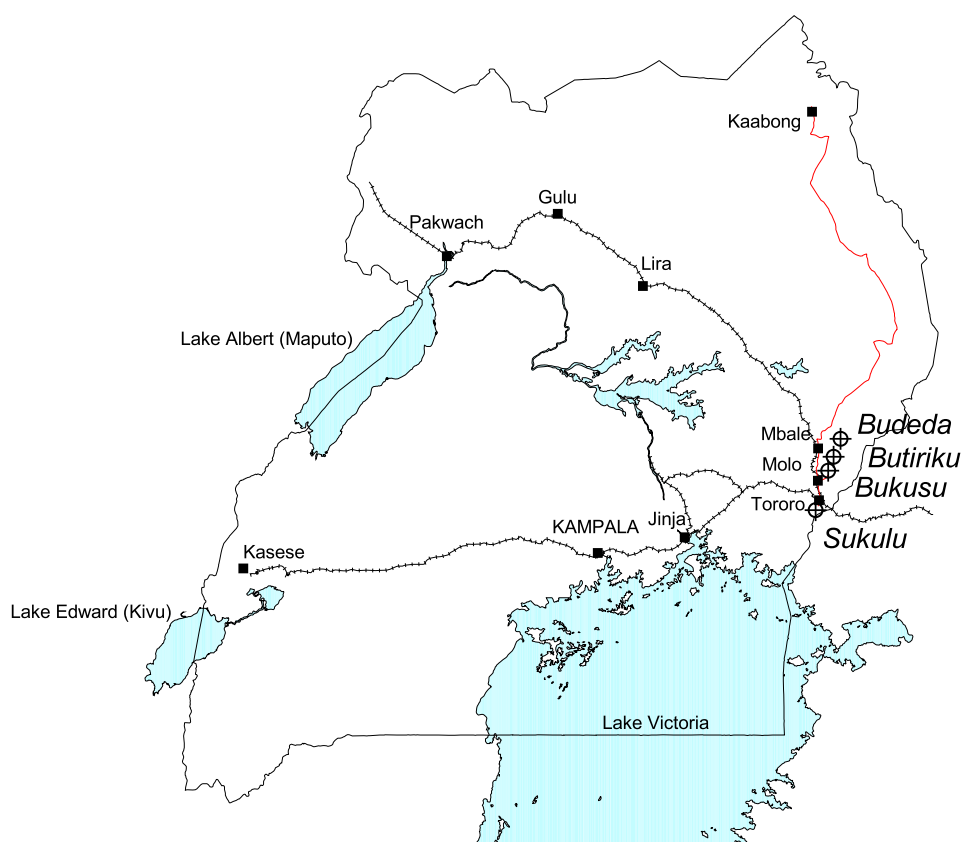
Kato, Zapata, et al. (1995) evaluated the agronomic effectiveness of two natural phosphate rocks (PRs) from North Carolina (USA) and Togo and their 50% partially acidulated products (PAPRs) in two greenhouse experiments using P-32 isotopic dilution techniques. In the first experiment rye grass was grown in a soil from Ghana. The proportion of P in the plant derived from the P fertilizer ranged from about 10% for the PRs up to 80% for the PAPRs, the P fertilizer recovery was less than 1% for a 60-day growth period. In the second experiment, average values of P in the maize plants derived from the PAPRs ranged from 35% to 75% in 3 different soils *whereas both PRs were ineffective.*

IFDC (2001) report that Dossa from the University of Abidjan in Togo, compared two forms of phosphate rock (PR) and soluble phosphate (SSP) as sources of phosphorus (P) for common cereal/legume rotations of the West African savannas with crop residues recirculated to maintain the organic matter status of the soil. The study compared two soils, one with and one almost without P-fixation. Dossa's work at IFDC-Africa shows that the second year after PR is applied, yield increases for cereals and legumes are still negligible on the P-fixing soils. However, on the non-P-fixing soil, a 12% increase in cereal yield was observed, compared with 35% for SSP. Taking the recovery of nitrogen fertilizer as a measure of impact on nitrogen uptake and crop production, nitrogen recovery appeared at least twice as high using SSP rather than phosphate rock on the non-P-fixing soil. Dossa (IFDC, 2001) concluded that on the P-fixing soil, nitrogen recovery with SSP compared with that with phosphate rock was substantially lower than on non-P-fixing soils due to the decreased efficiency of SSP. When phosphate rock was the source of phosphorus, the recovery of nitrogen by the cereal crop was similar on the P-fixing and the non-P-fixing soil; *in both cases the recovery was low. Dossa also concluded that if phosphate rock's effect on crop yields does not increase considerably in the coming years, PR will only be useful as an amendment if its price is substantially lower than the price of soluble phosphates.*

Tossa (2000) investigated the influence of soil properties and organic inputs on phosphorus cycling in herbaceous legume-based cropping systems in the West African derived Savanna and a study executed by ITRA and IFDC-Africa (on request of the EU delegation) evaluated the economic feasibility of using Hahotoe rock for cocoa, coffee and cotton (Anon., 1998a).

Additional sources: (Abekoe and Tiessen, 1998; Acheampong, 1995; Adediran et al., 1998; Arocena et al., 1995; Bagayoko and Coulibaly, 1995; Bationo, 1994; Bationo et al., 1995; Bationo et al., 1992b; Bationo et al., 1996; Binh and Fayard, 1995; Chien et al., 1993; Dahoui, 1995; Diouf, 1995; Diouf et al., 1995; Dodor et al., 1999; Ernani and Barber, 1991; Gerner and Baanante, 1995; Gerner and Mokwunye, 1995; Haque and Lupwayi, 1998a; Harsch, 1999; IFA, 2000a; IFDC, 2000b; IFDC, 2001; IITA, 1999a; Iretskaya et al., 1998; Johnson, 1995; Johnson et al., 1989; Juo and Kang, 1979; Kato et al., 1995; Ker, 1995; Kpomblekou et al., 1991; Kuyvenhoven and Lanser, 1999; Lompo et al., 1995; Lowell and Well, 1995; Maduakor, 1991; McClellan and Notholt, 1986; Mokwunye, 1995a; Mokwunye, 1995b; OwusuBennoah and Acquaye, 1996; Rhodes et al., 1996; Sagoe et al., 1998a; Sagoe et al., 1998b; Smaling, 1995; Teboh, 1995; Uyovbisere and Lombim, 1991; Van Kauwenbergh et al., 1991a; Vanlauwe et al., 1999; Visker et al., 1995; West Africa Rice Development Association, 1999)

Uganda



Location, Quantity, Quality

Upper Cretaceous to Paleogene alkaline-carbonatite igneous complexes in Uganda, like those in Malawi, Tanzania and Zambia, have been investigated extensively as potential sources of phosphate for either fertilizer production or for use as direct application material. The most important resources in southeastern Uganda, are the residual accumulations developed as a result of weathering on and around the Sukulu and Bukusu (Busumbu) carbonatite complexes, situated near Tororo, just northeast of Lake Victoria.

The Sukulu deposit located 6 km SW of Tororo, close to the port of Jinja on Lake Victoria and near the main railway line from Mombasa to Kampala, has resources of 230 Mt containing 11 to 13% P_2O_5 . The phosphate resources comprise unconsolidated reddish to chocolate-brown residual soils, varying from 15 to 67 m in thickness, that have developed in a series of dry valleys on the Sukulu Complex. The soils comprise a complex assemblage of about 25% apatite, 30% magnetite-haematite, 15% quartz, 10% kaolinite, 10% Al-phosphates (crandallite group), and minor amounts of zircon, perovskite, pyrochlore and baddeleyite. Characterization of a sample of Sukulu ore by the IFDC revealed that it has low grade and quality and that 20% of the P_2O_5 occurs as secondary phosphates, principally of the crandalite group. Concentrates are very high grade (about 40% P_2O_5) and quality ($Fe_2O_3+Al_2O_3/P_2O_5 = 0.02$). X-ray studies indicate that the fluorhydroxy-apatite has low reactivity, which would require very fine grinding prior to chemical processing. NAC soluble P_2O_5 is low (1.6%) confirming that it is not suitable for use as a direct application fertilizer under most soil and climatic conditions.

Similar ferruginous residual soils containing 25-30% P₂O₅ have developed over carbonatite and magnetite-apatite-phlogopite rock at the Bukusu Complex, 25 km NNE of Tororo. The Bukusu complex measures about 13 km in diameter and is probably the largest carbonatite complex in Africa. Residual soils are 30 to 60 m thick and derived from an underlying, poorly exposed belt of apatite-magnetite-rich rocks and biotite-pyroxenites, which forms an arcuate dissected ridge around the carbonatite. The weathered zone extends to a depth of 60 m. Primary apatite has in places been partially or completely replaced to produce a cream to buff coloured, hard, but slag-like and cavernous rock (phoscrete) which generally contains over 25% P₂O₅ and consists chiefly of francolite (carbonate fluorapatite). Reserves of >1 Mt averaging approximately 21% P₂O₅ have been outlined. The mining lease area around the old Busumbu quarry is reported to contain indicated reserves of at least 5 Mt of phosphate rock and soft phosphatic soil containing between 8 and 35% P₂O₅ (Notholt, 1994). This represents only part of the entire deposit, however, and a total resource of some 50 Mt may be present (Notholt, 1994). Minor occurrences of apatite associated with carbonatite have been identified at Budeda (<1-2% P₂O₅) Butiriku (large tonnages with up to 30% P₂O₅), Toror Hills, Totoro Hill (located under a township therefore of little value), Fort Portal (3-4% P₂O₅), Lake Kyekora and Katwe-Kikorongo. Available information indicates these occurrences have little potential (IFDC, 1988).

Past production (1960 onwards)

Production of high grade concentrates from the Sukulu carbonatite phosphate rock deposit started in 1962 but the mine closed in 1978 due to political problems. Production over the period 1962-1978 was 160,000 t of apatite concentrates (40% P₂O₅) derived from the beneficiation of 2.16 Mt of phosphate rich soil. The flotation concentrates were converted to SSP in a nearby superphosphate plant using acid produced from imported sulphur. About 22,000 t of SSP was produced in 1969, most of which was exported to Kenya. More recently, the potential for the production of SSP, PAPR and phosphoric acid, TSP, DAP and MAP from the Sukulu deposit has been evaluated by the IFDC. Sukulu phosphate rock has been used as a direct application fertilizer for agronomic experiments but it is not known if farmers have ever used it commercially. Between 1944 and 1964, similar residual phosphate rock deposits at Bukusu were worked. The 58,100 t of 20-25% P₂O₅ phosphate rock concentrates produced during this period were exported to Kenya for conversion to soda-phosphate (28% P₂O₅). It is reported that ground Bukusu phosphate rock containing about 17% P₂O₅ was used as direct application fertilizer, probably on the sugarcane plantations in the Lugazi area.

Future development

The Sukulu deposits have recently been re-investigated as part of a plan to re-launch the phosphate industry in Uganda and produce 50,000 tpa of P₂O₅ for the manufacture of single superphosphate and ammoniated superphosphate. It is reported that the French firm Rhodia Chimie has won a license to mine phosphates at Sukulu in eastern Uganda and that the government had initially wanted to take a stake in the project but subsequently decided to leave it entirely in private hands (Africa Energy & Mining, 2000). Rhodia Chimie plans to mine phosphates for the production of fertiliser at Sukulu provided that it can raise \$300m to finance the project and secure the huge investment required for infrastructure. Rhodia Chimie wants the railway link between Uganda and the Kenyan capital to be improved to facilitate bulk exports to neighbouring countries. The French firm and its partner, local firm Madhvani International, hope to produce 100,000 tonnes/year of phosphate fertilisers and export 1m tonnes of apatite

Research and testing at independent laboratories and the soil science Department at the University of Kampala has identified technical problems with the existing phosphate resource at Bukusu for the intended applications. However, treatment methods are under investigation with encouraging early results. For the time being, this project is being deferred (International Business Investments, 2001).

Sources: (Africa Energy & Mining, 2000; Atkinson and Hale, 1993; Balu-Tabaaro, 1986; Government of Uganda, 2000; IDRC, 1996; International Business Investments, 2000; International Business Investments, 2001; International Mining Development, 2000; Kabagambe, 1989; Mathers, 1994; McClellan and Notholt, 1986; Notholt,

1994a; Notholt, 1999; Reedman, 1984; Schlueter, 1995; Taylor, 1955; Van Straaten, 1999; Van Straaten and Pride, 1993)

Agronomic testing and use

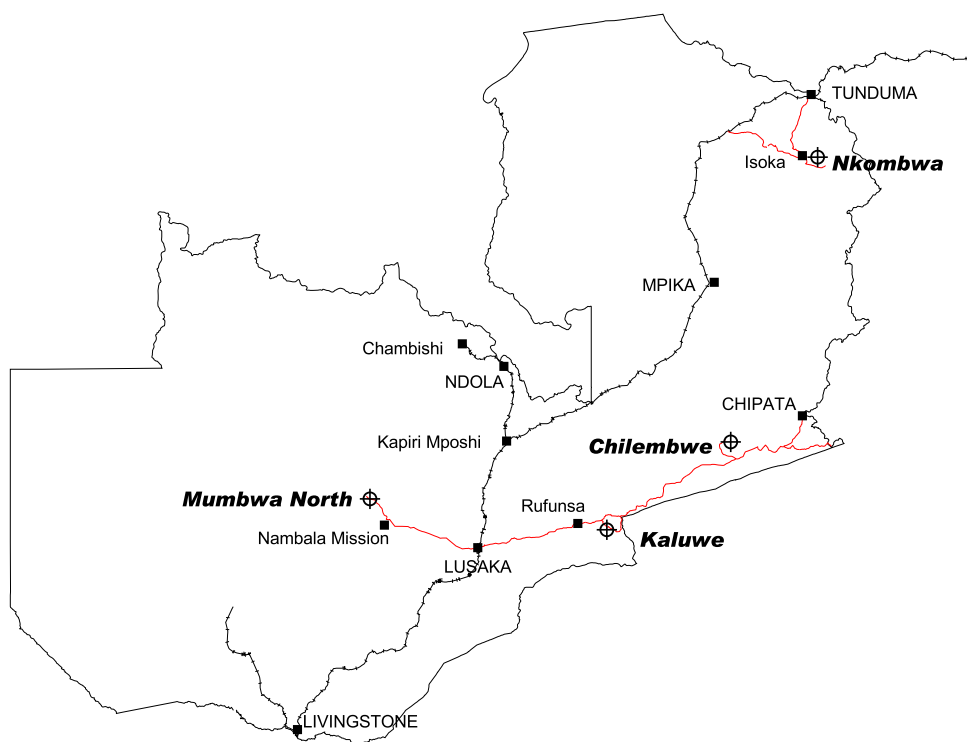
Butegwa, Mullins, et al. (1996a; 1996b) carried out a greenhouse agronomic evaluation of fertilizer products derived from Sukulu Hills unreactive phosphate rock. Raw PR (which contained 34% Fe₂O₃), beneficiated or concentrate PR, partially acidulated PR (PAPR) and PR compacted with triple superphosphate (TSP) were evaluated. Compacted materials had a P ratio of PR:TSP = 50:50. PAPR materials were made by 50% acidulation with H₂SO₄ and TSP was used as a reference fertilizer. Fertilizers were applied to an acidic (pH = 5.4) Hiwassee loam (clayey, kaolinitic, thermic Rhodic Kanhapludults) at rates of 0, 50, 100, 200, 300 and 400 mg P kg⁻¹ soil. Two successive corn crops were grown for 6 weeks. Compacted concentrate PR + TSP and raw PR + TSP were 94.4 and 89.7% as effective as TSP, respectively, in increasing dry-matter yields for the first corn crop. PAPR from the concentrate was 54.8% as effective as TSP. *Raw PR, concentrate PR and the PAPR from the raw PR were ineffective in increasing dry-matter yields. The same trends were obtained when P uptake was used to compare effectiveness.* Butegwa, Mullins, et al. (1996a) concluded that the ineffectiveness of the raw PR and its corresponding PAPR was attributed to a high Fe₂O₃ content in the raw PR. Butegwa, Mullins, et al. (1996b) also evaluated the impact of increasing P-fixation capacity on the effectiveness of phosphate fertilizers derived from Sukulu Hills phosphate rock. Amongst other conclusions, the authors noted that the PR concentrate alone was an ineffective P source.

Nakileza and Nsubuga (1999) described agronomic trials of Tororo RP and soda phosphate compared with DSP. Responses to RP were small compared with DSP, although the RP had been recommended (in 1949) for building up soil phosphate levels. Trials of RP, PAPR, RP compacted with SSP and TSP on maize and field beans were carried out by IFDC in collaboration with Makerere University (Ssali, pers. comm. in Nakileza and Nsubuga, 1999). No significant differences in responses were recorded for the different P sources. CIAT evaluated the more soluble Bubutu RP on field beans and found no response whereas use of SP increased yield (Wortmann pers. comm. in Nakileza and Nsubuga, 1999). Wortmann, McIntyre, et al. (2000) investigated the agronomic effectiveness, nutrient uptake, nitrogen fixation and water use of annual soil improving legumes with reference to their role in the management of soil fertility under the low-input management conditions of resource poor farmers. The study compared five annual legumes for fixation of atmospheric nitrogen, soil water uptake, soil P and nitrate recovery, and effects on subsequent crops and for phosphorus recovery from Busumbu P rock. *Canavalia* produced the most biomass, fixed the most N, was most efficient in extraction of soil nitrate, and supplied the most N to subsequent food crops. It was also most effective in improving soil productivity. *Mucuna* produced less biomass than *canavalia* but derived a greater proportion of plant N from the atmosphere whereas *Crotalaria* and *lablab* fixed little nitrogen. *Lablab* and soybean produced the least biomass. Wortmann, McIntyre, et al. (2000) observed that *all legumes and food crops failed to acquire significant amounts of P from Busumbu soft rock on this moderately acidic soil.* The ratios of C:P in the legume biomass were high enough to cause an early net immobilization of P.

Smithson et al. (2001) studied two contrasting phosphate rocks (PRs) for their agronomic performance: Minjingu PR (MPR, Tanzania) with about 13% total P and 3% neutral ammonium citrate (NAC) soluble P and Busumbu PR (BPR, Uganda) with about 14% total P and 0.3% NAC-soluble P in the weathered "soft rock" fraction of BPR, after removal of magnetic Fe oxides. MPR, BPR and BPR:TSP mixtures were compared with against TSP in test strips on 16 smallholder farms in 2 locations in eastern Uganda but there was no response to applied P in any form. Performance of BPR is poor, though Smithson (2001) concluded that its lower cost and location near to P-deficient areas make it attractive in some situations.

Additional sources: (Baobab-News, 2000; Bekunda et al., 1997; Butegwa et al., 1996a; Butegwa et al., 1996b; FAO, 2000b; FAO, 2000c; ICRAF, 1997; IDRC, 1996; IFA, 2000a; IFDC, 1988; Ker, 1995; Lowell and Well, 1995; Nakileza and Nsubuga, 1999; Smithson et al., 2001; Van Straaten, 1998; Van Straaten, 1999; Wortmann et al., 2000)

Zambia



Location, Quantity, Quality

Phosphate deposits in Zambia are associated with carbonatite at Nkombwa, located 25 km E of Isoka in northeast Zambia, and at Kaluwe, Nachomba, Mwambuto and Chasweta, located near Rufunsa (200 km east of Lusaka). Syenite related phosphate deposits occur at Chilembwe (40 km NE of Petauke and 400 km E of Lusaka) and at Mumbwa, located 180 km NW of Lusaka.

Although Nkombwa has the largest phosphate rock resources (200 Mt grading 4.5% P_2O_5), these deposits probably have very low economic potential as most of the phosphate occurs as isokite for which no effective beneficiation technology exists. Characterisation of some rocks and soils from Nkombwa in which most of the P_2O_5 was present as apatite, led the IFDC to conclude that although there would be major mineral processing problems, use of the apatite and the dolomite gangue as a liming product might make the exploitation of the apatite-bearing parts of the Nkombwa phosphate resources economically viable (IFDC, 1988).

The Kaluwe carbonatite sill is one of at least five carbonatite complexes in the Feira-Rufunsa region near the Mozambique border. It comprises phosphate rock grading 0.5 to 8.5% P_2O_5 . Residual phosphate resources of 6.6 Mt grading 5% P_2O_5 have been delineated but beneficiation will be difficult because the apatite grains are coated with iron oxide. In spite of the low grade, tests by various organizations, including the Zambia School of Mines, have shown that it is technically feasible to produce commercially usable apatite concentrates. Whereas total resources are quite substantial (Table 1), significant phosphate reserves in rock and residual soil are negligible and Kaluwe is considered uneconomic as a primary source of phosphate. Higher phosphate concentrations, ranging up to about 14% P_2O_5 , were found in the overlying soils during investigations by the Trans-Canada Agrogeology Project (Notholt, 1994a). Low NAC soluble P_2O_5 would probably render any apatite concentrates unsuitable for use as direct application fertilizer. Combined use of the apatite as a P_2O_5 source and the calcite as a liming product may be economically feasible (IFDC, 1988).

The Chilembwe phosphate-rock body comprises mainly apatite, quartz, feldspar, biotite, hornblende, magnetite-haematite-goethite and ilmenite. Total estimated resources are 1.6 Mt (12% P₂O₅). Individual deposits are relatively small. Some of the phosphate rock can be beneficiated to yield high-grade concentrates with 36-38% P₂O₅. The possibility of working the deposits on a relatively small scale of around 10,000 tpa of 30% P₂O₅ concentrate or about one-half of Zambia's present requirement, has been evaluated (Notholt, 1994). A feasibility study indicated that utilization of the Chilembwe phosphate rock for manufacture of SSP or fused magnesium phosphate fertilizers, although technically feasible, would be sub-economic. Low NAC solubility (1-1.7% P₂O₅) renders the Chilembwe PR unsuitable for direct application (IFDC, 1988). High Cl concentrations may preclude its use for the production of phosphoric acid.

Total estimated resources for the Mumbwa deposit are 0.6 Mt (5% P₂O₅).

Sources: (Bailey, 1960; Borsch, 1991; Borsch, 1993; Chileshe et al., 2000; Lombe, 1991; McClellan and Notholt, 1986; Muchena, 1991; Mulela, 1991; Notholt, 1994a; Notholt, 1999; Simukanga et al., 1994; Sliwa, 1991; Tether and Money, 1991; Turner et al., 1989; ZFTDC, 1991) (IFDC, 1988)

Agronomic testing and use

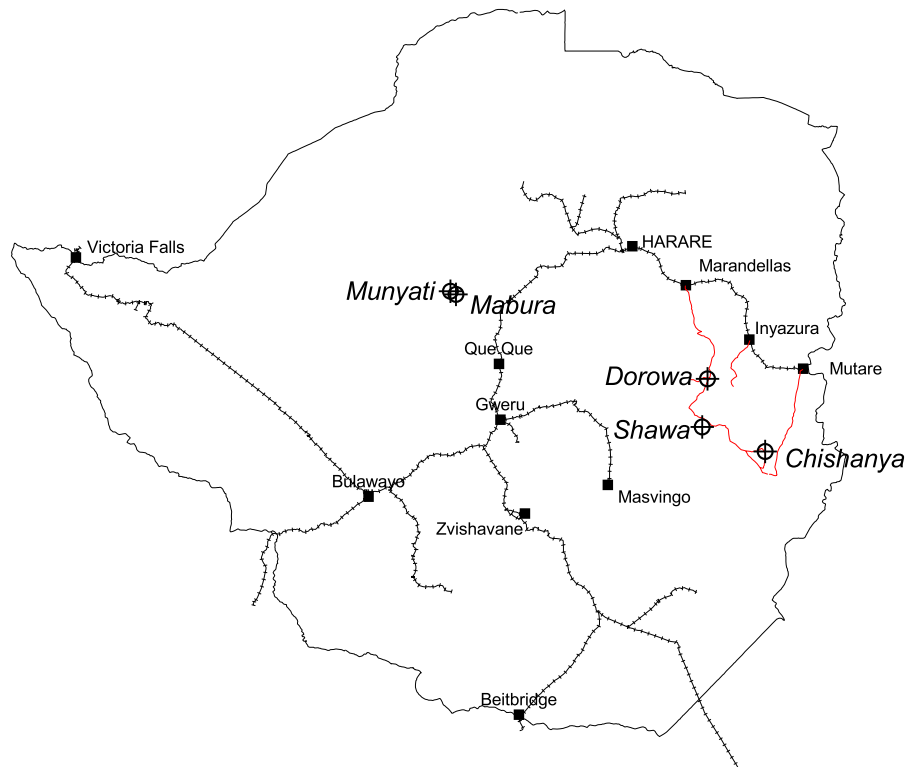
Bunyolo (1991) briefly described the crop response to phosphate fertilization in Zambia. He confirmed that the highly to moderately weathered soils of Zambia are P deficient and that all crops showed a positive response to fertilizer P. The trials results quoted in this paper date back to the 1960's and 1970's and did not involve the testing of rock phosphate.

Phiri, Goma et al. (1991) reported on an agronomic evaluation of direct application of ground phosphate rocks and PAPR in the high rainfall zone of Zambia. Goma, Phiri, et al. (1991) evaluated fused magnesium phosphate (FMP) in acid soils of high rainfall zone of Zambia. In general, FMP gave higher yields in all test crops compared with SSP. A significant positive residual effect from the FMP was observed in trials with maize. TSP plus lime gave superior yields to either FMP or TSP at the same or higher application rates. Groundnut responded positively to P from all sources. The authors conclude that on high P-fixation capacity soils, non-conventional fertilizers such as FMP can be more effective than soluble SSP and TSP. In addition, FMP contains other beneficial nutrients (Ca and Mg) and has a liming effect.

Phiri, Goma et al. (1991) reported an agronomic evaluation of direct application of ground phosphates and partially acidulated phosphate rock in the high rainfall zone of northern Zambia which rainfall is high (1200 mm) and soils are deficient in nutrients. Finely ground PR from Chilembwe and Mumbwa were tested on a number of soil types. Responses from PR were inferior to SSP and TSP for the whole range of annual short duration crops. However, Phiri, Goma et al. (1991) concluded that 50% PAPR can be as agronomically effective as SSP and TSP.

Additional sources: (Bekunda et al., 1997; Bunyolo, 1991; Chileshe et al., 2000; FAO, 2000b; FAO, 2000c; Frederick, 1991; Goma et al., 1991; Harsch, 1999; IDRC, 1996; IFA, 2000a; Ker, 1995; Nkonde et al., 1991a; Phiri and Damaseke, 1999; Phiri et al., 1991; Sanchez et al., 1997; Ssali, 1991)

Zimbabwe



Location, Quantity, Quality

Phosphate rock resources have been identified in the Dorowa, Shawa, and Chishanya carbonatites complexes. The Dorowa mine, located 64 km SW of Inyazura and about 200 km to the SE of Harare, provides a major part of Zimbabwe's domestic phosphate requirements.

Reserves at Dorowa are estimated to be 73 Mt with an average grade of 6.6% P_2O_5 . Characterisation studies of Dorowa concentrate with 33% P_2O_5 (IFDC, 1988) indicated a slightly enhanced $Fe_2O_3 + Al_2O_3 + MgO/P_2O_5$ ratio (0.13 compared with the normal limit of 0.11 for commercial ores). Low NAC soluble P_2O_5 (0.8%) would render the concentrate generally unsuitable for direct application.

Most of the apatite resources at Shawa, located 16 km SSW of Dorowa, are in residual soils; these amount to 20 Mt grading 11% P_2O_5 of which only 16 Mt containing 10.4% P_2O_5 and less than 1% CO_2 could be treated in the existing beneficiation plant at Dorowa.

Chishanya is the only other carbonatite in Zimbabwe with measured phosphate rock resources - these amount to only 1,600 ton/metre with an average grade of 8% P_2O_5 . Selective mining of 2-3 m wide arcuate dikes containing up to 15% P_2O_5 may be possible but not this is unlikely considering that the nearby Dorowa and Shawa deposits can be more readily exploited.

Deposits of bat guano occur within caves at various sites in Zimbabwe, including Munyati and Mabura. Resources are very limited but they have been used as direct application fertilizer. Many of the guano deposits are very low grade, containing less than 8% combined N and phosphoric acid.

Current production

Since 1966, the Dorowa mine produced almost enough high grade (35% P₂O₅) apatite concentrates from the low grade (5-7% P₂O₅) residual igneous phosphate rock to supply the phosphate fertilizer manufacturing requirements of Zimbabwe. The concentrate is transported 250 km by tanker and rail to a fertilizer plant in Harare, which manufactures superphosphate and other types of phosphate fertilizers (Atkinson and Hale, 1993). 95% of the 1993 production was used in Zimbabwe with the remainder exported to neighbouring countries. Zimbabwe is currently the only producer in eastern Africa (Table 2).

Production of phosphate concentrates is currently approximately half of the mine capacity of 155,000 Mt (USGS, 1997). In 1996-1997, Zimbabwe Phosphate Industries' 16,000 t/yr phosphoric acid plant was upgraded and its annual capacity increased to 40,000t (USGS, 1997).

Sources: (Atkinson and Hale, 1993; Barber, 1989; Barber, 1991; Bowen, 1986; Fernandes, 1989a; Fernandes, 1989b; Fernandes and Ncube, 1998; IFDC, 1988; McClellan and Notholt, 1986; Notholt, 1999; Ssali, 1990; USGS, 1997; Van Straaten, 1995; Van Straaten, 1998; Van Straaten and Fernandes, 1995)

Table 24 Production of phosphate rock in Zimbabwe

	1991	1992	1993	1994	1995	1996	1997	1998	1999
Production '000t	121	150	155	155	134	123	94	91	85

Sources: BGS World Mineral Statistics, 2001; FAO Fertilizer Yearbook, 1998

Agronomic testing and use

Van Straaten, Fernandes, et al. (1994) reported on the development of local phosphate fertilizers in Zimbabwe. Instead of shipping phosphate concentrates from the mine at Dorowa to the capital Harare for further chemical processing, the aim was to produce an inexpensive modified phosphate fertilizer at, or close to, the phosphate mine. Various simple pelletizing and compacting techniques were being tested, and the first pellets, prepared with a simple rotating disc pelletizer, have been produced. The basic materials used for the adapted phosphate fertilizers are the run-of-mill concentrate (DPR) and the (so far wasted) flue dust from the Dorowa Mine, as well as various amounts of triple superphosphate (TSP) manufactured by Zimphos in Harare, and a selection of binders from various food wastes. These materials have been compacted and pelletized using low-cost techniques, and a variety of blends have been found to be suitable for use. A rotary disk device turns out fertilizer pellets. Van Straaten from the University of Guelph was quoted as saying that "Farmers can now process the fertilizer themselves in nearby villages" (IDRC, 1996). Van Straaten considers that this new product could be used in many other countries such as Burundi, Ethiopia, Malawi, Mozambique, Tanzania, Uganda, and Zambia, all of which contain phosphate deposits. Van Straaten and Fernandes reported in 1999 that these blends were being tested on maize grown on three different soils in pot trials, in the field, and in on-farm trials (Van Straaten, 1999).

Van Straaten, Fernandes, et al. (1995) reported the successful agronomic testing of low-cost fertilizers in Zimbabwe. Definitive results of phosphate dissolution studies confirmed the hypothesis that hydrolysis-induced acidulation takes place in the apatite-TSP-water system. The agronomic responses to applications of a range of blends in greenhouse trials, and on fields in different natural regions of Zimbabwe, were reported to be encouraging. The data indicate that compacted blends are agronomically more effective than pelletized blends, and that *unmodified rock phosphates are relatively ineffective in the short term*. The effect of P-fertilizer materials on corn dry-matter yield, and the relative agronomic effectiveness (RAE) of the materials, shows that phosphate blends with 50% rock phosphate and 50% locally produced triple superphosphate are only slightly less effective than triple superphosphate. The RAE's for compacted phosphate blends (ratio 50/50) and pelletized blends (ratio 50/50) were 88.3% and

85.6% as compared to TSP (100%). The RAE's of the compacted and pelletized blends at a ratio 30% TSP and 70% rock phosphate were 82.4% and 80.9%, respectively. Van Straaten, Fernandes, et al. (1995) asserted that *these findings indicate that some of these low-cost fertilizers are agronomically very effective at a much lower economic cost*. A series of incubator and greenhouse studies in Canada on phospho-composting showed that an increase in P uptake by plants can be achieved by mixing phosphate blends into the cattle manure prior to composting. This should help to improve indigenous farming practices using cattle manure. Van Straaten and Fernandes (1995) reviewed the development of agrogeology in eastern and southern Africa with particular reference to developments in phosphate utilisation in Zimbabwe.

Recent research in Zimbabwe focussed on the characterization and potential utilization of phosphate tailings dump materials, mainly vermiculite and smectite, as well as phosphate fines from the Dorowa phosphate mine in eastern Zimbabwe (Van Straaten, 1999). The research on apatite dissolution in agglomerated phosphate blends continued with laboratory scanning electron microscopy studies. The results provided evidence of a reaction between Dorowa apatite and TSP supporting the hypothesis of induced in-situ acidulation of phosphates. The project is currently developing adapted low-tech pelletizers to produce low-cost phosphate fertilizers with 'waste materials' from the Dorowa phosphate mining operation and locally produced TSP. An IDRC-funded phosphate project in Zimbabwe is currently developing a local low-cost pelletizer to produce phosphate blends near the phosphate mine of Dorowa. P-rich vermiculite based tailings from this mine are being investigated for their potential use as additives to local cattle manures. To understand the fundamental phosphate chemistry and mineralogy of blends detailed studies are being conducted using SEM, XRD, microprobe analyses (Van Straaten, 1999).

Additional sources: (DANIDA, 2000; FAO, 2000b; FAO, 2000c; Fernandes, 1996a; Fernandes, 1996b; IDRC, 1996; IDRC, 1997; Ker, 1995; Lowell and Well, 1995; Piha, 1993; Van Straaten, 1998; Van Straaten, 1999; Van Straaten and Fernandes, 1995; Van Straaten et al., 1994; Van Straaten et al., 1995)

Other countries

No records were encountered of phosphate rock resources or of the agronomic testing of phosphate rock as a direct application fertilizer in Botswana, Equatorial Guinea, Gabon, the Gambia, Lesotho, Sierra Leone or Swaziland.

SUMMARY

A summary of the quantity, quality (%P₂O₅), past/current production, agronomic testing, use and development potential of the phosphate resources of sub-Saharan Africa, together with their type and geological age, is provided in the following Table.

Country	Deposit	Type	Geological Age	Quantity of resources (Mt)	Average or range P ₂ O ₅ (%)	Current (past) production ('000 tonnes/y)	Current use	Suitability for direct application	Agronomic testing or use of local PR	Development potential
Angola	Cabinda	Sed	U. Cretaceous-Eocene	16 (3.3 proven)	12-34					low - variation in thickness and lack of transport
Angola	Coluge & Lendiacolo	Sed	U. Cretaceous-Eocene		26-32					Low
Angola	Longonjo	Ign	?							Low
Angola	Quindonacaxa	Sed	U. Cretaceous-Eocene	200	18-27	Experimental production in 1981 (18)			used for DA in 1980's	low - variation in thickness and lack of transport
Angola	Subida	Sed	U. Cretaceous-Eocene		5					Low
Benin	Kpome	Sed	Eocene		2-9					low
Benin	Lokossa	Sed	Eocene		?					low
Benin	Mekrou	Sed	Late Precambrian	5 (3.3 Mt reserves)	20-26			low		potentially most important- could be developed if hydro-electric dam project approved
Benin	Pobe	Sed	Eocene		27-30					
Benin	Tofio	Sed	Eocene		23					low
Burkina Faso	Aloub Djouana	Sed	Upper Proterozoic					low		
Burkina Faso	Arly	Sed	Upper Proterozoic	4	26-32			low		
Burkina Faso	Diapaga	Sed	Upper Proterozoic	224	15-32					
Burkina Faso	Kodjari	Sed	Upper Proterozoic	80 to 300	15-32	0.5 - 1	used for DA and agronomic trials	low	maize, rice, sugar cane, sorghum, cowpea	use for mucuna cover crop in rotation with cereal crops

<i>Country</i>	<i>Deposit</i>	<i>Type</i>	<i>Geological Age</i>	<i>Quantity of resources (Mt)</i>	<i>Average or range P2O5 (%)</i>	<i>Current (past) production ('000 tonnes/y)</i>	<i>Current use</i>	<i>Suitability for direct application</i>	<i>Agronomic testing or use of local PR</i>	<i>Development potential</i>
Burundi	Matongo-Bandaga	Ign	Cretaceous	25	11		composited PR used for potatoes	low		exploitation difficult as deposit heterogeneous; reactivity of PR low; calcination would enhance reactivity
Cameroon	Bonge River Valley	Sed	L. Eocene		12-18					low
Central Africa Republic	Bakouma	Sed	Eocene							low due to high uranium
Democratic Republic of the Congo	Bingu	Ign	Cretaceous					low		low
Democratic Republic of the Congo	Homas Caves	Guano	Recent							low
Democratic Republic of the Congo	Lueshe Valley	Ign	Cretaceous	30	4-10			low		apatite a potential by-product if pyrochlore extracted from carbonatite
Ethiopia	Bikilal	Ign	?	200			barley, rape, pasture	low		high Fe and Al would prevent production of inorganic fertilizers
Ethiopia	Gorrahei	Sed	Eocene							low
Gabon	Coastal area	Sed	U. Cretaceous		8-32					
Gabon	Mabounie	Ign	Late Proterozoic	140				low		commercial exploitation to produce apatite for export being evaluated
Gabon	Offshore	Sed	Recent							
Gambia		Sed	U. Cretaceous-Eocene							
Ghana	Daboya	Sed	U. Cretaceous-Eocene							
Ghana	Keta Basin	Sed	U. Cretaceous-Eocene		25					low due to low grade
Ghana	Kitampo	Sed	U. Cretaceous-Eocene							
Ghana	Kumpase	Sed	U. Cretaceous-Eocene							
Ghana	Northern area	Sed	U. Cretaceous-Eocene							

<i>Country</i>	<i>Deposit</i>	<i>Type</i>	<i>Geological Age</i>	<i>Quantity of resources (Mt)</i>	<i>Average or range P2O5 (%)</i>	<i>Current (past) production ('000 tonnes/y)</i>	<i>Current use direct application</i>	<i>Suitability for Agronomic testing or use of local PR</i>	<i>Development potential</i>
Ghana	Sekondi	Sed	U. Devonian-Late Cretaceous	15					low due to low grade
Ghana	Sherigu	Sed	U. Cretaceous-Eocene						
Ghana	Wale-Wale	Sed	U. Cretaceous-Eocene						
Guinea Bissau	Farim	Sed	U. Cretaceous-Eocene	166	30				Evaluated in 1998 and consumers and investors being sought for mine producing 1.5Mt/y concentrate; thick overburden may make exploitation uneconomic
Kenya	Ikutha	Ign	?				low		
Kenya	Lodosoil	Ign	Cretaceous				low		
Kenya	Longalonga	Meta	?				low		
Kenya	Mount Elgon	Ign	Cretaceous		1-4		low		
Kenya	Mrima Hill	Ign	Precambrian		3-4 (max 25)		low		
Kenya	Rangwa	Ign	Cretaceous		0.5-5.8		low		low due to low grade
Kenya	Songhor	Ign	Cretaceous				low		
Kenya	Thura River	Ign	?				low		
Liberia	Bomi Hills	Sed	Precambrian	1	32				low due to high Fe and Al, and complex mineralogy
Madagascar	Antonibe Peninsula	Sed	Paleocene						low
Madagascar	Lake Alaotra	Sed	Cretaceous						low
Madagascar	Majunga Basin	Sed	Cretaceous						low
Madagascar	Marvoay	Sed	Cretaceous						low
Madagascar	Soalala	Sed	Cretaceous						low
Malawi	Chilwa Island	Ign	Cretaceous				low		low
Malawi	Kangankunde	Ign	Cretaceous				low		low
Malawi	Mlindi	Ign	Precambrian				low		low
Malawi	Tundulu	Ign	Cretaceous	0.8	>20		agronomic tests	tea, maize	potential source of DA fertilizer for tea
Mali	Anderakoyen	Sed	L-M Eocene		23-30				difficult to produce inorganic fertilizers due to high Fe and Al
Mali	Assa Karei Valley	Sed	L-M Eocene		23-30				
Mali	Chanamague	Sed	L-M Eocene		23-30				difficult to produce inorganic

Country	Deposit	Type	Geological Age	Quantity of resources (Mt)	Average or range P2O5 (%)	Current (past) production ('000 tonnes/y)	Current use	Suitability for direct application	Agronomic testing or use of local PR	Development potential
Mali	In Tassit	Sed	L-M Eocene		23-30					fertilizers due to high Fe and Al
Mali	Tamaguelet	Sed	L-M Eocene	20 to 25	15-32	(<10)	medium	cotton		difficult to produce inorganic fertilizers due to high Fe and Al
Mali	Wadi-Ganchiran	Sed	L-M Eocene		23-30					problems with thick overburden and hard caprock, and high transport costs; but mining licence issued in 2000
Mauritania	Bofal	Sed	L Eocene	106	19-20		Low-Med			thick overburden and hard caprock, and high transport costs
Mauritania	Loubboira	Sed	L Eocene	29	19-20		Low-Med			direct application may be feasible
Mauritania	Sive	Sed	L Eocene	1	23-30	small	used by local farmers for DA			
Mauritania	Ornolde	Sed	L Eocene	4	25-30					low
Mauritania	Zemmour el Akhdhar	Sed	L Eocene							low
Mozambique	Evate	Ign	? Proterozoic	156	9		low			
Mozambique	Muande, Tete	Ign	Proterozoic	4150	5		low			apatite by-product if deposit mined for iron ore
Mozambique	Magude	Sed	U Cretaceous		0.3-3.1					low
Mozambique	Vilanculos	Guano	Recent	<1	9-10					low
Mozambique	Buzi	Guano	Recent							low
Namibia	Cape Cross	Guano	Recent		9-25	(<1 - 4)				low
Namibia	Continental shelf	Sed	Recent		4					low
Namibia	Islands	Guano	Recent							low
Namibia	Kalkfeld	Ign	Cretaceous				low			low - too small, low grade and remote
Namibia	Ondurakorume	Ign	Cretaceous				low			low - too small, low grade and remote
Namibia	Osongombo	Ign	Cretaceous				low			low - too small, low grade and remote
Namibia	Epembe	Ign	Cretaceous		3.5		low			low - too small, low grade and remote
Niger	Akkar	Sed	Eocene-Eocene			(small quantities for DA)				
Niger	Gaoy	Sed	Eocene-Eocene							
Niger	Tahoua	Sed	Eocene-Eocene	100	18-35	(1)	agronomic trials	low	millet, sorghum, peanut	potential use as DA fertilizer

<i>Country</i>	<i>Deposit</i>	<i>Type</i>	<i>Geological Age</i>	<i>Quantity of resources (Mt)</i>	<i>Average or range P2O5 (%)</i>	<i>Current (past) production ('000 tonnes/y)</i>	<i>Current use</i>	<i>Suitability for direct application</i>	<i>Agronomic testing or use of local PR</i>	<i>Development potential</i>
Niger	Tapoa	Sed	Precambrian	1250 (200 reserves)	27			low-medium		largest PR resources in West Africa; potential use as DA fertilizer
Nigeria	Ifo Junction & Oshoun	Sed	L Eocene	1	22-32					low - small PR deposit with high Fe and Al
Nigeria	Imo State	Sed	Eocene		32					occurrence
Nigeria	S. Enugu	Sed	Eocene							some potential for use as DA fertilizer especially in Mucuna - maize rotations
Nigeria	Sokoto State	Sed	L Eocene	5	34		agronomic trials	maize, sorghum		occurrence
Republic of the Congo	Comba	Sed	Pre-Cambrian		28-35					low grade siliceous PR
Republic of the Congo	Seviède-Holle	Sed	U. Cretaceous-Eocene	15	21-35					low grade
Republic of the Congo	Sintou-Kola	Sed	U. Cretaceous-Eocene	0.3	21					low grade
Senegal	Lam Lam	Sed	Eocene	4	33			medium		
Senegal	Matam (Ouali Diala)	Sed	Eocene	40	29			medium		
Senegal	Pallo	Sed	Recent	90 to 100	28	64	Fertilizer production	med-high		Major phosphate mine in production
Senegal	Taiba	Sed	Eocene	100	18-39	1,800	Fertilizer production	medium	millet, cowpea, peanut	Major phosphate mine in production; effective as DA fertilizer if used in combination with manure; Government encouraging use of PR for soil regeneration in peanut production areas
Senegal	Pire Goureye	Sed	Eocene							
Senegal	Mekhe	Sed	Eocene							
Senegal	Casamance	Sed	Eocene							
Senegal	Namel	Sed	Eocene							
Somalia	Bur Acaba	Sed	Precambrian		24					low
Somalia	Mait Island	Guano	Recent		10-28					low
South Africa	1: Varswater (Langebaan Road)	Sed	Neogene	37.5	10	(25)				
South Africa	2: Sandheuwel	Sed	Neogene	23.6	6					
South Africa	3: Paternoster	Sed	Neogene	10	5					
South Africa	4: Duyker Eiland	Sed	Neogene	3.6	9.5					

Country	Deposit	Type	Geological Age	Quantity of resources (Mt)	Average or range P2O5 (%)	Current (past) production ('000 tonnes/y)	Current use	Suitability for direct application	Agronomic testing or use of local PR	Development potential
South Africa	5: Constable Hill	Sed	Neogene	0.3	27.5	(10)				
South Africa	6: Elandsfontyn	Sed	?							
South Africa	7: Hoedjiespunt	Sed	?		15-16	Past producer		low		
South Africa	Bandolier Kop	Ign	Permian	0.1	10-26			low		
South Africa	Glover	Ign	Permian	3	33	Past producer		low		
South Africa	Kenhardt	Ign	Permian					low		
South Africa	Kruidfontein	Ign	Permian					low		
South Africa	Lamberts Bay	Sed	Permian							Occurrence
South Africa	Mamre	Sed	Permian	0.05	21-27					Occurrence
South Africa	Maijesfontein	Sed	Permian							
South Africa	Middleberg	Sed	Permian							
South Africa	Namaqualand	Sed	Permian							
South Africa	Palabora	Ign	Precambrian	13,000 - 30,000	6.8	2,950	Fertilizer production	low		Major phosphate mine in production
South Africa	Potgietersrus	Sed	Permian							
South Africa	Saldanha Bay (1-7)	Sed	Neogene	37.5	10	25			used as DA fertilizer	Mine in production - PR for inorganic fertilizer manufacture and some used for DA
South Africa	Schiel	Ign	Permian	36	5			low		
South Africa	Spitzkop	Ign	Permian					low		
South Africa	Weenen	Sed	Permian							
South Africa	Zoetendaesviel	Guano	Recent	0.04	24					
Sudan	Halaib	Sed	Cretaceous - Eocene							
Sudan	Uro-Kurun	Sed	?	<1						
Tanzania	Amboni Caves	Guano	Recent							
Tanzania	Chali Hills	Sed	Recent		up to 20					
Tanzania	Latham Island	Guano	Recent	<1						
Tanzania	Minjingu	Sed	Recent	10	20	2	Agronomic trials	medium	wheat, canola, maize, soybean; agroforestry, mucuna	Plant using PR for inorganic fertilizer production closed; good potential for using PR for DA
Tanzania	Ngualla	Ign	Cretaceous		<1-7.4			low		
Tanzania	Panda Hill	Ign	Cretaceous	125	6 (max) in hard-rock; 17-25 in residual ore			low	wheat, canola, maize, soybean	low
Tanzania	Sangu-Ikola	Ign	Cretaceous					low		low
Tanzania	Songwe Scarp	Ign	Cretaceous		3-10% in carbonatite;			low		low

Country	Deposit	Type	Geological Age	Quantity of resources (Mt)	Average or range P2O5 (%)	Current (past) production ('000 tonnes/y)	Current use	Suitability for direct application	Agronomic testing or use of local PR	Development potential
					>17% in weathered material					
Tanzania	Zizi	Ign	Cretaceous	2	9 (4.5-10.5)			low		low
Tanzania	Songwe	Ign	Cretaceous					low		
Togo	Bassar	Sed	L Eocene							occurrence
Togo	Hahotoe-Akoumape-Kpogame	Sed	L Eocene	100	28-32	1,710	Fertilizer production	medium	maize, cowpea, cereal/legume rotations	Major phosphate mine in production; high Cd content
Uganda	Budeda	Ign	Cretaceous		<1-2			low		low
Uganda	Bukusu-Busumbu	Ign	Cretaceous	50-150	8-10 (25-35 in residual soil)	(3)	Agronomic trials	low		
Uganda	Butiriku	Ign	Cretaceous		up to 30			low		low
Uganda	Sukulu	Ign	Cretaceous	230	11-13	(19)	Agronomic trials	low	maize	recent evaluation for 50,000 tpa P2O5 SSP and amm. SP production; planned production 100,000t/y P fertilizers and export 1Mt apatite; project deferred.
Zambia	Chilembwe	Ign	Cretaceous	1.6	12			low	maize	Use for SSP or fused magnesium phosphate fertilizer sub-economic; PR ineffective for DA
Zambia	Kaluwe	Ign	Cretaceous	7 to 200	5			low		low
Zambia	Mumbwa North	Ign	Cretaceous	0.6	5			low		low
Zambia	Nkombwa	Ign	Cretaceous	200	4.5			low		Beneficiation impossible
Zimbabwe	Chishanya	Ign	Cretaceous		8-25			low		low
Zimbabwe	Dorowa	Ign	Cretaceous	73	6.6	85	Fertilizer production	low	various	Major phosphate mine in production; compacted PR-TSP may be agronomically effective fertilizer
Zimbabwe	Shawa	Ign	Cretaceous	20	10.8			low		low
Zimbabwe	Mabura	Guano	Recent					low		low
Zimbabwe	Munyati River	Guano	Recent					low		low

Explanation: Ign = igneous, Sed = sedimentary, DA = direct application, PR = phosphate rock; MT = million tonnes

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