

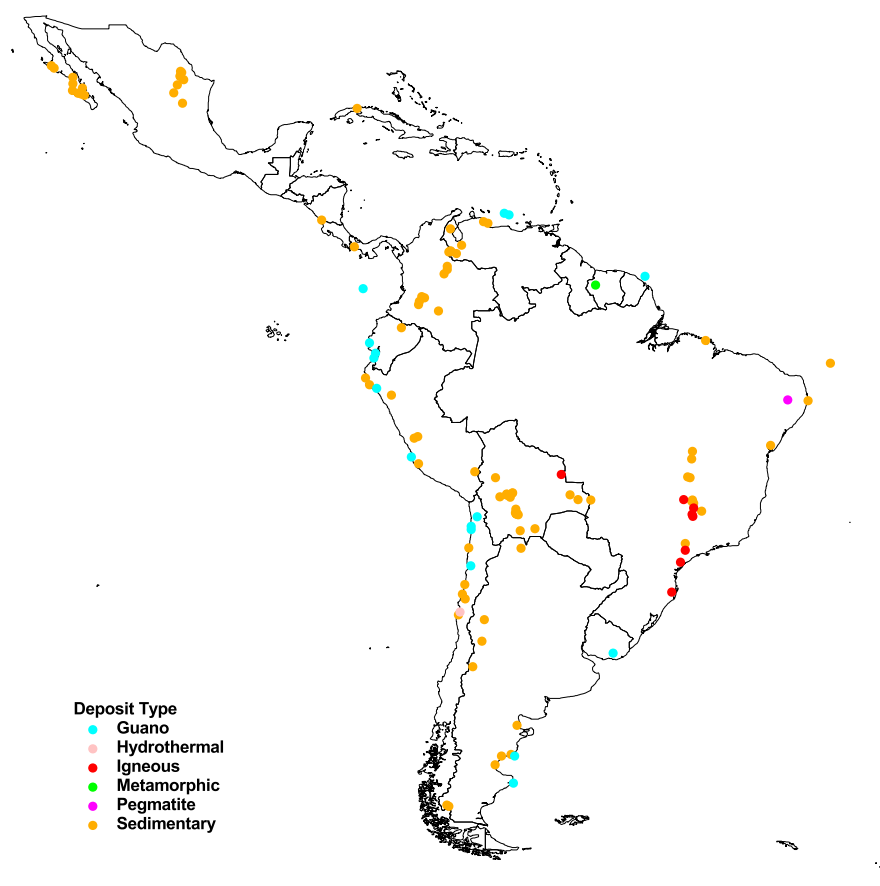


**British  
Geological Survey**  
NATURAL ENVIRONMENT RESEARCH COUNCIL

**DFID** Department for  
International  
Development

# Local phosphate resources for sustainable development in Central and South America

Economic Minerals and Geochemical Baseline Programme  
Report CR/02/122/N





BRITISH GEOLOGICAL SURVEY

REPORT CR/02/122

# Local phosphate resources for sustainable development in Central and South America

J D Appleton and A J G Notholt

## *Key words*

phosphate, resources, Central and South America, agronomic, fertilizer, direct application.

## *Front cover*

Distribution of phosphate mineral resources in Central and South America

## *Bibliographical reference*

APPLETON, J D and NOTHOLT, A J G 2002. Local phosphate resources for sustainable development in Central and South America. *British Geological Survey Report*, CR/02/122/N. 96pp.

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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 and Steven Van Kauwenberg (International Fertilizer Development Centre, Muscle Shoals, Alabama, USA), 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). In some cases it was more appropriate to include text written by Arthur. It is for this reason, and with the full approval of Agnes, that Arthur is named as joint author of this report.

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 Central and South America where phosphorus (P) deficiency is recognised as a major constraint 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 many 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 Central and South America 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.

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 Central and South America. This report presents the second of a series of three regional reviews (covering sub-Saharan Africa, Asia, and Central and South America) that seek to provide advisers with a concise summary of national and regional information on locally available phosphate resources. The report deals with Central and South America with special emphasis on Bolivia, Brazil, Colombia, Peru and Venezuela.

The first section of the report contains a review of the phosphate mineral resources of Central and South America including information on phosphate rock and phosphate fertilizer production, consumption, and export.

The second section of the report comprises sixteen 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 Central and South America, together with their geological type and age is provided in the final section of the report.

The first volume of the series, covering Sub-Saharan Africa, contains generic reviews of:

- 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.

*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. This can only be achieved by the appropriate advisers and local authorities. 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 areas of Central and South America where phosphorus (P) deficiency is recognised as a major constraint 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 many 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 Central and South America 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 Central and South America. This report presents the second of a series of three regional reviews (covering sub-Saharan Africa, Central and South America, and Asia) that seek to provide advisers with a concise summary of national and regional information on locally available phosphate resources. The report deals with Central and South America with special emphasis on Bolivia, Brazil, Colombia, Peru and Venezuela.

This report is an output for the DFID funded research project R7370 *Local Phosphate Resources for Sustainable Development* and is a contribution towards DFID IUD'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 relevant mineral resources and agricultural organisations (e.g. FAO, IFDC, ICRAF, UNIP, UNIDO, IFA, Potash & Phosphate Institute). An *Endnote* database was compiled of bibliographic references and abstracts together with information from web sites and this now includes over 2400 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 a review of the phosphate mineral resources of Central and South America including information on phosphate rock and phosphate fertilizer production, consumption, and export.

The second section of the report comprises sixteen 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.
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*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. This can only be achieved by the appropriate advisers and local authorities. 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.

## RESOURCES & PRODUCTION

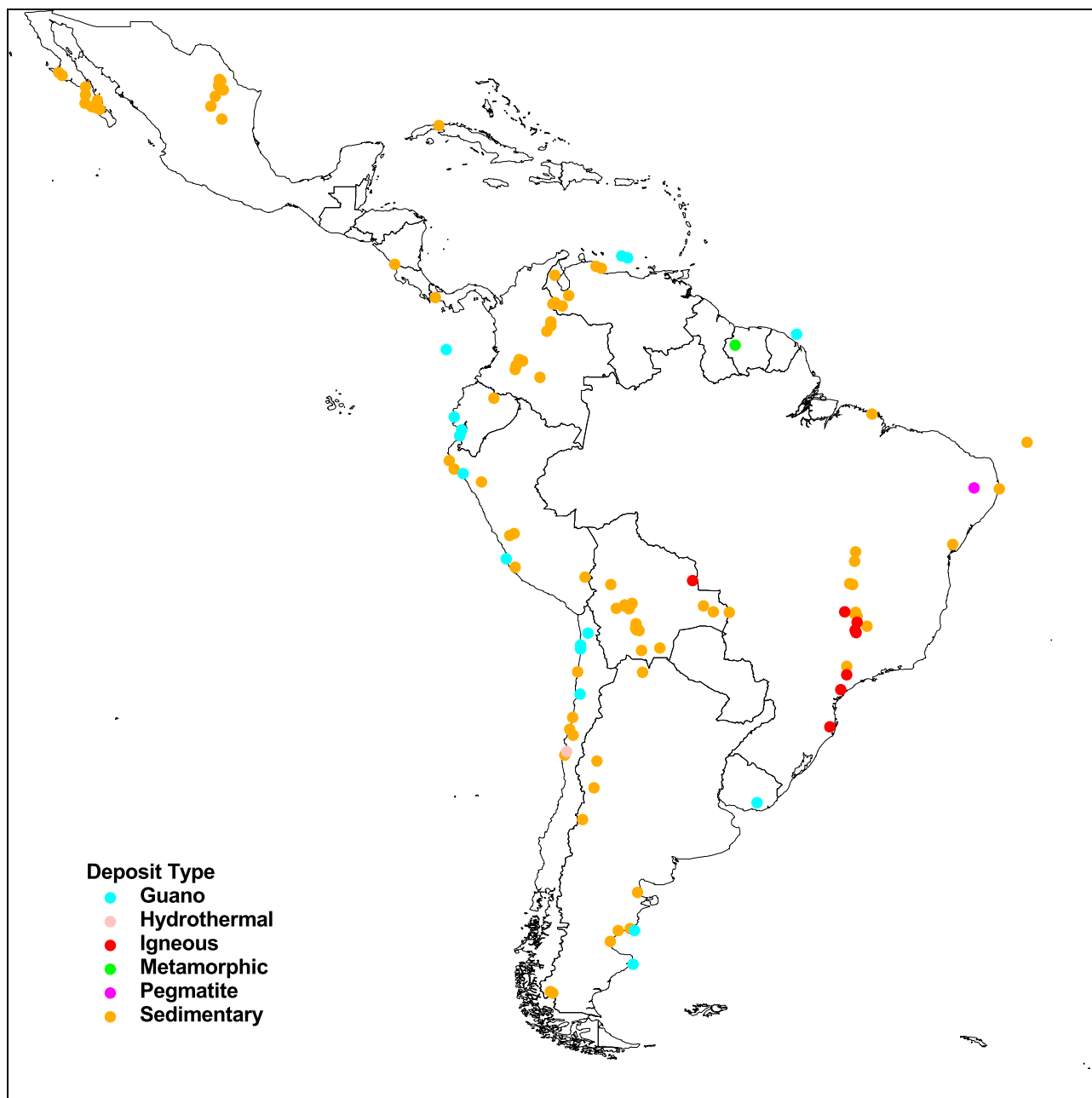
Phosphate rocks in Central and South America are of two major types. Sedimentary deposits of phosphate rock, formed in coastal marine or lacustrine environments as the result of biogenic activity, are predominant in Mexico, Venezuela, Colombia, Peru, Bolivia, and to a lesser extent in Brazil. Phosphate deposits associated with alkaline and carbonatite igneous complexes, most of Cretaceous age, occur predominantly in Brazil. Some of the igneous deposits are hard rock, for example the Jacupiranga deposit, 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. Araxa, Catalao, and Tapira). Historically important bird guano deposits occur at a number of localities along the west coast of South America, particularly in Peru and Chile.

Much of South America has existed as a stable craton since Precambrian times and is composed predominantly of Precambrian igneous and metamorphic rocks. Phosphorites of this age are known only from Brazil. Phosphate rock of Ordovician, Silurian and Triassic age occurs locally in South America, but the three main phosphogenic episodes are associated with marine sediments of Jurassic, Upper Cretaceous, and Neogene (Tertiary) age. In other sectors of Central and South America, the palaeogeographic conditions are not particularly favourable for the development of major sedimentary phosphate rock deposits.

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 perennial crops grown on very acid soils in areas with high rainfall.

Detailed information on the geology, resources and characteristics of the phosphate deposits of Central and South America is available in a number of key sources (Burnett and Riggs, 1990; Cook and Shergold, 1986; Escalera and Ricaldi, 1985; Notholt, 1994a; Notholt, 1999; Notholt and Hartley, 1983; Notholt et al., 1989; Ricaldi and Escalera, 1984a; Ricaldi and Escalera, 1985; Savage, 1987) (Sheldon et al., 1990; Sheldon and Davidson, 1987) as well as in hundreds of scientific papers, and reports produced by Geological Surveys and mining companies. The quantity of resources varies from less than 250,000 tonnes to greater than 1,500 million tonnes and the average  $P_2O_5$  concentration ranges from 5% to 38%. Resource estimates are available for 45 phosphate rock deposits in Central and South America (Table 1). Only a very brief summary of the quantity, quality and location of the main phosphate rock deposits in Central and South America 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 quality 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. 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.

Phosphate rock deposits in Central and South America are irregularly distributed and many are too small, remotely situated in mountainous terrain, or lack adequate infrastructure, to be of economic importance at present. The major phosphate rock producers are Brazil, Mexico, Venezuela and Colombia (Table 2). Brazil, Mexico, Venezuela, and Colombia produce significant quantities of manufactured chemical fertilizers - most of which are used domestically (Table 4 and 5). Small amounts of phosphate rock are also produced in Peru. It is estimated that less than 1% of the phosphate rock produced in Central and South America is used as direct application fertilizer. In Brazil, nearly all the phosphate rock used for direct application is imported from north Africa and the Middle East.



*Location of phosphate deposits in Central and South America*

Table 1 Approximate phosphate rock resources (Million tonnes; Mt) and grades in Central and South American countries (Data from a range of sources including Notholt (1994a), Notholt (1999) and León (1991)).

Country	Deposit	Type	Age	Resources Mt	Average P <sub>2</sub> O <sub>5</sub> (%)
Bolivia	Camino Nuevo (km 47)	Sedimentary	Ordovician	0.2	26
Bolivia	Capinota	Sedimentary	Ordovician	2.8	25
Bolivia	Sepulturas	Sedimentary	Recent	0.3	9
Brazil	Anitapolis	Igneous	Cretaceous	300	5
Brazil	Araxa	Igneous	Cretaceous	500	14
Brazil	Catalao I	Igneous	Cretaceous	400	5
Brazil	Ipanema	Igneous	Cretaceous	120	7
Brazil	Jacupiranga	Igneous	Cretaceous	200	5
Brazil	Patrocinio	Igneous	Cretaceous	200	10
Brazil	Registro	Igneous	Cretaceous	18	16
Brazil	Tapira	Igneous	Cretaceous	750	9
Brazil	Sume	Pegmatite	?	0.25	38
Brazil	Cerro do Abaete	Sedimentary	Pre-Cambrian	1	12
Brazil	Lagamar	Sedimentary	Pre-Cambrian	5	27
Brazil	Rocinha 1	Sedimentary	Pre-Cambrian	227	7
Brazil	Rocinha 2	Sedimentary	Pre-Cambrian	3.6	12
Brazil	Rata	Sedimentary	Recent	0.7	18
Brazil	Paulista	Sedimentary	U. Cretaceous	50	21
Chile	Guanillos, Pabellon de Pica, Punta de Lobos, Tarapaca	Guano	Recent	1.5	15
Chile	La Serena	Hydrothermal	?	2.5	27
Chile	Bahia Inglesa - Caldera	Sedimentary	Tertiary	15	18
Chile	Mejillones	Sedimentary	Tertiary	54	6
Chile	Tongoy	Sedimentary	Tertiary	15	16
Colombia	Malpelo Is	Guano	Recent	0.45	27
Colombia	Boyaca (Pesca)	Sedimentary	Cretaceous	500	22
Colombia	Huila I (Media Luna)	Sedimentary	Cretaceous	17	27
Colombia	Sardinata (N. Santander)	Sedimentary	Cretaceous	15	22
Ecuador	Napo	Sedimentary	Cretaceous	185	25
Mexico	Mercedes y Hermania	Sedimentary	Jurassic	0.16	25
Mexico	Sierra de la Carbonera (Saltillo)	Sedimentary	Jurassic	154	16
Mexico	Sierra de Santa Rosa	Sedimentary	Jurassic	13	16
Mexico	San Juan de la Costa	Sedimentary	Late Oligocene	24	18
Mexico	El Capote y La Casualidad	Sedimentary	Middle Cretaceous	0.11	20
Mexico	San Hilario	Sedimentary	Palaeogene- Neogene	841	12
Mexico	Santo Domingo	Sedimentary	Recent	1077	5
Peru	Chincha Islands, Lobos de Tierra & others	Guano	Recent	2	12
Peru	Sechura	Sedimentary	Middle Miocene	1500	30
Venezuela	Isla La Orchila	Guano	Recent	0.025	20
Venezuela	Lobatera	Sedimentary	Cretaceous	1	23
Venezuela	Los Monos (Navay)	Sedimentary	Cretaceous	80	16
Venezuela	Merida State	Sedimentary	Cretaceous	70	18
Venezuela	Monte Fresco	Sedimentary	Cretaceous	300	26
Venezuela	Zulia State	Sedimentary	Cretaceous	18	11
Venezuela	Cerro Riecito	Sedimentary	Miocene	20	30
Venezuela	Lizardo	Sedimentary	Miocene	20	25

*Table 2 Production of phosphate rock ('000 tonnes) in Central and South America*

Country	1989	1991	1995	1997	1999
Brazil (d)	3,655	3,209	3,896	4,276	4,301
Chile	nd	nd	12	13	...
Colombia	31	30	*50	45	*50
Mexico	656	596	622	714	927
Peru	15	*30	88	52	# 9
Venezuela	195	250	86	291	366

\* = estimate; nd = no data; (d) = including beneficiated and directly shipped material

Source: World Mineral Statistics 1995-99, BGS 2001; # USGS, 1999; IFA

*Table 3 Imports and exports of phosphate rock ('000 tonnes) in Central and South America*

Country	1995	1996	1997	1998	1999
Brazil	532	654	676	781	619
Chile	54	34	20	13	...
Colombia	88	50	80	88	...
Cuba	*50	*50	*50	*50	...
Mexico	1,378	1,757	1,730	2,139	1,862
Peru	...	(15)	(69)	(23)	(15)
Uruguay	11	31	18	57	40
Venezuela	67	44	72	73	163

\* = estimate

Source: World Mineral Statistics 1995-99, BGS 2001

Fertilizer production statistics for selected countries are compared with total production for the whole of Central America and South America in Tables 4 and 5.

Table 4. Fertilizer production in selected countries of Central and South America in 1990 ('000 tonnes  $P_2O_5$ ; source: IFA)

Country	Ground rock, direct application				Total straight phosphate				Ammonium phosphate P				NPK P				Total Phosphate			
	Prod.	Import	Export	Consum.	Prod.	Import	Export	Consum.	Prod.	Import	Export	Consum.	Prod.	Import	Export	Consum.	Prod.	Import	Export	Consum.
<b>1990/91 – 1990</b>																				
Costa Rica	0.0	0.0	0.0	0.0	0.0	4.1	0.0	4.0	0.0	10.7	0.0	0.0	0.0	0.0	0.0	11.0	0.0	15.0	0.0	15.0
Cuba	0.0	1.4	0.0	0.0	0.0	75.0	0.0	73.6	0.0	0.0	0.0	0.0	7.0	0.0	0.0	8.4	7.0	75.0	0.0	82.0
Dominican Republic	0.0	0.0	0.0	0.0	0.0	1.1	0.0	1.1	0.0	19.1	0.0	19.1	0.0	0.0	0.0	0.0	0.0	20.2	0.0	20.2
El Salvador	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	16.6	0.0	0.0	0.0	3.0	0.0	3.0	0.1	21.3	0.0	18.9
Guatemala	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.3	0.0	0.0	7.0	18.7	7.0	27.0	7.0	27.0	7.0	27.0
Mexico	0.0	0.0	0.0	0.0	137.5	0.0	0.0	132.1	212.6	21.7	64.1	203.2	33.2	0.0	0.0	38.5	383.3	21.7	64.1	373.8
Nicaragua	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.2	0.0	3.0	0.0	0.0	0.0	3.0	0.0	12.0	0.0	6.0
Trinidad & Tobago	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	0.0	0.0	0.2	0.0	0.2
Others Central America	0.0	0.0	0.0	0.0	0.0	3.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	28.3	0.0	28.3	0.0	31.3	0.0	31.3
Central America	0.0	1.4	0.0	0.0	137.6	83.2	0.0	213.9	212.6	84.6	64.1	225.3	47.2	50.2	7.0	119.2	397.4	223.7	71.1	574.4
Argentina	0.0	0.5	0.0	0.5	0.0	4.7	0.0	7.4	0.0	38.0	0.0	39.1	0.0	0.0	0.0	4.9	0.0	42.7	0.0	51.5
Brazil	33.7	0.0	0.0	33.7	671.0	72.4	0.0	743.4	283.6	42.1	3.6	322.1	136.1	0.0	0.0	136.1	1090.7	114.5	3.6	1201.6
Chile	0.0	0.0	0.0	0.0	5.0	67.2	0.0	79.3	0.0	28.1	0.0	34.5	0.0	0.0	0.0	0.0	5.0	95.3	0.0	113.8
Colombia	5.2	0.0	0.0	5.2	21.3	0.0	0.0	21.3	0.0	27.7	0.0	27.7	77.7	0.0	0.0	77.7	99.0	27.7	0.0	126.7
Ecuador	0.0	0.0	0.0	0.0	0.0	1.7	0.0	1.7	0.0	7.3	0.0	0.0	0.0	0.0	0.0	7.3	0.0	9.0	0.0	9.0
Peru	0.0	0.0	0.0	0.0	2.5	4.8	0.0	6.4	0.0	4.9	0.0	6.0	2.2	0.0	0.0	0.4	4.7	9.7	0.0	12.8
Uruguay	12.0	6.5	7.0	2.7	12.0	13.7	17.0	5.2	0.0	22.2	0.0	35.7	0.0	0.4	0.0	0.3	12.0	36.3	17.0	41.2
Venezuela	0.0	0.0	0.0	0.0	0.0	7.2	0.0	7.0	0.0	32.2	0.0	22.0	57.2	55.6	0.0	90.0	57.2	95.0	0.0	119.0
Others South America	0.0	0.0	0.0	0.0	0.0	3.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	16.9	0.0	16.9	0.0	19.9	0.0	19.9
South America	50.9	7.0	7.0	42.1	711.8	174.7	17.0	874.7	283.6	202.5	3.6	487.1	273.2	72.9	0.0	333.6	1268.6	450.1	20.6	1695.5



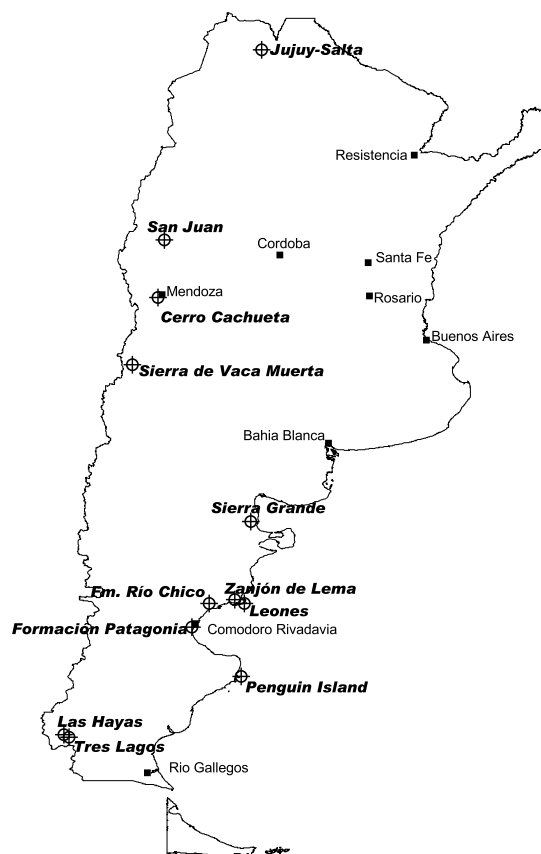
Table 5. Fertilizer production in selected countries of Central and South America in 1998 ('000 tonnes  $P_2O_5$ ; source: IFA)

Country	Ground rock, direct application				Total straight phosphate				Ammonium phosphate P				NPK P				Total Phosphate				
	Prod.	Import	Export	Consum.	Prod.	Import	Export	Consum.	Prod.	Import	Export	Consum.	Prod.	Import	Export	Consum.	Prod.	Import	Export	Consum.	
1998/99 – 1998																					
Costa Rica	0.0	0.0	0.0	0.0	0.0	2.0	0.0	2.0	0.0	20.0	0.0	0.0	0.0	0.0	11.0	0.0	31.0	0.0	33.0	0.0	33.0
Cuba	0.0	0.0	0.0	0.0	0.0	9.1	0.0	9.1	0.0	5.7	0.0	5.7	0.0	0.0	0.0	0.0	0.0	14.8	0.0	14.8	
Dominican Republic	0.0	0.0	0.0	0.0	0.0	2.0	0.0	2.0	0.0	19.6	0.0	18.3	0.0	0.0	1.3	0.0	0.0	21.6	1.3	20.3	
El Salvador	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.4	0.0	8.4	0.0	1.6	0.0	1.6	0.0	16.0	0.0	16.0	
Guatemala	0.0	0.0	0.0	0.0	0.0	4.0	0.0	4.0	0.0	68.0	0.0	0.0	0.0	9.0	0.0	77.0	0.0	81.0	0.0	81.0	
Mexico	0.0	0.0	0.0	0.0	162.2	0.3	104.2	58.0	292.2	143.1	238.2	197.0	25.0	15.0	0.0	40.0	479.4	158.4	342.4	295.0	
Nicaragua	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.0	0.0	9.0	0.0	1.5	0.0	1.5	0.0	10.5	0.0	10.5	
Trinidad & Tobago	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	0.0	0.0	1.0	0.0	1.0	
Others Central America	0.0	0.0	0.0	0.0	0.0	2.0	0.0	2.0	0.0	25.0	0.0	25.0	0.0	23.0	0.0	23.0	0.0	50.0	0.0	50.0	
Central America	0.0	0.0	0.0	0.0	162.2	19.4	104.2	77.1	292.2	298.8	238.2	263.4	25.0	61.1	1.3	174.1	479.4	386.3	343.7	521.6	
Argentina	0.0	0.8	0.0	0.8	0.0	12.7	0.0	12.8	0.0	275.3	1.2	281.9	0.0	7.0	0.0	26.0	0.0	295.0	1.2	320.7	
Brazil	38.6	0.0	0.0	38.6	929.4	196.9	2.1	1124.2	368.3	480.4	2.4	846.3	71.3	14.0	33.4	51.9	1369.0	691.3	37.9	2022.4	
Chile	0.0	0.0	0.0	0.0	0.0	109.7	0.0	113.0	0.0	59.5	0.0	60.0	0.0	0.0	0.0	0.0	0.0	169.2	0.0	173.0	
Colombia	6.0	36.5	0.0	6.3	9.3	39.5	0.0	12.6	0.0	79.9	0.0	18.8	0.0	0.0	1.7	95.6	9.3	119.4	1.7	127.0	
Ecuador	0.0	0.0	0.0	0.0	0.0	3.4	0.0	3.4	0.0	23.5	0.0	23.5	0.0	2.6	0.0	2.6	0.0	29.5	0.0	29.5	
Peru	0.0	0.0	0.0	0.0	3.0	2.9	0.0	5.9	0.0	41.5	0.0	41.5	0.0	0.0	0.0	0.0	3.0	44.4	0.0	47.4	
Uruguay	2.0	0.0	0.0	2.0	9.3	9.4	7.2	11.5	0.0	53.0	0.0	53.0	0.0	1.0	0.0	1.0	9.3	63.4	7.2	65.5	
Venezuela	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	37.8	7.6	24.3	21.1	28.0	10.0	14.7	23.3	72.8	17.6	39.0	51.4	
Others South America	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	0.0	3.0	0.0	24.0	0.0	24.0	0.0	27.0	0.0	27.0	
South America	46.6	37.3	0.0	47.7	951.0	374.5	9.3	1283.4	406.1	1023.7	27.9	1349.1	99.3	58.6	49.8	224.4	1463.4	1456.8	87.0	2863.9	

## **COUNTRY PROFILES**



# Argentina



## *Location, Quantity, Quality*

Ordovician phosphate rock resources comprising 0.5 to 5 m thick beds of fossiliferous phosphatic quartz arenites with 3-17%  $P_2O_5$  have been outlined in Jujuy and Salta Provinces, northern Argentina, in a belt lying between 22° and 24°30'S and 65°20' and 64°30'W (Fernandez, 1985; Leanza, 1984). Mining is not feasible because of constraints imposed by structural and depositional settings (Leanza et al., 1989b).

Siluro-Devonian phosphatic sedimentary iron ores containing 2-3%  $P_2O_5$  form part of the Sierra Grande Formation in southeastern Rio Negro Province. Beneficiation trials showed that a concentrate with 36%  $P_2O_5$  could be produced from tailings containing 7-8%  $P_2O_5$  (Savage, 1987), but these were highly ferruginous with 6% Fe and unsuitable for fertiliser manufacture.

Devonian phosphorite occurs also in San Juan Province where the main phosphorite bed is 10-65 cm thick and contains up to 14.4%  $P_2O_5$ . Resources are only 23000 tonnes distributed in 8 beds over 10 km with low  $P_2O_5$  contents of 2 to 5% (Leanza, 1984; Leanza et al., 1989b). Whereas these could be extracted by open cast mining this is unlikely to be an economic proposition because the ore would have to be upgraded before it could be utilised.

Triassic phosphate deposits occur on the southern flank of Cerro Cacheuta in northern Mendoza where concretionary phosphorite lenses up to 0.3 m thick and with up to 29%  $P_2O_5$  are found in bituminous shales exposed over a distance of at least 7 km (Leanza et al., 1989b).

Weakly phosphatic sediments have been described from near the Jurassic-Cretaceous boundary and also the Upper Cretaceous succession (Leanza et al., 1989b). Lenticular beds of phosphatic limestones and phosphatic calcareous sandstones occur in the Sierra de Vaca Muerta area. The beds are thin (10 to 90 cm) and have low  $P_2O_5$  (ranging from 1 to 10% but generally <5%). These resources have no commercial values because of their low grade and unfavourable structural setting (Leanza et al., 1989b). 10-30 cm thick phosphatic limestones with up to 8%  $P_2O_5$  occur in the Cretaceous Las Hayas Formation in the Lago Argentino area, the Cerro Barragan area (3 km S of Las Hayas creek) and the Tres Lagos area (Leanza et al., 1989b).

Early Palaeocene radioactive phosphates 9-29%  $P_2O_5$  have been reported from the Zanjón de Lema area and Late Palaeocene phosphatic tuffs and phoscretes occur in the Rio Chico Formation of the San Jorge basin (east-central Chubut Province). Eocene-Oligocene phosphorite occurrences along the Argentine Patagonian coast between 42° and 50°S include phosphatic limestones, phosphatic tuffs and concretionary phosphates with 2-36%  $P_2O_5$ . The tuffs occur in 0.95-1.20 thick beds with 4-6%  $P_2O_5$  (Leanza et al., 1989b).

Apatite occurs in mica and beryl pegmatites in the Andean mountain regions of San Juan, San Luis, Córdoba, La Rioja and Catamarca provinces, but none has proved of economic interest as a source of apatite (Notholt, 1999).

Phosphatic guano occurrences have been recorded on numerous small islands off the Patagonian coast between Peninsula Valdés and Bahía Grand. Of these, the deposits on Isla Leones (45°03'S, 65°36'W), Chubut Province, and Isla Penguino (47°54'S, 65°43'W) in Santa Cruz Province, provided significant tonnages during the latter half of the 19th century (Notholt, 1999). Reserves of guano were reported to be about 15,000 tons with more than 8%  $P_2O_5$ .

According to Leanza (1989b), there is potential for offshore phosphorites east of Tierra del Fuego and at 49 degrees S, east of Gran Bajo de San Julian - but none have been discovered so far.

Greater detail on individual occurrences may be obtained from Fernandez (1985) who concluded that no economically exploitable deposits of phosphate rock have yet been located within Argentina.

### *Production*

The guano deposits on Isla Leones and Isla Penguino, provided significant tonnages during the latter half of the 19th century. Most of the production was shipped to the United Kingdom, which received 84,360 tons between 1846 and 1863. Phosphatic guano was also worked on the mainland at Monte Leon, 40 km SW of Puerto Santa Cruz, between 1936 and 1938. Leanza (1989b) reports that guano on Isla Leones was worked sporadically.

*Sources:* (Anon., 1989; Fernandez, 1983; Fernandez, 1984; Fernandez, 1985; Fernandez, 1998; Gay and Hillar, 1975; Leanza, 1972; Leanza et al., 1979; Leanza, 1983; Leanza, 1984; Leanza et al., 1989a; Leanza et al., 1987; Leanza et al., 1980; Leanza et al., 1985; Leanza et al., 1986; Leanza et al., 1989b; Mastandrea et al., 1983; Mastandrea et al., 1982; Mastandrea et al., 1975; Notholt, 1994a; Notholt and Hartley, 1983; Notholt et al., 1989; Olivero et al., 1998; Savage, 1987; Scasso and Castro, 1999)

### *Agronomic testing and use*

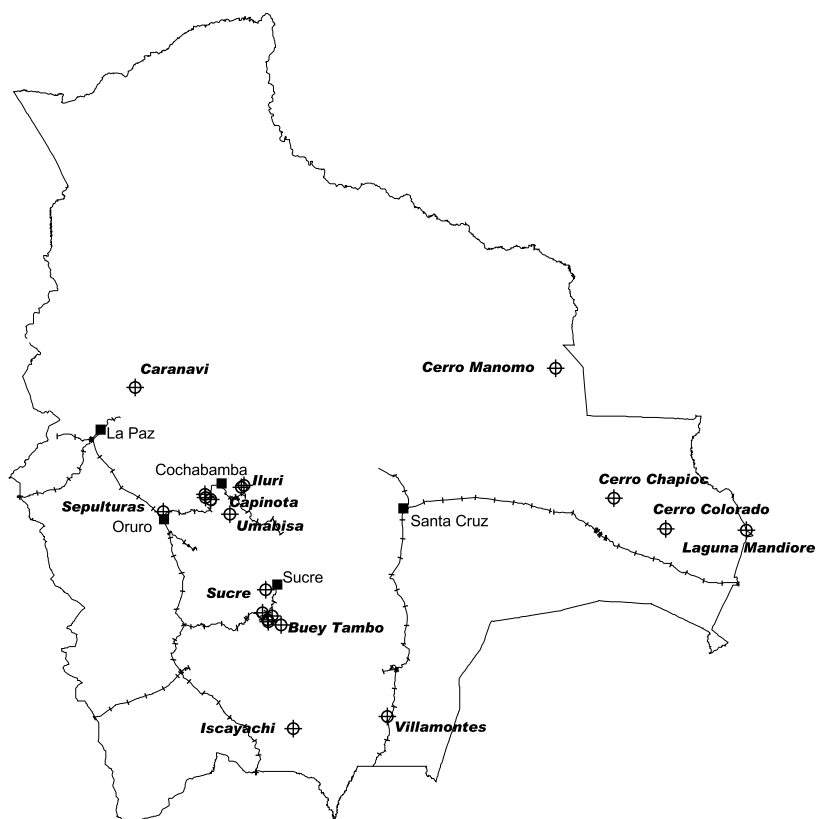
Little data is readily available on use of phosphate rock for direct application in Argentina. Indeed Fernandez (Fernandez, 1985) observed that phosphate rock has been used only for agronomic trials prior to 1985.

Camelo (1997) showed that rock phosphate contained the highest levels of Cd and Zn compared with other fertilizers commonly used in Argentina and concluded that continuous fertilization of soils with these rock phosphates could increase the heavy metal contents above natural abundances in soils, and lead to the transfer of heavy metals to the human food chain.

Melgar et al. (1998) assessed whether direct utilization of phosphate rock might be an economical option for farmers growing rice (*Oryza sativa*, L.) in soils characterised by low levels of available phosphorus (P). The direct and residual effect of TSP and North Carolina rock phosphate (NCRP) on rice grain yield, P absorption and P soil availability was determined on acid soils in Corrientes area at P rates of 0, 13, 27 and 40 kg ha<sup>-1</sup>. TSP and NCRP behaved similarly at equal rates of applied P, suggesting that NCRP may be used as a substitute for TSP. The biggest contrast with the control over a three-year period was obtained with 13 kg ha<sup>-1</sup> of P, which increased grain yields from 5.13 to 5.95 Mg ha<sup>-1</sup>.

*Sources:* (Camelo et al., 1997; Fernandez, 1985; Melgar et al., 1998)

# Bolivia



## *Location, Quantity, Quality*

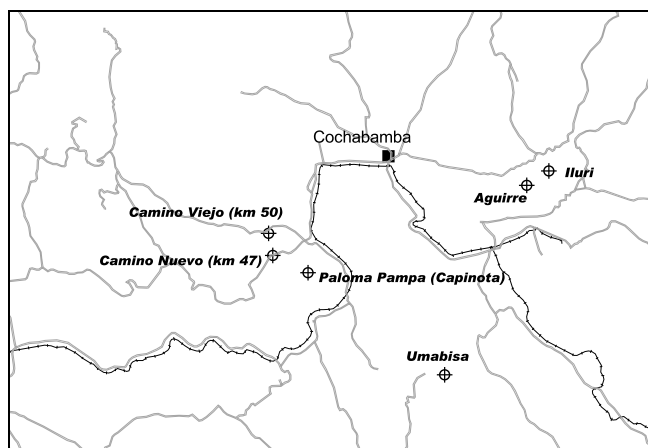
### Ordovician

Geological studies have identified Precambrian, Ordovician, Cretaceous and Recent phosphate rock occurrences in Bolivia, sixteen of which are sedimentary phosphates of Upper Ordovician age. Small, thin lenses of phosphorite have been detected in Ordovician marine sedimentary rocks that stretch from the Argentine border in the south to the frontier with Peru. In 1976, detailed geological investigations were carried out by GEOBOL in association with RTZ, with the objective of locating approximately 1,500,000 tonnes of measured and indicated phosphate rock reserves for a proposed fertilizer plant. It was concluded that the Upper Ordovician sedimentary phosphate rock resources of the Caradocian Anzaldo Formation located in the Capinota area, approximately 35 km to the south west of Cochabamba (66°21'W, 17°39'S), had the greatest economic potential. A total of fifteen phosphate-bearing zones have been identified in the Capinota area. Resources amount to 2.8 million tons of which 1.2 million tons, with an average grade of 25.4%  $P_2O_5$  are in 1.1 m thick phosphate rock horizon "capa 37" in the Paloma Pampa sector, 13 km NW of Capinota and 9km SSW of Parotani (GEOBOL-ENAF, 1979).

The Capinota phosphorites comprise phosphatised shells and phosphatic pellets ranging up to 1000 microns in length in a chert-goethite matrix. The phosphatised shells are virtually pure apatite whilst phosphatic pellets contain traces of silica (Appleton, 1991). Apatite forms approximately 60% of the highest-grade phosphate rock. All the Ca in the higher grade rocks occurs in apatite although some of the lower grade rocks contain calcium carbonate (Appleton, 1991). The chemical reactivity of the Capinota phosphate rock indicated by its solubility in 2% citric acid (7.4%  $P_2O_5$ ) is similar to that of the Central Florida and Lobatera (Venezuela) phosphate rocks and higher than the Patos de Minas (Brazil) and Colombian (Huila, Sardinata

and Pesca) PR's which are (or have been) used as direct application fertilizers (Appleton, 1990; Appleton, 1991; Appleton, 1995; Goedert et al., 1987).

The average  $P_2O_5$  content of the phosphate rock at Capinota is only 25% and the average  $Fe_2O_3$ ,  $Al_2O_3$  and  $SiO_2$  concentrations are approximately 7%, 3% and 21% respectively. The ratio  $Fe_2O_3+Al_2O_3/P_2O_5$  (0.32 to 0.87) is about ten times higher than the recommended maximum value of 0.05 for phosphoric acid plants (Hignett, 1985) for which it would be necessary to beneficiate the phosphate rock to obtain a concentrate with at least 30%  $P_2O_5$  and less than 3-5%  $R_2O_3$  ( $Fe_2O_3 + Al_2O_3$ ). These impurities would not prevent the Capinota phosphate rock being used as a direct application fertilizer. Potentially toxic elements are low in the Capinota phosphate rock (e.g. <1 to 1 mg/kg Cd) so would not produce potential environmental problems.



*Location of phosphate rock resources in the Cochabamba area*

Preliminary experimental beneficiation tests of the Capinota phosphate rock showed that although it is possible to improve the phosphate rock grade, commercial grade phosphate concentrates were not produced (Appleton, 1995). In addition, the quantity of phosphate rock resources is probably insufficient to justify the capital investment required for a flotation beneficiation plant (estimated cost \$7-9 million) that would be needed to supply a phosphoric acid or TSP plant. The estimated  $P_2O_5$  consumption in Bolivia is only 8,500 t/year (Corvera, 1994), which is insufficient to justify the installation of a phosphoric acid plant solely to supply the Bolivian market.

Due to potential mining problems, including the extreme overburden ratio (1:55) and the restricted thickness of the main phosphate rock horizon, it would be possible to exploit only a small proportion of the phosphate rock resources in the Paloma Pampa sector by open cast mining. "Artisanal" underground mining by non-mechanised methods may be viable for small sectors of the geological resources at Capinota. However, due to the difficult mining conditions caused by the unstable "hanging wall"<sup>1</sup> shales, and the lack of local experience of this type of mining, it is considered that high mining costs would probably make underground mining at Capinota uneconomic.

There are other sites, such as at Km 47 on the new road from Cochabamba to Oruro, where Ordovician phosphate rock horizons (0.7 - 0.9 m thick) crop out at the surface and where the shale overburden is relatively thin (1 to 5 m). Approximately 140,000 and 200,000 t of inferred phosphate rock resources occur at two locations close to Km 47, approximately 11 km WSW of Parotani, where the phosphate rock could be exploited more economically than at Capinota by open cast methods. In addition, the phosphate rock resources at Km 47 are only about 1 km from the main road whereas at Capinota it would be necessary to construct a 5 km access road. Mining costs would be lowest at this location and exploitation could be started

<sup>1</sup> *hanging wall* refers to the rocks lying above the phosphate rock horizon. At Capinota these are fractured shales that would need to be supported during underground mining operations. Underground mining in these rocks would be dangerous and expensive.



without any substantial capital investment apart from crushing and grinding machinery. These are very small deposits by world standards but may have some potential for local use, especially for direct application on acid soils.

In addition to the Ordovician phosphate rock occurrences documented by Gonzales (1985; 1983), Notholt (1999) recorded that 10 to 30 cm thick phosphate beds containing an average of 24%  $P_2O_5$  occur near Chacarilla, in Sicasica province, La Paz Department, about 72 km WNW of Oruro. The phosphate beds are reported to be associated with fossiliferous ferruginous limestones and were the first marine phosphate deposits of Ordovician age to be discovered in South America. This locality is not reported in more recent reviews of the phosphate resources of Bolivia (Gonzales, 1985; Gonzalez, 1983).

### Middle Proterozoic

A quartzite of the Middle Proterozoic (1,600-1,280 Ma) Cristal Schist Formation was found to contain 10%  $P_2O_5$  (Appleton, 1991). Although a global phosphogenic episode in the Middle Proterozoic (? 1200-1600 Ma) has been recognised, sediments commonly associated with Proterozoic phosphorites have not been located in the Cristal Schist Formation.

### Upper Proterozoic-Eocambrian

Thin phosphate enriched bands with up to 11.9%  $P_2O_5$  are associated with Upper Proterozoic-Eocambrian jaspilitic hematitic ironstones at Cerro Colorado in E. Bolivia (Appleton, 1991; Litherland and 15 others, 1986). The ironstones are probably equivalent in age to the Patos de Minas phosphorites in Brazil.

### Cretaceous

A phosphate body of probable Cretaceous age and composed mainly of apatite, goethite and meta-autunite is associated with the Cerro Manomo silicified carbonatite complex in eastern Bolivia (Fletcher, 1980; Fletcher et al., 1981a). The apatite body is about 150 m long, 30 m wide and of unknown vertical extent.  $P_2O_5$  ranges from 4 to 25% (average 5%) whilst U ranges from 0.01 to 0.7% (average 0.1% U). Rare earth and niobium mineralisation is associated with the carbonatite complex (Burton, 1982; Burton, 1983; Fletcher et al., 1981a; Llanos, 1984).

### Recent

Recent superficial deposits of earthy phosphate occur between Huari and Soledad in Oruro Department at Huari-Challapata, Pazña, Poopó, Paria, Soledad, Sepulturas, Agua de Castilla. Of these, only the deposit at Sepulturas (7 km E of Oruro) has been examined in detail. It covers an area of 10,000 m<sup>2</sup> and is reported to have resources of about 300,000 m<sup>3</sup> with an average thickness of 0.5 m and average grade of 9.3%  $P_2O_5$  (Gonzalez, 1983).

In the vicinity of Laguna Mandiore, close to the Brazilian border, there are reports of phosphate deposits of unknown age that may reach 20 Mt (Gonzales, 1985; Gonzalez, 1983). This occurrence was not confirmed by *Proyecto Precambrico* (Appleton, 1991).

### *Production*

Notholt (Notholt, 1999) reported that deposits containing an average of 9%  $P_2O_5$  were discovered in 1951 in Sud Chichas Province about 40 km south of Sucre and were estimated at more than 1 million tons. These are presumably the Quivinchá, Buey Tambo, Betanzos and Lagunillas occurrences of Ordovician phosphate rock located about 55 km S of Sucre (Gonzales, 1985; Gonzalez, 1983). A small company was reported in 1952 to be producing between 80 and 100 tons of finely ground phosphate each year for direct

application to the soil; however, the phosphate is only slowly available because of the alkaline nature of the soils in this part of Bolivia. No further production appears to have taken place (Notholt, 1999). A few tonnes of phosphate rock from the Paloma Pampa and Km 47 localities in the Capinota area have been extracted and finely ground for use in agronomic trials.



*Location of phosphate rock resources in the Sucre area*

*Sources:* (Anon., 1983; Anon., 1987b; Appleton, 1989; Appleton, 1991; Appleton, 1994; Appleton, 1995; Arias, 1991; Armitage and Potts, 1994; Burton, 1982; Burton, 1983; Bustillos, 1969a; Bustillos, 1969b; Camacho, 1985; Camacho, 1985; Camacho, 1986; Camacho, 1987; Camacho and Maranon, 1987; Claure et al., 1997; Escalera and Ricaldi, 1985; Escalera, 1984; Fernandez, 1984; Fernandez, 1985; Fletcher, 1980; Fletcher et al., 1981a; Fletcher et al., 1981b; GEOBOL, ; GEOBOL, 1969; GEOBOL, 1973; GEOBOL, 1979; GEOBOL, 1983; GEOBOL, 1989; GEOBOL-ENAF, 1979; Gomez, 1984; Gonzales, 1983; Gonzales, 1985; Gonzalez, 1983; Gonzalez, 1984; Gustavson Associates Inc. et al., 1992; Hawkins, 1983; Hignett, 1985; Llanos, 1984; Luizaga and Camacho, 1985; Minería, 1972; Miranda and Roman, 1989; Notholt, 1994a; Notholt, 1994b; O'Leary, 1994; Ricaldi, 1983; Ricaldi and Escalera, 1984a; Ricaldi and Escalera, 1984b; Ricaldi and Escalera, 1985; Ricaldi and McClellan, 1987; Riddler, 1994; RTZ, 1976; Tanke and Clayton, 1984; Telleria, 1986; Torrico and Bellott, 1992; UMSS and S.A.M., 1982)

### *Agronomic testing and use*

Various sectors of the tropical zone of eastern Bolivia have climatic and soil characteristics appropriate for the direct application of phosphate rock. These include:

- rainfall of 1000-1900 mm/year;
- acid soils with low levels of P and Ca;
- extensive areas with degraded soils characterised by degraded soils with low agricultural productivity and abandoned farmland.

In contrast, the Valleys, Foothills and the Altiplano have characteristics indicating that use of direct application fertilizer is likely to be inappropriate:

- low rainfall (250-700 mm/year);
- soils with neutral to alkaline pH.

### Potatoes

Villaroel and Augstburger (1983a) investigated the response of potato crops to organic fertilizers mixed with phosphate rocks and fermenting agents as well as the response to the direct application of ground PR on slightly acid soils at 2500-3500 m. The response of potatoes to the P rock and organic fertilizer mixture was

satisfactory while the direct use of P rocks produced no significant response. Soil pH in the range 5.4-6.4, precipitation 622-840 mm, temperature 8-15°C, Olsen P 6, 9, 25 ppm.

Quiton et al. (1983) examined the response to rock phosphate application in potato cultivation in the Cochabamba region. Although the potato yield was negligible, a significant response was obtained to the application of TSP, by itself, and combined with urea, as well as using organic fertilizers. The conclusions from this study are not very clear and have presumably been updated in the paper by Rico et al. (1987) referred to above.

Villaroel (1985a) reported (i) no positive response to direct application of CPR for potatoes in the Andean zone at Toralpa (3460 msnm, 558 mm precipitation/year; soil P (Olsen) 9 ppm; Ca 2.5 meq/100 g soil) and (ii) an enhanced response to ground CPR mixed with bone flour compared with a urea-ground bone mixture. TSP produced superior yields to CPR and no residual P effect was observed as a consequence of CPR application.

Bellott (1989) compared the impact of acidulated CPR and TSP for crops grown on alkaline (pH 7.8) soils at Pirque, in the Valles Bajos zone. For potatoes, only TSP appeared to significantly increase yield (+ 43%), whereas N (urea) was much more limiting (urea alone increased yield by 117%). No significant differences in yield of carrots were recorded in a trial to test for residual effects. The same applied to onions grown after potatoes or maize.

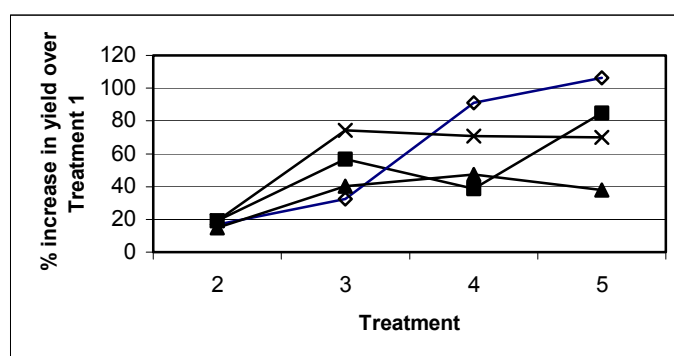
In 1999, preliminary results were reported from the FAO-funded *Fertisuelos* project that investigated whether it was possible to improve the solubility of CPR through composting with animal manure and cereal straw. The five treatments are given in Table 6.

Table 6. Fertiliser treatments in FAO Fertisuelos potato trials

Treatments	T1	T2	T3	T4	T5
CPR (kg/ha)	0	800	0	800	0
Organic compost without CPR (kg/ha)	0	0	10000	10000	0
Organic compost with CPR (kg/ha)	0	0	0	0	10800*
Nitrogen (kg/ha)	40	40	40	40	40

\* comprising 800 kg CPR mixed with 10000 kg compost at the start of the composting process

The percentage increase in potato yield related to the organic compost and CPR revealed that whereas there was a small increase in yield with Treatment 2 that can be attributed to ground CPR, much higher yield increases were recorded for compost. At two of the four trial sites, the highest yields were obtained when CPR was incorporated with manure and cereal waste at the start of the composting process, suggesting that P was released or converted to a more soluble state as a result of composting.



Increase of potato yields produced by organic compost and ground Capinota phosphate rock (FAO Fertisuelos, unpublished results)

### Beans, groundnuts, maize, rice,

Villaroel and Augstburger (1983b) evaluated the conditions for the efficient anaerobic fermentation of PR with cow manure ("bioabono vacuna") in an OLADE biodigester and aerobic composting. Yields using these organic manures were compared with TSP, CPR, PR+urea when applied to *vicia faba* (bean) at a dose of 120kg P<sub>2</sub>O<sub>5</sub> kg/ha. It was concluded that in general, N, P, Mg and Ca levels were higher following aerobic fermentation. Due to lack of rainfall and high temperature during the trial, the coefficients of variation were very high making it impossible to detect statistically significant differences in relative yield between the different applications. All fertilizer applications gave higher yield than the control with the highest being for the "bioabono vacuna". There were wide differences between the application levels for the different fertilizers - for example the "bioabono vacuno" was applied at 54,545 kg/ha whilst DAP was applied at 260 kg/ha and PR at 870 kg/ha. The influence of other factors, apart from P, cannot be effectively determined from the results of these trials. Further (more rigorous) trials are required to test these fertilizers.

The response of rice to CPR, CPR+urea, DAP, TSP, organic manure (AMRL : *Abono Mineral de Recursos Naturales*) and Kallpachasqa Huana (KH : AGRUCO organic fertilizer) was examined in field trials at the "La Jota" experimental station in the Chapare region (rainfall 3000mm, temperature 24°C, 360 amsl, tropical rain forest area, deep alluvial soils with pH 4, 4.5ppm P) (Carerra, 1983). Significant increases in yield were recorded for AMRL, DAP, and CPR+urea. In general it was observed that CPR was more effective within AMRL. DAP, AMRL and CPR+urea appear to offer economic benefits. Carerra (1983) concluded that (i) the use of fertilizers was a viable method of increasing rice yields in the low fertility soils of the Chapare region; (ii) response to CPR and CPR+urea was significantly less than AMRL (which includes CPR); (iii) DAP is an appropriate commercial fertilizer for the zone whereas TSP and KH are not; (iv) CPR is more effective when applied with urea or in AMSL; (v) P and N should be applied together; presumably due to the interaction between these nutrients. In Carerra's experiments (1983) the fertilizers were broadcast, which is generally the approved method for PR and organic manures but not for TSP, DAP and urea, which are normally applied in bands close to the plants. This appears to be a fundamental flaw in the trials, which may partially or totally invalidate the conclusions. The mean yield for the "control" was 2400kg/ha whereas the yields for CPR (2900 kg), PR+urea (3073 kg), DAP (3390 kg) and AMRL (3741 kg) were significantly higher whilst lower yields were recorded for TSP (2484 kg) and KH (2747 kg). An economic evaluation showed that CPR, CPR+urea, DAP and AMRL provided an increase in income of between 9 and 20%. It is relevant to note that the cost ratio DAP/CPR used in the economic assessment was 5.7 whereas the independently calculated ratio calculated by Appleton (1989) was 6.2.

Araxa (Brazil) and Sechura (Peru) PRs were compared with TSP on ultisols in the San Ignacio area (Hinjosa, 1983). There was no significant difference between corn and grain yields for the three P sources after two to three years. The response of the low reactivity Araxa PR was only slightly less than the reactive Sechura PR suggesting that the relatively low reactivity Capinota PR could be used on this type of soil, at a significantly lower cost. Site characteristics were rainfall 1156mm; temperature 25°C; soils: Typic (oxic) Paleudult - low fertility, low CIC, low P, and low pH (high Fe and Al sesquioxides). A maize-groundnut 5-year crop rotation was used for the trials. The comparisons of PR with TSP were based on annual applications of TSP (30, 60, 120 kg/ha P<sub>2</sub>O<sub>5</sub>) and single applications of PR (300, 600, 1200 kg P<sub>2</sub>O<sub>5</sub>). The PR applications are thus equivalent to 60, 120, 240 kg P<sub>2</sub>O<sub>5</sub>/ha over the full 5-year period although the paper appears to report results for only the first 2-3 years. Applying PR at double the rate for water soluble TSP is a procedure that has been followed in trials in Malawi and would probably be economically viable as PR would be expected to cost approximately 50% as much per unit of P<sub>2</sub>O<sub>5</sub> as TSP. As the trials were carried out on the Experimental Station in San Ignacio, it is possible that soil conditions were not typical of the area and previous fertilizer applications may have influenced the results of the trials. Further trials are required on plots outside the Experimental Station.

Augstburger and Rico (Augstburger and Rico, 1986) and Rico et al. (1987; 1988) demonstrated that in pot and field trials, in both the valley and high Andes zones there was no response to CPR application, neither in the first nor subsequent crops, independent of pH and type of crop (maize, wheat, beans and potatoes). Acidifying agents such as sulphur, ammonium sulphate or TSP had no effect on the reactivity of the CPR, neither in acid or alkaline soils, and a residual effect was not observed. 25% and 50% partially acidulated CPR produced a positive response on the alkaline soils of the valley zones. Aerobic fermentation with organic material slightly increased the reactivity of the CPR. In general, the reactivity of the CPR was low in

the entisols and inceptisols of the Andean zone. Trial site characteristics were: altitude 2600 -3790m, rainfall: 350-840 mm, soils: entisoles y inceptisoles, pH 5.4- 6.4; P Olsen 6-25 ppm. Augstburger and Rico (1986) noted that phosphate fertilization (whatever the source of P) was effective only when it is applied with N and possibly also with S.

Villarroel and Navia (1989) carried out pot trials to test different sources of P (TSP, CPR Capinota, Bayovar PR, partially acidulated CPR (PACPR), bone meal, and guano) for the growth of oats, clover and maize in (i) acid oxisol (pH 5.2; 14 ppm Bray P-1; Ca 0.7 meq/100 g) from the Chapare (360m, 24°C, 3000mm rainfall); (ii) an entisol (pH 5.9; 37 ppm Bray P-1; Ca 1.5 meq/100 g) from Toralpa (3460m, 558mm rainfall, temperature 8°C); and (iii) an inceptisol (pH 8.3; 90 ppm Bray P-1; Ca 6.0 meq/100 g) from Tamborada (2560m, 518mm rainfall, temperature 18°C). Villarroel and Navia (1989) concluded that Capinota PR applied directly to Chapare soil was more effective than 25% and 50% PACPR and that water soluble P-fertilizers such as TSP and PAPR were not effective due to P-fixation. In the moderately acid and alkaline soils from Toralpa and Tamborada, the Capinota and Bayovar (Sechura, Peru) PRs had similar RAEs to the 25% and 50% PAPR. The Capinota and Bayovar PRs showed similar RAE in all soils, although this is difficult to understand and contradicts previous pot-trials by León and others (1989; 1991), which showed a higher RAE for the more soluble Bayovar PR. The different sources of P showed a similar RAE in the moderately acid and alkaline soils but in the acid Chapare soil, the two PR's were more efficient than the other P-sources. There was a positive response to KCl in the Chapare soil but not in the Toralpa or Tamborada soils. These trials confirmed that the Capinota PR would be an effective P-fertilizer when used on acid oxisols of the tropical eastern lowlands of Bolivia.

Bellott (Bellott, 1991) confirmed earlier results when he reported that CPR did not produce a positive response in potatoes and cereals cultivated on entisols and inceptisol. Partially acidulated CPR (25% and 50%) produced a good response when used for wheat and potatoes; a more positive being obtained in crops grown on entisols compared with inceptisols. CPR mixed with manure and sulphur produced a positive response in clover to S but not to P. Biological acidulation of CPR by aerobic fermentation in the presence of manure and S did not increase the reactivity of the CPR. Bellott (1991) concluded that the results of the agronomic evaluations demonstrate the economic potential for substituting direct application fertilizer for superphosphate, taking into account the soil characteristics.

Direct application of CPR on oxisols of the eastern Bolivian lowlands produced a positive response for maize and rice at an application rate of 100 kg P ha<sup>-1</sup> (Bellott, 1994). An economic analysis indicated that for maize, TSP produced a rate of return of 38% compared with 83% for CPR. However, increases of yield from 3000 kg to 6000 kg/ha maize casts doubts over these results, which need to be confirmed. Bellott (1994) also observed a residual effect for CPR on low pH, Ca and P oxisols, with a greater response to CPR than to TSP. On the acid soils of the Chaparé region, CPR had a greater effect than 25 and 50% acidulated CPR. On these soils, SSP and TSP were not so effective due to the high P-fixation (Villarroel and Marvel Navia, 1989). In entisols, a better response was recorded for CPR granulated with TSP as a result of the higher soluble P content compared with partially acidulated CPR. This produced a better economic response than TSP (Bellott, 1994). Bellott (1994) concluded that it was necessary to carry out further field trials to confirm the single season, micro-plot results.

## Pasture

AGRUCO carried out various trials with organic fertilizers although the results were contradictory. Bellott (1991) reported that for clover, Capinota PR (CPR) mixed with manure and sulphur produced a response to S but not to P. Also biological acidification by aerobic fermentation in the presence of organic matter, CPR and sulphur did not increase the reactivity of the CPR (Bellott, 1991). In contrast, Augstburger y Rico (1986) identified a tendency towards better solubilisation of the CPR when the organic manure had been fermented together with CPR prior to application to soil. This was confirmed by Rico et al. (1987), who observed that the aerobic fermentation with organic matter slightly increased the reactivity of the CPR.

Most of the direct application phosphate fertiliser used in Latin America is applied to improved pastures. The agronomic efficiency of Capinota phosphate rock as source of P for pasture was assessed in a trial carried out in the Yapacani area of eastern Bolivia by the Centro de Investigación Agrícola Tropical (CIAT) (Martínez and Appleton, 1994). The objective of the trial was to compare the effect of Capinota PR (21%

P<sub>2</sub>O<sub>5</sub>) with TSP (46% P<sub>2</sub>O<sub>5</sub>) on the production of the pasture *Brachiaria decumbens*. The trial was carried out in the Yapacani area of the Department of Santa Cruz (17°30'S, 63°40'E; altitude 300 to 500 amsl), in the wet tropical lowland area of eastern Bolivia where the annual rainfall is 2000 mm and average temperature 23°C. The high rainfall, high temperature and soil characteristics of the Yapacani area should favour a positive response to P applied as rock phosphate. Although the pH, P and available Ca of the soil are low (Martínez and Appleton, 1994), they are not as low as in some parts of Brazil and Colombia where positive responses to PR have been recorded with *B. decumbens* and similar pasture crops (León and Arregocés, 1987; Saif, 1983). Growth response was compared at application rates of 0, 100 and 200 Kg P<sub>2</sub>O<sub>5</sub>/ha as CPR and TSP and 0 and 100 Kg N/ha as urea. Although the greatest increase in yield can be attributed to N (Appleton, 1994, Figure 9), an increase in yield with P application rate was also registered. Approximately twice the amount of P had to be applied as CPR to obtain the same increase as TSP. This is a reflection of the different solubility of the two P sources. The important interaction of N and P is clearly seen in the response to P when the N application rate is doubled from 100 to 200 kg/ha. There is a relatively minor increase in yield related to N alone, but the higher rate of N greatly increases the effectiveness of the P applied as CPR (Appleton, 1994, Figure 9).

#### Agronomic efficiency of partially acidulated CPR and CPR mixed with soluble fertilizers by compaction or granulation.

In a trial at the Calla experimental site near Cochabamba (soil pH 5.1, Ca 1.5; altitude 3850 m; rainfall 380 mm), potatoes responded to an application of 60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> whilst higher application rates reduced yields in all three P sources (TSP, co-granulated CPR-TSP and PA-CPR). The comparative efficiency of the three sources was TSP > granulated CPR-TSP > PA-CPR. The relatively low response to PA-CPR could be caused by the high concentrations of Fe and Al in the CPR as this will reduce the agronomic efficiency of the PA-CPR. This effect was also noted by León (1994) and Menon et al. (1991). According to León (1994), partial acidulation of many low and medium reactivity phosphate rocks can increase their agronomic efficiency, unless the PRs have high Fe and Al contents. The results of four field trials in Colombia (pH de 5-5.5; P Bray 2, 4, 12 ppm; Ca 0.1, 0.3, 6.9 meq/100 g) indicated that when the PR had low Fe and Al (e.g., Huila PR, Colombia), it is possible to obtain agronomic responses with PAPR equal to those with PR compacted with TSP. However, where Fe and Al are high, the response for PR compacted with TSP is higher than for the PAPR. It is possible that the presence of free Ca (from carbonates) will contribute to the nutrition requirements of wheat and soya where these are grown on acid soils with low Ca levels. León (1994) suggested that this might explain the positive residual effect observed. The trials indicated that it is economically better to apply low doses of soluble P (as TSP or PAPR) before each sowing than apply high rates after the first sowing and relying on the benefit from the residual effect.

In contrast, Villarroel and Navia (1989) suggested that the direct application of CPR is more effective than 25% and 50% PA-CPR and that TSP and PA-CPR did not have a residual effect due to the high fixation capacity of the soils.

However, whereas preliminary agronomic trial results indicated that compaction-granulation produces a higher agronomic efficiency than PA-CPR (León, 1989; Menon, 1990; Menon et al., 1991) the most recent results obtained using compacted CPR in Colombia have been contradictory and PA-CPR appears to produce better responses than previously obtained (personal communication from Luis León, IFDC/CIAT to Ing. Juan Bellot, UMSS, June 17, 1991).

Greater economic benefit accrues from the application of P as CPR compared with TSP due to the lower cost of CPR (Martínez and Appleton, 1994). Whereas the principal increase in yield and economic benefit accrues from the application of urea (N), 40-60 kg/ha P<sub>2</sub>O<sub>5</sub> is removed each year in the pasture crop from soils with low P reserves, so it is necessary to replace this P in order to maintain the fertility of the soil. CPR would be expected to have a greater residual effect than TSP but this has not been assessed in field trials. Agronomic trials in Colombia indicate that compaction of CPR with TSP and urea would produce improved responses with annual crops (León, 1989).

#### Summary

In summary, it can be concluded that agronomic evaluations of Capinota phosphate rock have shown that it was not an effective fertilizer under low temperature, low to moderate rainfall climatic conditions and on the neutral or alkaline soils of the Andean zone, but there is some potential for its use in the high rainfall, hot tropical lowland areas characterised by low pH, low P oxisols which cover about 19% of the surface of Bolivia (Amurrio, 1991). Augstburger (1983) highlighted the inefficiency of isolated actions in agriculture (such as the testing a new plant variety or fertilizer) and the need for an integrated approach. Artificially low prices of donated imported fertilizers (in the early 1980's) meant that locally produced organic fertilizers were relatively expensive. Augstburger (1983) noted the need for the Bolivian Government to protect the national production of fertilizers, such as ground CPR and organic manure/PR/hoof and horn type mixtures.

Appleton (Appleton, 1995) recommended that the Ordovician phosphate rock resources at Km 47 on the new road from Cochabamba to Oruro should be evaluated with a view to using ground phosphate rock as a direct application fertilizer for appropriate crops and for the reactivation of degraded soils in the tropical zones of Bolivia characterised by high precipitation and temperatures, and acid soils with low available P and Ca concentrations. To date, these research programmes have not been initiated.

*Sources:* (Alvarez et al., 1981; Amurrio, 1991; Anon., 1983; Anon., 1987b; Appleton, 1989; Appleton, 1994; Augstburger, 1983; Augstburger and Rico, 1986; Bellott, 1991; Bellott, 1994; Bellott and Navia, 1990; Carerra, 1983; Chien and Hammond, 1988; CIAT-IFDC, 1979; Corvera, 1994; Escalera and Ricaldi, 1985; Escalera, 1984; Espinoza, 1985; FAO, 1990; Hanke, 1983; Hincosa, 1983; IFDC, 1979; León, 1994; León and Arregocés, 1987; León and Hammond, 1983; MACA-FAO, 1992; Martínez, 1987; Martínez and Appleton, 1994; Proyecto Fertisuelos, 1998; Quiton et al., 1983; Ricaldi and Escalera, 1984a; Ricaldi and Escalera, 1984b; Rico et al., 1987; Rico et al., 1988; Rodríguez, 1989; Saif, 1983; Salinas, 1983; Terra, 1992; Villarroel, 1985a; Villarroel, 1985b; Villarroel and Augstburger, 1983a; Villarroel and Marvel Navia, 1989; Villarroel and Augstburger, 1983b)

# Brazil



## *Location, Quantity, Quality*

Phosphate deposits of both sedimentary and igneous origin have been discovered in many parts of Brazil, mainly as a result of detailed exploration by the Departamento Nacional da Producao Mineral (DNPM), frequently in collaboration with other State and commercial organizations, and Universities. Most of the resources occur in apatite-rich residual deposits overlying carbonatite complexes, with less significant amounts in sedimentary phosphate rock and aluminium phosphate deposits. Small deposits of phosphatic guano and phosphatised bedrock occur on a few islands off the coast of Brazil

## Precambrian

Precambrian sedimentary phosphate rock deposits were first discovered near Abaeté, about 140 km southeast of Patos de Minas in Minas Gerais State. Subsequently, large deposits of yellow and red, silty and sandy pelletal phosphate rock were discovered 55 km northwest of Patos de Minas. These occur as irregular lenses up to 500 m long and 8 m thick within a 3 km long NE-SW trending belt of folded and faulted Bambui Group rocks. The mineralized zone is about 400 m wide at the Rocinha mine, and has a northeast lateral extension of about 10 km. The surface weathered ore zone is about 30-40 m thick. At Rocinha, francolite is the principal phosphate mineral and this occurs predominantly as fine-grained crystals or pelletal aggregates in a generally argillaceous material. The francolite aggregates are very fragile and easily broken, which causes ore processing problems. Precambrian phosphate rock is also mined at Lagamar, close to Patos de Minas. Additional resources occur at Cerro do Abaete, about 150 km SE of Rocinha. Lenticular beds of phosphorite occur in the lower part of the Sete Lagoas Formation at



Formosa, Cabeceiras, Nova Roma, Campos Belos and Monte Alegre, lying 300 to 600 km N of Rocinha, in Goiás State (Notholt, 1994a).

### Cretaceous

Upper Cretaceous sedimentary phosphate rocks have been exploited near Recife in Pernambuco State, in northeastern Brazil. The gently dipping, discontinuous, phosphate rock beds occupy a narrow strip along the coast from Recife northwards. Near Olinda (Paulista), the phosphate beds are from 20 cm to 3.9 m thick, averaging about 2 m. They comprise a yellowish-white, friable rock with 25 to 30%  $P_2O_5$ , or a grey, hard variety containing only 6 to 8%  $P_2O_5$ . The phosphorite contains 0.008 to 0.016%  $U_3O_8$ . To the south, similar sedimentary rocks occur in Sergipe State, and the occurrence of Upper Cretaceous phosphatic limestone in Bahia State, northeast of Feira de Santana, suggests that the phosphate facies may extend from Pernambuco into the Reconcavo coastal sedimentary basin. The deposits formerly worked near Recife are generally less than 4 m thick. Drilling revealed reserves of about 45 million tons near Olinda, with grades ranging from 6 to 22%  $P_2O_5$ . Additional resources of 4.8 million tons averaging ranges from 15 to 22%  $P_2O_5$  in a phosphate bed up to 1.2 m thick have been discovered in the vicinity. The overburden usually does not exceed 21 m but may reach 42 m. Total resources in the phosphate-bearing area north of Recife amount to about 50 million tons of all grades of rock, of which 11 million tons are considered suitable for open pit mining (Notholt, 1999).

### Aluminium phosphates

In the northern part of Maranhao State, iron and aluminium-rich phosphate deposits produced by lateritic weathering occur on Trauira and Pirocaua, two of a number of low-lying hills surrounded by mangrove swamp. The two deposits are similar in size and total reserves with 20-30%  $P_2O_5$  were estimated in 1958 to be about 20 million tons. Trauira (1°25'S, 45°30'W), lies near the mouth of the Maracacume River, some 25 km E and slightly N of Pirocaua. It comprises 5 to 7 m thick surface layer of heterogeneous phosphatized ironstone with concretions of partly phosphatized iron oxide, all cemented by aluminium phosphate, which is also a major constituent of the underlying 1 to 2 m of spherulitic phosphate. The superficial deposits contain up to 28%  $P_2O_5$ , 44%  $Al_2O_3$  and 48%  $Fe_2O_3$  but are unlikely to become economically important because of their inaccessible location. Agricultural tests carried out between 1950 and 1952 by the *Instituto de Ecologia e Experimentacao Agricolas* showed that a mixture of calcined phosphate and lime could be applied usefully to the soil as fertilizer (Notholt, 1999).

Iron-aluminium phosphates occur on the islands of Rata and Meio at the northern end of the Fernando de Noronha group of islets. Most of Rata (3°49'S, 32°25'E) is composed of phonolite and ankaratrite, with a covering of coral limestone on the southern side of the island. Extensive alteration of these rocks has produced a layer ranging from a few inches to nearly 7 ft in thickness. Reserves were estimated at nearly 473,000 tons, assuming an average thickness of about 3 ft, containing 28%  $P_2O_5$ . On Meio, situated south-west of Rata, phosphate ore contains 7 to 18%  $P_2O_5$ . Reserves on both islands were estimated to total 600,000 to 700,000 tons averaging 18%  $P_2O_5$  (Notholt, 1999).

### Igneous phosphate deposits

Almost all the economically important phosphate resources are located in the southern part of Brazil, of which the alkaline-carbonatite igneous complexes and, particularly their weathered derivatives are the most important. More than 20 Cretaceous-Lower Tertiary carbonatite complexes collectively contain large reserves of Nb, P, Ti and REE. The most important phosphate deposits are in lateritic soils developed by post-Tertiary weathering on the Catalao I intrusion, situated in southern Goiás State in the municipalities of Catalao and Ouvidor, about 15 km ENE of Catalao. The lateritic soils in some areas reach 250 m in thickness although they are generally average 30 m, with enrichments in phosphate, titanium, niobium, rare earths and vermiculite. Drilling has demonstrated that the Catalao I complex consists mainly of rocks composed almost entirely of biotite mica (biotitite), together with restricted amounts of serpentinised ultra-basic rocks such as peridotite and pyroxenite (Notholt, 1994a).

Intensive weathering of carbonatite has produced a thick, red-brown residual mantle at Barreiro do Araxa, about 8 km south of Araxa that is worked for pyrochlore (niobium) and apatite (phosphate) at two separate locations. Apatite-rich carbonate-phlogopite-apatite-magnetite rocks occur in the central part of the complex, which is about 4.5 km in diameter and intrudes metamorphic rocks of the Middle Precambrian Araxa Group. The residual mantle has a highly variable composition that reflects the composition of the underlying rocks. An upper zone of granular or earthy material contains up to 10% apatite, 6% pyrochlore, 35% magnetite, 42% limonite and 21% barytes. Proven reserves of 15%  $P_2O_5$  apatite ore are about 116 Mt (Notholt, 1994a).

Residual lateritic soils 30 m in thickness mantle the Tapira Carbonatite Complex, located about 35 km south of Araxa. The Tapira carbonatite complex is almost circular, about 6 km in diameter, and mainly comprises diopsidic pyroxenites, with minor amounts of calcite carbonatite (sövite), secondary quartz-rich rock (silexite), and peridotite. Fresh apatite-bearing carbonatite is overlain successively by weathered carbonatite, apatite (P) – anatase (Ti) ore, anatase ore, and a clayey cap. The complex, which is also exploited for its titanium resources, contains the largest resources of phosphate rock in Brazil (Table 1) based on a cut-off grade of 5%  $P_2O_5$ .

The Jacupiranga Igneous Complex, situated 13 km west of Jacupiranga in Sao Paulo State, was the first hard-rock carbonatite to be worked commercially for apatite. The complex is an oval-shaped, almost vertical, plug and underlies an area of about 65 km<sup>2</sup>. The core of the carbonatite complex contains approximately 12% apatite (5%  $P_2O_5$ ), 71% calcite and 7% dolomite and is mined in the southern part of the complex over an area of about 1,000 x 300 m (Notholt, 1994a).

#### Apatite vein deposits

Lenses and veins of apatite in pegmatites cutting Precambrian marbles and mica schists occur in central Paraíba State, where the Sume deposits were discovered in 1943. At Sume, apatite veins occur to depths of 50 m with thicknesses generally ranging from a few centimetres to about 1.2 m. Measured and inferred reserves were estimated at 250,000 tons, of which about one-third averages 38%  $P_2O_5$  (Notholt, 1999).

#### *Production*

By far the most important source of supply is Brazil, based on six producers. The highest level of output is derived from the Tapira deposits, Minas Gerais, which have been worked by open-pit methods since 1979. Production capacity is some 1.1 Mtpa of concentrate averaging 35%  $P_2O_5$ , the product being carried by 120 km slurry pipeline to a fertilizer plant at Uberaba. About 50 km to the north, the Araxa deposits have been worked since 1960 to produce two concentrates with 34% and 36%  $P_2O_5$  respectively. These products are also consumed in fertilizer manufacture, but small quantities of lower grade crushed rock are used for direct application to the soil and in the manufacture of thermophosphates. High grade apatite concentrates are also produced from the Catalao I igneous complex in Goiás State, and the Jacupiranga complex in Minas Gerais has the distinction of being the first primary carbonatite to be worked commercially as a source of PR. Carbonatite averaging nearly 5%  $P_2O_5$  is mined to yield about 575,000 tpa of concentrate grading over 35%  $P_2O_5$  for use in fertilizer manufacture. High-purity calcium carbonate (calcite) obtained as a co-product is used in cement manufacture. There has been some limited output from the Patos de Minas area, where the Rocinha mine came into operation in 1976, followed in 1983 by a second mine, Lagamar, situated further to the northwest. An output of around 200,000 tpa grading 25-30%  $P_2O_5$  has been achieved from the Patos de Minas area. The deposits at Olinda (Forno da Cal) were opened in 1955 when production reached nearly 1 million tons ore per annum containing 22.6%  $P_2O_5$ . The ore was beneficiated to produce two grades of concentrate with 33-35%  $P_2O_5$  and 24-25%  $P_2O_5$ ; the former was used for superphosphate manufacture and the latter was blended with the higher-grade phosphate to provide a product containing 28-30%  $P_2O_5$  for direct application to the soil. It is reported that operations ceased at the end of 1967 in the face of competition from rock imported from the USA (Notholt, 1999). However, Olinda was one of the phosphate rock mines reported to be in

operation in 1991. The others were Patos de Minas (Rocinha), Lagamar, Catalao, Araxa, Tapira, Jacupiranga and Anitapolis (Anderi and Scheid, 1991). Most of the production came from six mines in 1986. By 1999, 95.6% of the total production (4.1 Mt) came from four companies operating two mines at Araxa, two at Tapira and one at Catalao (Ouvidor) (Table 7).

Several apatite pegmatite deposits in the Sume district were worked on a small scale since the Second World War and the phosphate rock was transported to Ibura on the outskirts of Recife for use by the *Empresa de Productos Quimicos e Fertilizantes (Profertil)* in the manufacture of superphosphate. The average grade of the rock formerly mined was about 32%. Production since 1955 did not exceed 1,000 tons per annum and no production was recorded after 1961.

A few cargoes of iron-aluminium phosphate with 28% P<sub>2</sub>O<sub>5</sub> are reported to have been apparently shipped from Rata Island during the First World War (Notholt, 1999).

Table 7. Production capacity of phosphate rock miners in Brazil (1986 and 1999)

Deposit	P <sub>2</sub> O <sub>5</sub> content (%)	Production capacity (x 1000t phosphate rock) 1999*	Production capacity (x 1000t) 1986**	
			(concentrates)	P <sub>2</sub> O <sub>5</sub>
Jacupiranga	36	?	680	245
Araxá	36	5,000	900	324
-ditto-	28	5,000	50	14
-ditto-	24	?	200	48
Catalao I (Ouvidor)	38	4,400	525	237
Catalao II	38	?	958	363
Tapira	35	10,500	1100	396
Patos de Minas (Rocinha)	24	?	192	46
Lagamar	33	?	150	50

Source: \* USGS Minerals Yearbook 1999; \*\*Lobo, 1986 in Anderi (1991)

*Sources:* (Alba et al., 1983; Albuquerque and Giannerini, 1981; Angeiras, 1988; Angeiras et al., 1981; Anon., 1981; Anon., 1987a; Aps and Born, 1975; ArrudaNeto et al., 1997; Avila Vergara Valmor, 1979; Barbour, 1973; Barron, 1982; Berbert, 1984; Beurlen, 1995a; Beurlen, 1995b; Bhaskara, 1984; Boggiani et al., 1998; Born, 1989a; Born, 1989b; Born and Kahn, 1993; Born et al., 1996; Brajnikov, 1951; Brandao et al., 1994; Carvalho et al., 1970; Cassedanne and Cassedanne, 1976; Castro, 1968; Cathcart, 1974; Cathcart, 1976; Cathcart, 1978; Cathcart, 1979; CBMM, 1984; Cerqueira de Rezende et al., 1982; Coelho et al., 1987; Cook and Shergold, 1982; Costa, 1997; Costa et al., 1991a; Costa et al., 1991b; Cruz et al., 1976; Da Costa et al., 1989; Da Costa and Sa, 1980; Da Rocha Araujo et al., 1992; Damasceno, 1989; Dardenne et al., 1986; Dasilva et al., 1984; De Albuquerque and De Araujo, 1981; De Albuquerque and Giannerini, 1979; De Albuquerque and Giannerini, 1989; De Araujo et al., 1981; De Araujo Sa and De Gildo, 1976; de Barros et al., 2001; De Carvalho, 1974; De Carvalho and Bressan, 1989; De Carvalho and De Araujo, 1974; De Lima, 1976; De Lucena, 1992; De Oliveira et al., 1982; De Oliveira and Imbernon, 1998; Favali et al., 1984; Felicissimo, 1978; Ferraz, 1999; Ferreira et al., 1979; Flicoteaux and Melfi, 2000; Fukuma et al., 2000; Gabe and Rodella, 1999; Gomes, 1984; Goudarzi et al., 1971; Goudarzi et al., 1974; Goudarzi et al., 1972; Guimaraes, 1946; Guimaraes, 1967; Guimaraes and Peres, 1999; Horita, 1993; Jager and Feitosa, 1978; Jago and Gittins, 1991; Kamitani and Hirano, 1990; Kegel, 1954; Kegel, 1955; Knecht, 1948; Kyle and Misi, 1991; Kyle and Misi, 1997; Ladeira, 1972; Leal et al., 1984; Leal et al., 1993; Lessa and Guimaraes, 1975; Loureiro, 1980; Macambira, 1978; Maciel, 1952; Martins and Marquez, 1983; Melcher, 1966; Mendonca et al., 1980; Menor et al., 1979; Menor et al., 1999; Milliman and Amaral, 1974; Misi, 1992; Misi and Kyle, 1994a; Misi and Kyle, 1994b; Misi and Veizer, 1998; Nader et al., 1989; Netto, 1984; Netto et al., 1991; Netto and Upadhyay, 1984; Notholt, 1994a; Porphirio and Vidal, 1987; Rao and Netto, 1985; Rolff, 1975; Sa et al., 1984; Saad et al., 1997; Sad and Torres, 1978; Sameshima and Yamamoto, 1995; Savage, 1987; Schwab et al., 1983; Sobrinho, 1949; Soubies et al., 1990; Soubies et al., 1991; Tenorio, 1983; Tenorio, 1984; Toledo and Suslick, 1993; Traversa et al., 2001; Valente, 1980; Veiga and Couto, 1981; Waber et al., 1992; Walter et al., 1995; White, 1958) of which the key sources are:

(Anderi and Scheid, 1991; Born, 1989a; Born, 1989b; Cathcart, 1979; CBMM, 1984; Damasceno, 1989; Dardenne et al., 1986; De Carvalho and Bressan, 1989; Notholt, 1994a; Rao and Netto, 1985; Savage, 1987; Tenorio, 1983; Tenorio, 1984).

### *Agronomic testing and use*

Most of Brazilian soils, especially those in the "cerrado" region, have extremely low levels of total and available phosphorus (P) for cultivated crops and also have high P fixation capacity caused by clays and iron oxides. As a consequence of this, phosphate fertilizer has to be applied at high rates in order to obtain adequate crop yields from these soils. Scheid et al. (1991) reviewed available data for agronomic trials and concluded that :

1. Brazilian rock phosphates in general, present low solubility and low agronomic efficiency for annual crops. Their use is justified only for acid tolerant pasture species formation and for certain perennial crops (coffee, citrus) and reforestation with species such as *Eucalyptus*. Recent data indicate that the less soluble Brazilian phosphate rocks, such as Araxá, can substitute for more soluble sources if the *Eucalyptus* growth period is at least 3 years. The best yields are obtained from a combination of broadcast low solubility rock phosphates and more soluble sources at the planting site. In the case of sandy soils, more soluble sources are more efficient.
2. Even if the positive industrial aspects of partially acidulated rock phosphates are taken into account, these products will only be viable for annual crops if the costs for the farmer are established as a function of the soluble  $P_2O_5$  fraction. Partially acidulated rock phosphates, however, can be adequate for pastures and perennial crops.
3. Thermophosphates represent an excellent agronomic option for most acid soils of the Brazilian "cerrado", justifying increases in production in Brazil.
4. The traditional soluble sources (superphosphate and ammonium phosphates) are highly efficient and justify their production.
5. Long-term field experiments (10 or more years) have shown cumulative absorption of applied soluble phosphorus to the order of 60 to 70%. This indicates that phosphorus fixation problems are minimized with cropping time.
6. Considering the diversity of soils, climates and crops in the Brazilian agriculture, it is valid to produce and commercialize several kinds of phosphate fertilizer in Brazil.
7. The agronomic efficiency of phosphate fertilizers produced in Brazil for annual crops is, in general, proportional to the percentage of soluble  $P_2O_5$  in relation to total  $P_2O_5$ .
8. The agronomic efficiency of phosphate fertilizers produced and commercialised in Brazil is much more a function of adequate soil and crop management than change in industrial technology. In the specific situation of water soluble phosphorus fertilizers, the use of small rates of lime per hectare is one serious limiting factor to increase the agronomic efficiency of these products (Scheid et al., 1991)

### Annual crops (soya, rice, beans and cassava)

Since 1989, unground reactive rock phosphates from Gafsa and Arad have been sold in the Brazilian fertilizer market for use as direct application fertilizer on acid, P-deficient Brazilian soils. About 300 thousand tonnes reactive rock phosphates were sold in 2000. Trials with Daoui rock phosphate from Morocco were carried out to test its reactivity compared to other traditional reactive rocks (Gafsa and Arad) and TSP (Horowitz and Simões Maçãs, 2001). Two different trials were conducted over 7 years in different regions of Brazil using a range of annual crops. Due to the P deficiency of the soils in the two trials, the addition of P fertilizer increased the yields of annual crops for all the cultivations. For the first trial, the agronomic efficiency was similar for all P sources (superphosphate, Daoui rock phosphate, Gafsa rock phosphate and Arad rock phosphate). In the second trial, triple superphosphate had the highest yields in comparison to all sedimentary rock phosphates (Gafsa, Daoui and Arad) in the first two cultivations. For the last two cultivations, all the sources had the same efficiency. Horowitz and Simões Maçãs (2001) concluded that Daoui rock phosphate can be considered an efficient source of P and that its agronomic performance is similar to that of the Gafsa and Arad rock phosphates.

Coutinho et al. (1991) evaluated the agronomic efficiency of phosphate fertilizers for soybean production on dark-red latosol in Sao Paulo State using four phosphates fertilizers (triple superphosphate, fused magnesium phosphate, granulated Gafsa rock, and Patos de Minas rock phosphate), applied at rates of 100 and 200 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub>. Fertilization with phosphorus resulted in increased grain yield and in the soil and plant P contents. The efficiency of the P sources decreased in the sequence triple superphosphate, fused magnesium phosphate, Gafsa granulated rock phosphate and Patos de Minas rock phosphate. The efficiency of the Gafsa granulated rock phosphate was considerably higher when the residual effect of the second year was considered, whereas Patos de Minas rock phosphate was not an efficient source of phosphorus for soya. Fused magnesium phosphate did not modify significantly the pH value and Ca and Mg contents of the soil and plant leaves.

Fageria et al. (1991) conducted a field experiment for five consecutive years to determine the response of upland rice (*Oryza sativa* L.) and common bean (*Phaseolus vulgaris* L.) to eight P sources applied at three rates to an Oxisol in Central Brazil. The P sources tested were triple superphosphate (TSP), Arafertil partially acidulated phosphate (APAP), partially acidulated Patos phosphate rock (PAPPR), Araxa phosphate concentrates (APC), Catalao rock phosphate (CRP), Jacupiranga rock phosphate (JRP), Patos de Minas rock phosphate (PMRP), and Abaete rock phosphate (ARP). P application rates used were 87, 174 and 262 kg P ha<sup>-1</sup>. Yield response to P sources and rates varied from crop to crop. Rice and bean yields were significantly correlated with Bray 1 P, but not Mehlich 1 P. In the first year, TSP and the two partially acidulated phosphate rocks (APAP, PAPPR) produced higher grain yields. In the second and all remaining years of the experiment, the efficiency of phosphate rock sources as measured by grain yield was equivalent to TSP or partially acidulated P sources. The results suggest that these phosphate rock sources could be used in rice-bean rotations on Brazilian Oxisols. Fageria et al. (1991) concluded that yield losses in the first year could be partially offset by the addition of a small amount of soluble P.

Nogueira et al. (1992) studied the influence of rock phosphate and gypsum application on cassava grown on clayey textured, dark red latosol. 0, 1000, 2000 and 3000 kg/ha of Araxa rock phosphate and 0, 500, 1000 kg ha<sup>-1</sup> of gypsum were applied in May 1986. *Crotalaria* was planted without fertilizers about 45 days later and incorporated into the soil by a disk plough at the beginning of the pod stage in February 1989. Sixty days after green manure (*Crotalaria*) incorporation the sub-plot soil samples were chemically analysed. *Cassava* (*Manihot esculenta*), IAC 12829 cultivar, was planted in 15 November 1987 and harvested in May 1989. Leaf surface and petiole nutrient contents were determined, and the root and shoot yield, harvest index, plants height were evaluated. Green manure, gypsum and rock phosphate affected the yield and yield components, and also the soil chemical characteristics. The results indicated that these low cost soil amendments and green manure could be used to provide enhanced cassava yields.

### Pasture

Couto et al. (1991) assessed the response of *Andropogon* grass to P fertilizers and lime in a dark-red Latosol of the Cerrado region. The effect of P applied at establishment, from two P sources and three annual fertilization rates were investigated at two lime levels in a virgin clayey Haplustox. Lime reduced the amount of P needed to produce 2000 kg/ha of forage dry matter from 180 to 78 P kg ha<sup>-1</sup>. Forage yield obtained with a rock phosphate RP improved on time reaching similar yield than with same level of P applied as triple superphosphate (TSP) in the fourth year. The initial P rate of 52 P kg ha<sup>-1</sup> applied as TSP was high enough when lime was also applied. Higher P rates improved first and second year productivity only. Check plots receiving 13 or 26 P kg ha<sup>-1</sup> annually produced higher forage yields by the third year than plots receiving the highest initial P rate.

The agronomic and economic effectiveness of a commercial source of partially acidulated rock phosphate (PARP) was evaluated over 25 months on a forest soil in the Amazon region using the forage grass *Brachiaria brizantha* cv. *Marandu* as the test crop. The PARP had 46% of the total P<sub>2</sub>O<sub>5</sub> soluble in neutral ammonium citrate + water, and single superphosphate (SSP) was used as the control fertilizer. Both fertilizers were applied at the rates of 50 and 100 kg ha<sup>-1</sup> total P<sub>2</sub>O<sub>5</sub> and compared with a control (0 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub>). The average PARP agronomic efficiency, calculated from the total P uptake, was 64%, and no increase was observed between the first and the last observation periods. The PARP proved to be less economical than the SSP to produce the same forage yields. Total P<sub>2</sub>O<sub>5</sub> content of PARP should not be

considered when using it for the fertilization of *B. brizantha* pasture - the amount of soluble  $P_2O_5$  is a more appropriate guide to fertilizer efficiency (Dias and Neto, 1992).

Two pot experiments were conducted in a greenhouse to evaluate the effects of phosphorus sources, lime and gypsum applications on dry matter production and tillering of *Brachiaria brizantha* cv. *Marandu* and *Andropogon gayanus* cv. *Planaltina* in a Latossol variant Una (Oxisol) (Passos et al., 1997). Treatments included five P sources: Triple Superphosphate, Yoorin Magnesian Thermophosphate, Partially Acidulated Araxa Rock Phosphate, Araxa Rock Phosphate and Control (without P); and three types of soil correction: no liming, liming and liming plus gypsum. Six cuttings of forage were made during 258 days after emergence. The results showed that in the absence of gypsum, even with the application of lime, the Araxa Rock Phosphate and Yoorin Magnesian Thermophosphate produced less dry matter than the Partially Acidulated Araxa Rock Phosphate and Triple Superphosphate. The combination of Yoorin Magnesian Thermophosphate with lime and gypsum resulted in the highest dry matter production by the forage grasses. Liming tended to increase dry matter production of *Brachiaria brizantha*, while this effect varied for *Andropogon gayanus* as a function of the P sources. The tillering of *Brachiaria brizantha* was less affected by P sources. For *Andropogon gayanus*, the application of Araxa Rock Phosphate and the Yoorin Magnesian Thermophosphate, in the absence of liming, resulted in the highest number of tillers only after the first cutting.

Rossi et al. (1997) studied the effect of liming and phosphorous sources in the production of *Brachiaria brizantha* and critical levels of phosphorus in a sample of an Oxisol (Latosol) from Campos das Vertentes (MG). The experiment was conducted in a greenhouse in pots. The experimental design was completely randomised in a 2 x 5 x 4 factorial arrangement with three replications and two phosphorus sources (Triple Superphosphate - TS and Araxa Rock Phosphate - ARP), five levels of P (50, 150, 300, 500, and 700 mg P/dm<sup>3</sup> soil), and four limestone levels (0, 1/2, 1, and 2 times the level necessary to elevate the base saturation to 50%, with level one corresponding to 1.6 t of lime per ha). Five cuttings were made during a 243-day period after emergence. The *Brachiaria brizantha* grown in this soil responded to the application of P and limestone, indicating that both are needed to attain adequate production of this forage. For dry matter production, the levels of limestone corresponding to 1.6 t ha<sup>-1</sup> with TS, and 0.8 t/ha with ARP were the most efficient. The critical levels of P in the soil and in the plant varied as a function of the extractors, P sources, and limestone levels.

Soares et al. (2000) evaluated the use of coarse-ground Gafsa rock phosphate (GRP) in the recuperation of a degraded *Brachiaria decumbens* cv. *Basilisk* pasture on a clayey dark-red latosol (Haplustox) of the Cerrado in the Federal District, Brazil. GRP was compared with triple superphosphate (TSP) at a  $P_2O_5$  rate of 100 kg ha<sup>-1</sup> both applied by broadcasting. A control treatment without P was included together with two other variables: (1) incorporation of the phosphate with and without a harrow; and (2) supplementary fertilization (SF) with Ca, Mg, N, K, S and micronutrients (presence and absence). The response to phosphate application was only observed with the simultaneous application of SF; incorporation was essential for increasing the efficiency of GRP; with incorporation, the efficiency of GRP was equal to that of TSP; without incorporation, TSP was significantly superior to GRP ( $p < 0.05$ ).

### Trees (Eucalyptus, rubber)

Venturin et al. (1995) evaluated the effects of Araxá rock phosphate, lime and gypsum on rubber seedlings under greenhouse conditions on the growth and macronutrient uptake by rubber tree seedlings (*Hevea sp.*) grown in a very clayey, dark red latosol from the "Cerrado" region. Five phosphate levels (5, 50, 100, 150, 200 kg/ha  $P_2O_5$ ) were tested in combination with five combinations of lime and gypsum (no gypsum and no lime, 100% lime, 33% lime + 67% gypsum, 67% lime + 33% gypsum and 100% gypsum). None of the lime and gypsum combinations affected plant height or diameter; combinations of lime and gypsum had no effect on dry matter yield, but they were superior to lime or gypsum applied separately. The trial did not appear to indicate any significant response to the Araxá phosphate rock.

Dias et al. (2000) evaluated the effect of different placement and rates of two phosphorus (P) fertilizers on P-availability by three methods of extraction, nine years after application to a Brazilian Oxisol cultivated with *Eucalyptus camaldulensis*. Single superphosphate (SSP) and Araxá rock phosphate (ARP) were tested in three rates (100, 200, and 400 kg ha<sup>-1</sup> of  $P_2O_5$ ). Each fertilizer was either (1) surface-applied in bands (0.6 m either side of the rows of trees) and incorporated before planting or (2) incorporated into furrows (0.2 m deep in the tree rows) before planting. As additional treatments, the combination of ARP (96 kg ha<sup>-1</sup> of  $P_2O_5$  applied in broadcast, or bands, or in furrows) + SSP (54 kg ha<sup>-1</sup> of  $P_2O_5$  localized in the planting hole before planting) were tested. Soil sub samples from two layers (0-15 and 25-40 cm) were taken from each plot (from the planting rows or between the planting rows) and analysed for pH in water (1:2.5), available P by Mehlich-1, Bray-1 and anionic resin, exchangeable Ca, and Al by 1 mol L<sup>-1</sup> KCl. For both methods of fertilizer placement, the highest values of available P were observed in the surface soil and in the planting row, and were strongly related to fertilizer rate. Samples taken between the planting rows did not exhibit treatment effects on available P. The higher values of available P obtained with Mehlich-1 and the lower eucalyptus plant uptake efficiency of fertilizer-P from banded RP confirms that this extractant can overestimate the availability of P in soils receiving ARP. The use of anion exchange resin in this situation to estimate available P is confirmed. The results obtained with the localized application of ARP indicate that root system activity (i.e. P and Ca uptake and acidification of rhizosphere) as a factor in increasing fertilizer dissolution rates.

Fernandez et al. (2000) evaluated the response of *Eucalyptus camaldulensis* to different sources, rates and placement of phosphate fertilizers on an oxisol in the northwest of Minas Gerais State. Araxá rock phosphate (ARP) and single superphosphate (SSP) at rates equivalent to 100, 200 and 400 kg ha<sup>-1</sup>  $P_2O_5$ , were applied in bands (1.2 m of width in the soil surface) or in furrows (0.2 m deep in the tree rows). In addition, a combination of ARP (96 kg ha<sup>-1</sup>  $P_2O_5$ ), in furrows, or in bands, or broadcast, with SSP (54 kg ha<sup>-1</sup>  $P_2O_5$ ) placed in the planting holes was also evaluated. The treatments were evaluated 9.5 years after planting by measuring the biomass and nutrient contents in the tree shoots, and litter. Fertilizer application increased tree stem volume and overall biomass compared to control plots with no-phosphate fertilizer. ARP and SSP produced better results when they were applied in furrows leading to enhanced absorption of P by the plants and increases in dry matter production. Fertilizer placement in furrows resulted in the highest plant uptake rate of the P fertilizers applied. The combination of SSP placed in the planting hole, with ARP applied in the furrow, produced the highest stem volume and shoot dry matter, emphasizing the influence of the initial fertilization on the final yield. The trials demonstrated that the combined use of low and high solubility forms of P fertilizer in a localized placement effectively deals with the high initial demand of P by the seedlings and also provides a long term P source that permits high productivity (Fernandez et al., 2000).

*Sources:*(Afif et al., 1995; Agbenin and Tiessen, 1994; Agbenin and Tiessen, 1995a; Agbenin and Tiessen, 1995b; Alagawadi and Gaur, 1992; Araujo and Dealmeida, 1993; Araujo et al., 1992; Cabala-Rosand and Santana, 1983; Cabala-Rosand and Wild, 1982a; Cabala-Rosand and Wild, 1982b; Carvalho and van Raij, 1997; Coutinho et al., 1991; Couto et al., 1991; Cox, 1994; Da Silva and Van Raij, 1999; De Mesquita Filho and Torrent, 1993; Dias et al., 2000; Dias and Neto, 1992; Diederichs, 1991; Dynia and Camargo, 1998; Ernani and Barber, 1991; Fageria et al., 1991; Fageria et al., 1997; Faquin et al., 1997; Fernandes et al., 2000; Fernandez et al., 2000; Ferreira and Tiessen, 1995; Fontes, 1995; Fontes and Weed, 1996; Fontes et al., 1992; Franco and DeFaria, 1997; Gatiboni et al., 2000; Goedert et al., 1990; Goedert et al., 1987; Guerra et al., 1995; Hammond, 1991; Henry et al., 1985; Hughes and Gilkes, 1986; Hughes and Le Mare, 1982; Kronberg et al., 1986; Kumar et al., 1993; Le Mare, 1982; Le Mare, 1991; Le Mare and Hughes, 1982; Le Mare and Leon, 1990; Le Mare et al., 1987; Lenharo et al., 1993; León et al., 1986; Lessa and Anderson, 1996; Lilienfein et al., 2000; Lueken et al., 1982; Manhaes, 1993; McGrath et al., 2000;

McGrath et al., 2001; Melgar et al., 1998; Nahas, 1996; Nahas and Deassis, 1992; Nakagawa et al., 1993; Neufeldt et al., 2000; Nogueira et al., 1992; Oliveira et al., 1982; Passos et al., 1997; Peixoto et al., 1987; Peruzzo et al., 1994; Prochnow et al., 1997; Prochnow et al., 1998; Rodriguez and Fraga, 1999; Rossi et al., 1997; Salcedo et al., 1991; Scheid et al., 1991; Silva et al., 1997; Silva et al., 1988; Soares et al., 2000; Stamford et al., 1997; Tiessen et al., 1993; Tiessen et al., 1992; Urquiaga et al., 1982; Venturin et al., 1995; Vidal, 1987; Vidal, 1988; Wright et al., 1992) (Scheid et al., 1991)

## Chile



### *Location, Quantity, Quality*

Phosphate rock resources in Chile occur in three types of deposits: (i) Tertiary sedimentary rocks (phosphorites), (ii) apatite veins and (iii) accumulations of guano (Salas, 1985).



### Tertiary

Miocene-Pliocene sedimentary phosphate rocks are contained principally in three deposits: Mejillones (54 Mt 7%  $P_2O_5$ ), Caldera (15 Mt 18%  $P_2O_5$ ) and Tongoy (approximately 15 Mt and 15 to 18 %  $P_2O_5$ ). On the Mejillones Peninsula a mudstone unit near the top of the Miocene Caleta Herradura Formation includes phosphatic sandstone which is 3m to 5m thick and contains 6% to 7%  $P_2O_5$ . In the Bahia Inglesa-Caldera area a phosphorite bed ranges from 0.2 m to 3 m in thickness and outcrops over an area of 15 km<sup>2</sup>. Resources have been reported to range between 15 Mt with 18%  $P_2O_5$  to nearly 88 Mt with 7-17%  $P_2O_5$ , with about 5 Mt contained in a single bed averaging 16.3%  $P_2O_5$  and 61 ppm mg/kg. A deposit of low-grade phosphatic oolitic sandstone estimated to contain some 5-6 Mt is located at Tongoy, about 65 km south of La Serena. Whereas the main phosphate bed covers 405 km<sup>2</sup>, it is only about 0.6m thick and is locally covered by about 80 m of Quaternary sediments. In contrast, Notholt (1999) reported that the Tongoy-Guanaqueros deposits cover an area of only approximately 50 km<sup>2</sup> with the phosphate rock beds containing an average of only 7.2%  $P_2O_5$ . Additional Miocene phosphate rock deposits at Bahia Salado include a bed of concretionary phosphorite 0.4 m thick with 13-22%  $P_2O_5$ . Resources are estimated at 30 million tonnes averaging 17%  $P_2O_5$  (Notholt, 1999; Salas, 1985).

### Apatite veins

Apatite veins and lenses occur at many localities in the provinces of Coquimbo and Atacama, in northern Chile. The apatite deposits are thought to have a pneumatolytic or high-temperature hydrothermal origin and occur in dioritic and gabbroic rocks within a coastal belt about 160 miles long and up to 12 miles wide between Pueblo Hundido, southeast of Taltal, and south of Coquimbo. The veins and lenses generally vary from less than 1 m to approximately 10 m in length and in rare cases exceed 500 m. The veins and lenses are generally less than 4 m wide and comprise chlorapatite associated with magnetite, amphibole, and sericitic mica. The most important occurrence is at La Serena. A typical sample of vein phosphate rock contains 28%  $P_2O_5$ , 37% CaO, 9% SiO<sub>2</sub>, 2% Al<sub>2</sub>O<sub>3</sub>, 18% Fe<sub>2</sub>O<sub>3</sub>, 5% Cl, and traces of MgO and CO<sub>2</sub>. Total reserves were estimated at 2.5 million tons grading 25-28%  $P_2O_5$  and an additional 3 million tons with 10-12%  $P_2O_5$  (Notholt, 1999).

### Guano

Extensive deposits of phosphatic guano, similar to those of Peru, occur along the northern coast of Chile. In Tarapaca and Antofagasta provinces numerous deposits of phosphatic guano are associated with low-lying hills that were formerly islands. Guano has accumulated in wave-cut gullies, as well as covering the lower slopes, and in places attains a thickness of 20 m. Red, highly leached or 'fossil' guano (*guano roco*) is the most valuable phosphatic material and this has been used on cereal crops such as wheat. It is reported to contain an average of 18-20%  $P_2O_5$  and less than 2% N and K<sub>2</sub>O. Total reserves of red guano grading 18%  $P_2O_5$  are estimated at 1 million tons, with a further 500,000 tons grading less than 15%  $P_2O_5$ . Nine of the more important guano deposits contain between 12,000 and 70,000 tons, while on the elevated plateau of syenite and granite comprising the Mejillones Peninsula north of Antofagasta, reserves have been estimated at 400,000 tons of which 300,000 tons was considered to be of commercial grade. Guano deposits in the vicinity of Mejillones have an average thickness of nearly 6 m and are more leached than those found elsewhere on the Chilean coast, being characterized by the occurrence of magnesium, iron and aluminium phosphates (Notholt, 1999).

### *Past Production*

Most of the former production of the apatite vein deposits came from deposits in the mountainous terrain near La Serena, Coquimbo Province, where at least 16 deposits have been recorded, many containing 28-30%  $P_2O_5$ . Composite samples of apatite rock showed 26.3%  $P_2O_5$  and 4.8% Cl. The chief source was the Los Fosiles vein, located in a porphyry diorite about 12 miles south of La Serena and 3 miles west of the Longitudinal Railway. The vein is over 1.5 km long and up to 5 m wide, with an average width of 1 m. The apatite deposits were worked on a small scale from about 1936 until 1966. The Los Fosiles vein

in Coquimbo Province, was worked to a depth of about 200 m with an annual output of about 30,000 tons.

In southern Atacama Province, at least 14 vein deposits containing 18-30%  $P_2O_5$  were formerly worked, the principal sources being those of Arrayán, Las Lajas, Pirinas and Los Barros (Notholt, 1999). Until mining ceased in 1966, about 5,000 tons were extracted annually from each of the Las Lajas and Los Barros deposits for the manufacture of superphosphate. High mining and transportation costs led to a gradual decline in production and mining finally ceased in 1966 when the government subsidy was withdrawn.

The Cachiyuyo vein deposits were worked before the First World War producing annually about 3,000 tons grading 28%  $P_2O_5$ . The apatite rock was calcined in Coquimbo after mixing with sodium nitrate and coal; the 23 to 25%  $P_2O_5$  product was ground and sold locally as fertilizer. Another calcined product comprised apatite, sodium nitrate and sodium sulphate. The two products, each with 20% citric soluble  $P_2O_5$ , were marketed as '*Fosfato Pelicano*' and '*Fosfato Melón*' respectively; the combined output in 1948 amounting to 80,000 tons. Subsequently, however, the entire apatite production was finely ground for direct application fertilizer (Notholt, 1999).

The guano deposits of Pabellón de Pica, Punta de Lobos and Guanillos probably yielded most of the guano produced in Chile. Between 1906 and 1937, when exports were prohibited, output amounted to about 635,000 tons, of which nearly 552,000 tons comprised red guano. Production in 1938 was 53,000 tons but declined to 17,500 tons in 1942 because of a serious decline in the population of guano birds (Notholt, 1999). Most of the guano was mixed with imported and other local materials to produce a variety of fertilizers.

At the end of the Second World War, a superphosphate plant was built at Guayacán, south-east of Coquimbo, output in 1948 being about 90,000 tons with 20-22%  $P_2O_5$ . There is currently no production phosphate rock or phosphate fertilisers in Chile (Salas, 1985).

*Sources:* (Burnett and Oas, 1979; Notholt, 1994a; Salas, 1985; Savage, 1987; Sheldon et al., 1990; Valdebenito, 1989)

#### *Agronomic testing and use*

In Chile approximately 60% of the land with agricultural potential (2500000 ha) corresponds to soils of volcanic origin, with high phosphorus fixation capacity. This explains the importance of phosphate fertilizer of which about 112000 t  $P_2O_5$  per year is consumed. Rojas and Besoain (1991) described evaluations of the agronomic performance of the Mejillones, Bahía Inglesa and La Serena phosphate rocks in greenhouse and field trials using wheat, *Brassica napus*, lentils (*Lens culinaris*) and flooded rice grown in a range of soils and climate conditions. As would be expected, the agronomic effectiveness of the La Serena apatite rock was low due to its low solubility (reactivity). In contrast, the relatively reactive Mejillones and Bahía Inglesa phosphorites produced yields in the *Brassica* trial that were higher than TSP. The two ground phosphorites had agronomic efficiencies of 80-90% (compared with TSP) in the wheat trials (Rojas and Besoain, 1991).

*Sources:* (Bishop et al., 1994; Borie and Zunino, 1983; Galindo et al., 1972; Reyes, 1991b; Rojas and Besoain, 1991)

# Colombia



## *Location, Quantity, Quality*

### Cretaceous

The Eastern Cordillera of Colombia contains the bulk of the Mesozoic phosphate resources in South America. These lie within a belt of Late Cretaceous rocks some 100 km wide and 600 km long that extends from Huila Department in the south-west northwards through Tolima, Cundinamarca, Boyacá and Santander to the Department of Norte de Santander, close to the Venezuelan border. Phosphate beds occur in (i) the upper part of the La Luna Formation in the Maracaibo basin; (ii) the Galembó Member of the La Luna Formation in the middle part of the Magdalena River valley; and (iii) the Plaeners and Monserrate Formations in the central and southern parts of the Cretaceous phosphate belt. The major deposits are usually associated with siltstone, fine-grained sandstone, chert, and black shale. Individual phosphorite beds range from a few centimetres to 5 m but are commonly 1.5 m thick and contain 5-31%  $P_2O_5$ . Phosphorites with 22%  $P_2O_5$  or more are restricted to weathered zones from which carbonate has been leached (Zambrano and Mojica, 1990).

Phosphorite deposits with the greatest potential for development are located in Boyacá Department where they occur mainly in the Plaeners Formation. The main phosphorite sequence is 1.8 to 4.2 m thick and averages 22%  $P_2O_5$ . It comprises phosphorite interbedded with siltstone, grey shale, fine-grained claystone, and chert. In the Norte de Santander Department, phosphorites occur in the upper part of the La Luna Formation and the basal Tres Esquinas Member of the overlying Colon Formation. Proven reserves in a phosphorite unit 0.5 m to 3.5 m thick in the Sardinata zone total 4.9 Mt with an overburden not exceeding 12 m. A further 4.4 Mt exists at greater depth. The weathered phosphorite has, on

average, 22%  $P_2O_5$ . Resources available by underground mining amount to approximately 15 Mt. Underground resources of approximately 30 Mt are contained in the Galembo Member of the La Luna Formation in Santander Department. In the Vanegas-San Vicente area, a 1-4 m thick horizon containing up to 18%  $P_2O_5$ , has been of interest as a potential source of phosphate rock for direct application fertilizer.

Table 8. Cretaceous phosphate rock resources in Colombia

Department	Thickness (m)	Resources*		Reserves**	
		Grade (% $P_2O_5$ )	Quantity (Mt)	Area (km <sup>2</sup> )	Quantity (Mt)
Norte de Santander	0.5-5.4	8-37	60.0	58	45.1
Santander	0.3-1.8	13-27	32.6	10	32.7
Boyaca	0.5-5.0	5-27	499.8	166	140.6
Huila	0.5-2.4	9-31	152.0	74.9	138.0
TOTAL			744.4	308.9	346.4

\* (Mojica and Zambrano, 1985); \*\* (Mojica, 1987)

### Guano

Percolating guano solutions has led to the almost complete phosphatisation of intermediate to basic volcanic rocks on Malpelo Island (4°03'N, 81°31'W), a small volcanic island about 250 miles west of Buenaventura. The altered rock contains phosphosiderite and strengite and contains about 34 %  $P_2O_5$  and 33.4%  $Fe_2O_3$ . Phosphatised lava reserves are estimated at nearly 453,000 tons, assuming an average thickness of 3 ft. Samples from a depth of 0.5 m contained 25 to 30%  $P_2O_5$ , 23-27%  $Fe_2O_3$  and 2-8%  $Al_2O_3$ .

Martínez (1987; 1988; 1987) concluded that considering the quantity, quality and distribution of phosphate rock resources in Colombia, that nowhere are there reserves with sufficient quality and quantity to supply a fertilizer complex. Martínez (op. cit.) considered that the resources identified are adequate enough for the development of ground phosphate rock industry and/or for the production of partially acidulated phosphate rock.

### *Production*

Three deposits, Pesca, Sardinata, and Tesalia-La Juanita, are worked in Colombia for direct application fertilizer. The rock is extracted by underground mining at Pesca and Tesalia whereas Sardinata is an open-pit mine (Mojica and Zambrano, 1985; Zambrano and Mojica, 1990).

Phosphate rock has been used intermittently since 1970 and production grew slowly from 3,600 t in 1970 to 6,400 t in 1981 after which there was a sharp rise to 16,400 t in 1985 and 23,300 t in 1986 of which 16,800 t was used for direct application, the remainder being used for blending with water soluble fertilizers in the production of granulated NPK mixtures. In 1985, production was from two deposits: Sardinata produced 8,500 t and Tesalia (La Juanita) in the Huila district produced 14,822 t (Martínez, 1988). When the Pesca/Iza deposits came back into production, they were projected to produce a further 20,000 t/a giving a total capacity of about 48,000 t/a. Current production is reported to be approximately 50,000 t/a (equivalent to 10-15,000 t  $P_2O_5$ ). Even so, the bulk of requirements for ground phosphate rock are met by imports from Florida (36,500 t  $P_2O_5$ ).

Table 9. Installed phosphate rock production capacity in Colombia (Mojica and Zambrano, 1985).

Deposit	Productive capacity (t/h)	Productive grade (%P <sub>2</sub> O <sub>5</sub> )
Pesca (Boyacá)	20	20
Sardinata (N. de Santander)	10	35
Tesalia-La Juanita	10	21

In 1988, the price of ground rock phosphate in Colombia was \$45/tonne (ex. plant) (Martínez, 1988). Underground mining and transportation costs to plant for the Huila and Pesca deposits were \$8.7/tonne but only \$2.2/tonne for the opencast Sardinata mine (Martínez, 1988). In comparison, world average surface operation phosphate rock production costs are reported to be \$33.4/t whereas underground operation production costs are slightly higher at \$46.5/t PR (Fantel et al., 1989). For the application of phosphate rock to be economically viable as a fertilizer for improved pastures, it is suggested that the cost/unit of P<sub>2</sub>O<sub>5</sub> for ground PR should be less than 50% of the cost/unit P<sub>2</sub>O<sub>5</sub> in TSP or DAP (Goedert et al., 1987). In Colombia PR P<sub>2</sub>O<sub>5</sub> units costs are 30% and 50-60% of TSP unit/costs, respectively (Martínez, 1988).

Whereas the P<sub>2</sub>O<sub>5</sub> content of some of the Colombian phosphate rocks is only 22%, the cost advantage over imported fertilisers is sufficiently high to make ground phosphate rock economically effective for a range of crops grown on selected soils. Colombia is currently the only country in Latin America where local rock phosphate is used for direct application and where its production is developed on an industrial scale. Even in Brazil, where the Patos de Minas rock was originally used for direct application, this has now been discontinued and more reactive rock phosphates imported from North Africa and the Middle East are now used instead of the Patos de Minas rock (Chien, personal communication, July 2001).

A project was considered many years ago by the Instituto de Fomento Industrial to use Malpelo ferruginous phosphate in the manufacture of superphosphate but the project was never initiated.

*Sources:* (Alvarado and Sarmiento, 1945; Buergl and Botero, 1967; Carmona, 1978; Castano and Menicucci, 1984; Cathcart, 1971; Cathcart, 1975; Cathcart and Zambrano, 1969; Fabre and Osorio, 1981; Fantel et al., 1989; Follmi et al., 1992; Hammen and Nelson, 1955; León, 1991; Martínez, 1987; Martínez, 1988; Martínez et al., 1987; Mojica, 1984; Mojica and Zambrano, 1985; Mojica, 1967; Mojica, 1978; Notholt, 1994a; Ortiz, 1976; Ricaldi and McClellan, 1987; Rosas, 1984; Royo, 1941; Sarmiento and Parra, 1947; Warren, 1984; Yoris et al., 1996; Zambrano, 1978; Zambrano and Mojica, 1990)

### *Agronomic testing and use*

Navas (1987) and Sánchez and Navas (1991) reported the results of agronomic trials carried out over a twenty-year period to study the effectiveness of a range of P sources when applied to Entisols, Inceptisols and Oxisols. Direct application rock phosphate (RP), partially acidulated RP, RP granulated or compacted with highly soluble P-sources (such as TSP) were compared with TSP and basic slags using crops like corn, sorghum, peanuts, flooded rice, upland rice and *Brachiaria decumbens*. The efficiency of the Colombian phosphate rocks was found to depend on the soil characteristics, crop and phosphate rocks used. In Entisols there were not beneficial effects but in Inceptisols and Oxisols the agronomic effectiveness improved greatly. Phosphate rocks had a lower immediate effect on the first crop than the TSP or basic slag, but in the second crop, after one year, its efficiency equalled or surpassed that of the TSP. Sánchez and Navas (1991) demonstrated that the efficiency of phosphate rock used for direct application could be improved by supplying part of the P requirements with a highly soluble source at planting. With this practice, flooded rice showed a 20% increase in the agronomic efficiency of phosphate rock. Partial acidulation improved the efficiency in corn, flooded rice in some places and upland rice in Oxisols, although no response was found in sorghum. The residual effect in flooded and upland rice showed higher yields with higher rates of P<sub>2</sub>O<sub>5</sub> and in the second crop, partially acidulated rocks demonstrated better yields than direct application phosphate rocks and triple superphosphate. The residual effect in *Brachiaria decumbens* was excellent when high rates of P<sub>2</sub>O<sub>5</sub> were applied to an Oxisol. In this example, a single application of phosphate rock was as effective as an annual application of highly soluble sources (e.g. TSP). In a high terrace Oxisol, application of different P sources produced a

difference of 1 t ha<sup>-1</sup> of dry pasture per harvest compared to the treatment without P. Phosphate rocks induced no significant changes in pH, Ca and exchangeable aluminium. Bray II available P correlated with P<sub>2</sub>O<sub>5</sub> application rates whereas the Bray I method extracted very little P from these soils (Sánchez and Navas, 1991).

León (León, 1991) summarised the results of thirteen years of work by the IFDC and associated organisations on natural and modified phosphate rocks (PR) applied to tropical soils in Latin America. Much of the research was carried out in Colombia using local phosphate rocks. The results showed that many phosphate rocks, including ones with low reactivity, are promising for direct application in acid soils (pH < 5.5), especially if the residual effect is taken into account. Furthermore, modified phosphate rock can be used for annual crops with high P requirements in soils of pH 5.5 - 6.5, and high P fixation capacity. Agronomic trials in Colombia indicate that compaction of PR with TSP and urea produces improved responses with annual crops (León, 1989).

Chien et al. (1995) evaluated the effect of liming on the agronomic effectiveness of three phosphate rocks (PRs): Pesca and Huila from Colombia and Sechura from Peru as compared with TSP in a greenhouse experiment for an Al-tolerant soybean cultivar grown on an acid Ultisol. On both unlimed (pH 4.4) and limed (pH 5.0) soils, the agronomic effectiveness of P sources in terms of increasing seed yield followed the order of TSP > Sechura PR > Huila PR > Pesca PR > control. This mirrored the relative solubility of the P sources. Liming slightly decreased the effectiveness of Pesca PR, whereas liming had no effect on Huila PR. A significant increase in agronomic effectiveness was observed upon liming for Sechura PR and TSP. Soil-available P as extracted by the Pi method was closely related to the amount of N fixed by soybean crop that, in turn, was related to the soybean seed yield. Values of relative agronomic effectiveness (RAE) of PRs with respect to TSP were calculated by assuming the control = 0% and TSP = 100%. On unlimed soil, the RAE values of PRs were: Pesca PR = 31%, Huila PR = 42%, Sechura PR = 84%. On the limed soil, the RAE values were: Pesca PR = 8%, Huila PR = 24%, Sechura PR = 66%. Chien et al. (1995) concluded that the use of phosphate rock with respect to that of TSP for soybean crop is more favourable in the unlimed soil than in the limed soil, provided that the soybean plant is relatively Al-tolerant.

*Table 10. Characteristics of phosphate rock used for direct application in Colombia (Mojica and Zambrano, 1985)*

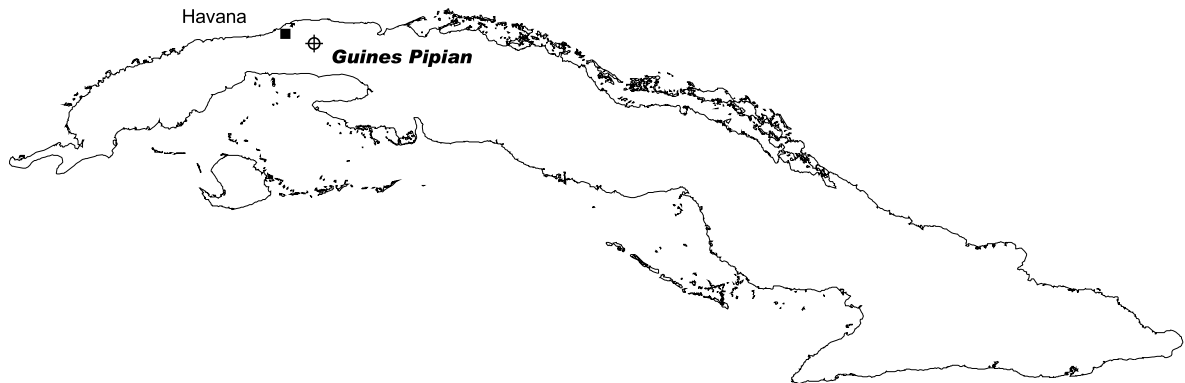
Deposit	Average Grade (%P <sub>2</sub> O <sub>5</sub> )	Solubility in NAC (%P <sub>2</sub> O <sub>5</sub> )*
Huila	19.4	3.5
Medio Luna	30.1	2.3
Pesca	19.4	2.4
Sardinata	35.4	**2.4

\*solubility in neutral ammonium citrate; \*\* solubility in neutral ammonium citrate after calcite removed.

Local phosphate rock resources are being used as direct application fertilizer on the acid infertile soils of the eastern plains and the hilly areas of the Andes for especially for pastures but also for rice, sugar cane and potatoes. Many farmers are reported to use the Huila phosphate rock for its liming effect more than as a P source (Martínez, 1988). Although the agronomic value of calcium from medium to high reactivity phosphate rock's, applied to acid soils has been demonstrated by Hellums et al. (1989), it is difficult to understand how this could be economically viable as the Huila rock contains only about 20% calcium carbonate.

*Sources:*(Chien et al., 1987; Chien et al., 1980; Chien et al., 1995; CIAT, 1982; CIAT, 1983; CIAT, 1984; CIAT-IFDC, 1979; De Benavides, 1975a; De Benavides, 1975b; Dodor et al., 1999; Fenster and León, 1978; Hammond, 1991; Hellums et al., 1989; Hofstede, 1995; Hughes and Gilkes, 1986; Hughes and Le Mare, 1982; INGEOMINAS, 1981; Le Mare, 1982; Le Mare and Hughes, 1982; Le Mare and Leon, 1990; Le Mare and León, 1989; León, 1991; León and Arregocés, 1987; León et al., 1986; Martínez, 1987; Martínez, 1988; Martínez et al., 1987; McGrath et al., 2000; Mokwunye and Chien, 1980; Navas, 1987; Sánchez and Navas, 1991; Sanz Scovino and Rowell, 1988).

# Cuba



## *Location, Quantity, Quality*

Miocene phosphorites discovered during the early 1960s in western Cuba represent an extension of the Neogene phosphorite province of the southeastern USA into the Caribbean Basin. Folded Middle Miocene phosphate-bearing sediments are up to 20 m thick and several small deposits have been delineated in southern Havana Province of which Loma Candela, Pipian and Meseta Rokha in the Guines Pipian district are the best developed. The predominantly pelletal phosphorites contain up to 9.5%  $P_2O_5$  and are composed largely of francolite, calcite and glauconite. Phosphatic calcarenites and phosphatic conglomerates with lower grades also occur locally. Beds of pelletal phosphorite from 0.2 to 3.5 m in thickness can be traced over distances of 2.5 to 10 km. Total resources in western Cuba are likely to be significant, but over much of this area the Miocene phosphate rocks are too deeply buried for these occurrences to be of economic interest at present (Notholt, 1994a).

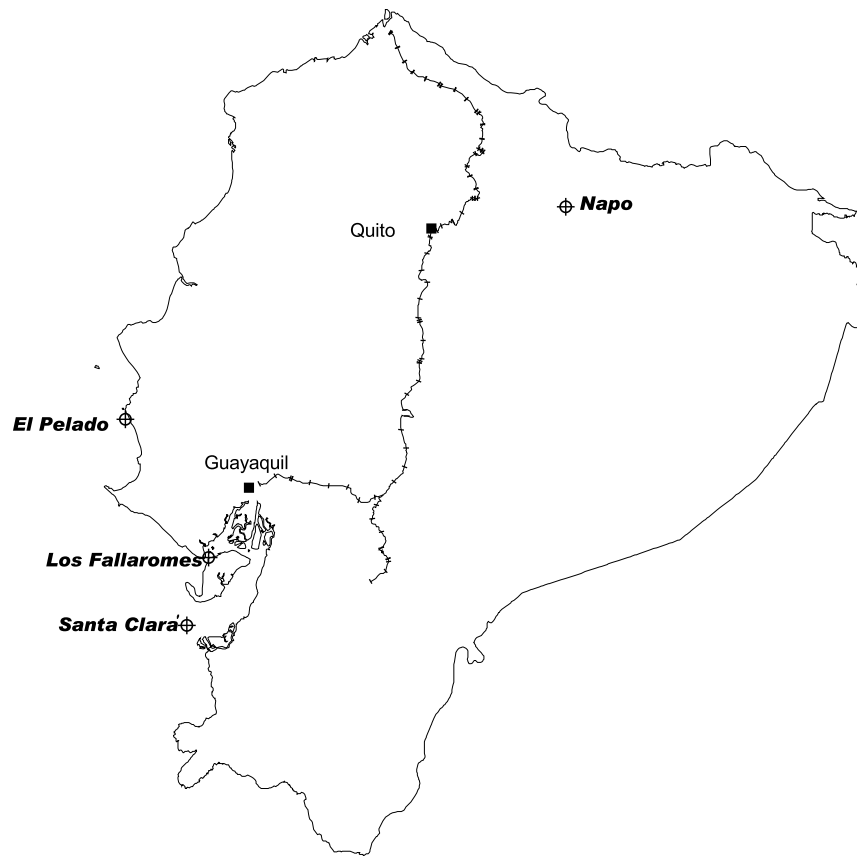
*Sources:* (Ilyin and Ratnikova, 1990; Notholt, 1994a)

## *Agronomic testing and use*

Villegas and Chang (1991) evaluated the potential use of rock phosphate and other sources of phosphorus as fertilizer for the principle crops grown in Cuba. For a variety of tropical crops including sugar cane, pasture, citrics, rice and forestry it was shown that by taking advantage of its long-term residual effect, the use of phosphate rock is a viable option that would help to reduce the need for imported soluble P fertilizers. The Guines Pipian phosphatic limestone contains only 9.5%  $P_2O_5$  so it is possible that the liming effect may have a greater impact on crop yield than phosphorus. It is difficult to assess the relative benefits of Ca and P applications from the results of trials (Villegas and Chang, 1991).

*Sources:* (Villegas and Chang, 1991; Zapata, 2001)

# Ecuador



## *Location, Quantity, Quality*

### Cretaceous

Upper Cretaceous phosphate rock occurs at a number of localities in the upper member of the Napo Formation in the Cordillera Oriental of Ecuador. Wilkinson (1982) discovered a phosphorite bed 0.7-1.4 m in thickness and averaging 25%  $P_2O_5$  in the vicinity of the Rio Coca- Rio Due watershed to the east of Reventador, Napo Province. The phosphorite reaches 3 m in thickness where it is interbedded with phosphatic shales, containing an average of 24%  $P_2O_5$ . The phosphorite bed occurs in the upper Napo Formation and crops out over a distance of 6 km to the east of Reventador. Total resources are estimated to be in the range 166 to 205 Mt containing 23 – 25%  $P_2O_5$ . Four major phosphate zones with average thicknesses of 0.6 to 0.8 m cover an area of 11 to 35 km<sup>2</sup> and have average grades of 8 to 37%  $P_2O_5$ . The overburden ranges from 70 to 180 m. so opencast mining is not likely to be economically feasible. Probable and possible reserves have been estimated as 40-52 Mt and 48-53 Mt, respectively. Torrez (1985) concluded that the reserves identified in the Napo Formation could be exploited economically, although a phosphate rock mine has not yet been developed.



## Guano

Phosphatic guano occurs on a number of small islands situated off the coast of Ecuador but no deposits of economic importance are known. The richest deposits, containing about 20%  $P_2O_5$  and 0.7% N, occur on El Pelado (1°41'S, 80°51'W) about 19 miles north of the port of La Libertad, Guayas Province. Deposits of lower grade have been identified on Los Farallones (2°44'S, 80°13'W) in Canal de Morro; Santa Clara (3°15'S, 80°23'W) in the Gulf of Guayaquil; and La Plata (3°15'S, 81°05'W) southwest of Cape San Lorenzo (Notholt, 1999).

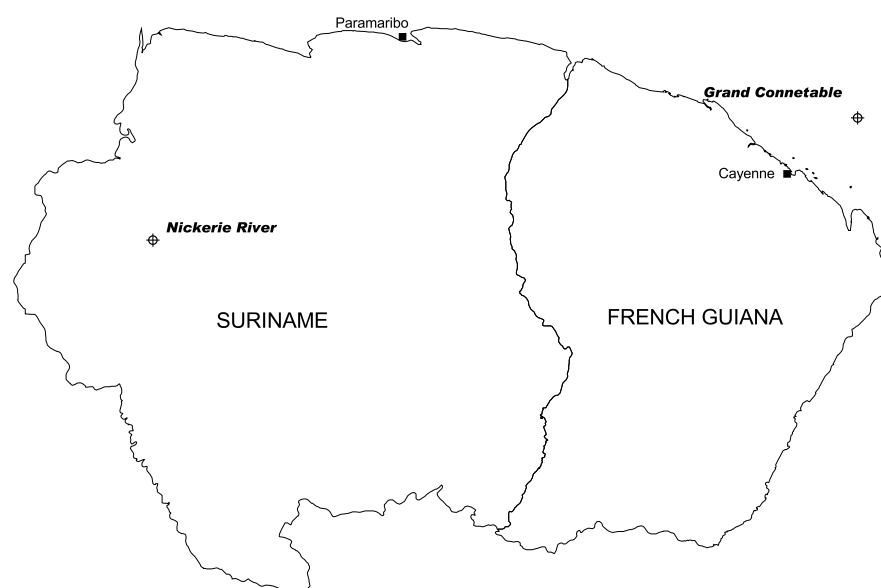
*Sources:* (Notholt, 1994a; Torrez, 1983; Torrez, 1984; Torrez, 1985; Vera, 1980; Wilkinson, 1982)

## *Agronomic testing and use*

Córdova (1991) evaluated the potential for using Napo phosphate rock as a source of phosphorus for crops in the upland zone of Ecuador. Three acid volcanic soils, with high P-fixation capacity, were evaluated in greenhouse trials over ten consecutive harvests of corn using 25% and 50% acidulated Napo phosphate rock and triple superphosphate at 150, 300 and 450 kg  $P_2O_5$  ha<sup>-1</sup>. The experiment was carried out in pots with 1500 ml soil capacity and 4 corn plants as the index crop in a complete randomise block design with three replications. Each harvest was executed 60 days after planting and 30 ppm of S and 0.4-meq k/100 ml were applied after the fifth harvest, and 30 ppm of S after the seventh harvest. N was applied with irrigated water at 3 ppm. Dry matter yields were always higher in the soil from the west region, followed by Pugru and Lote C soils, which relates to the P fixing capacity of each soil. Higher yields were recorded in all three soils with TSP up to the fourth harvest (250 days) and at the fifth harvest corn responses were similar for the three P sources and soils confirming that partially acidulated phosphate rock has a different agronomic effectiveness. Increases in rates of  $P_2O_5$  applied produced higher dry matter yields for each P source and soils. However, the increase of rates of P did not overcome the P-fixation capacity of the soils caused by their high humus content. 50% acidulated Napo phosphate rock showed a better response than the 25% acidulated rock and in some cases the response was better than with TSP.

*Sources* (Bossio and Cassman, 1991; Córdova, 1991; Espinosa, 1991; Korning et al., 1994)

# French Guiana and Suriname



## *Location, Quantity, Quality*

### French Guiana

Aluminium phosphate produced by the action of solutions derived from guano on gneiss and dolerite occur on the small island of Grand Connetable (4°50'N, 51°53'E), situated near the mouth of the Approuague River about 45 km east of Cayenne. The rocks on Grand Connetable are very weathered with the phosphate occurring near the bedrock mainly as vein-like masses up to about 2 m in thickness, of coarsely granular or spherical variscite. The variscite is usually white or green in colour, sometimes showing red colouration due to partial replacement by barrandite. Analysed samples of the phosphate rock contain 35-39%  $P_2O_5$ , 25-29%  $Al_2O_3$  and 2-8%  $Fe_2O_3$  (Notholt, 1999).

### Suriname

A Proterozoic phosphorite occurs on the Nickerie River where it transects the Bakhuis Mountains. The deposit comprises lenses of plagioclase-apatite-clinopyroxene rock within a sequence of metamorphic and igneous rocks comprising syenite, gneiss and granulite as well as mafic and ultramafic rocks. The main phosphate mineral is a strontium-bearing fluorapatite containing 4700 ppm Ce. The apatite zone is 50m wide, contains 2m wide apatite lenses and stretches over about 8 km.  $P_2O_5$  ranges up to 14% and but nearly 60% of the samples analysed contain less than 2%. Reserves of this low-grade occurrence are not yet defined (Dahlberg, 1989; De Vletter et al., 1998).

### *Production*

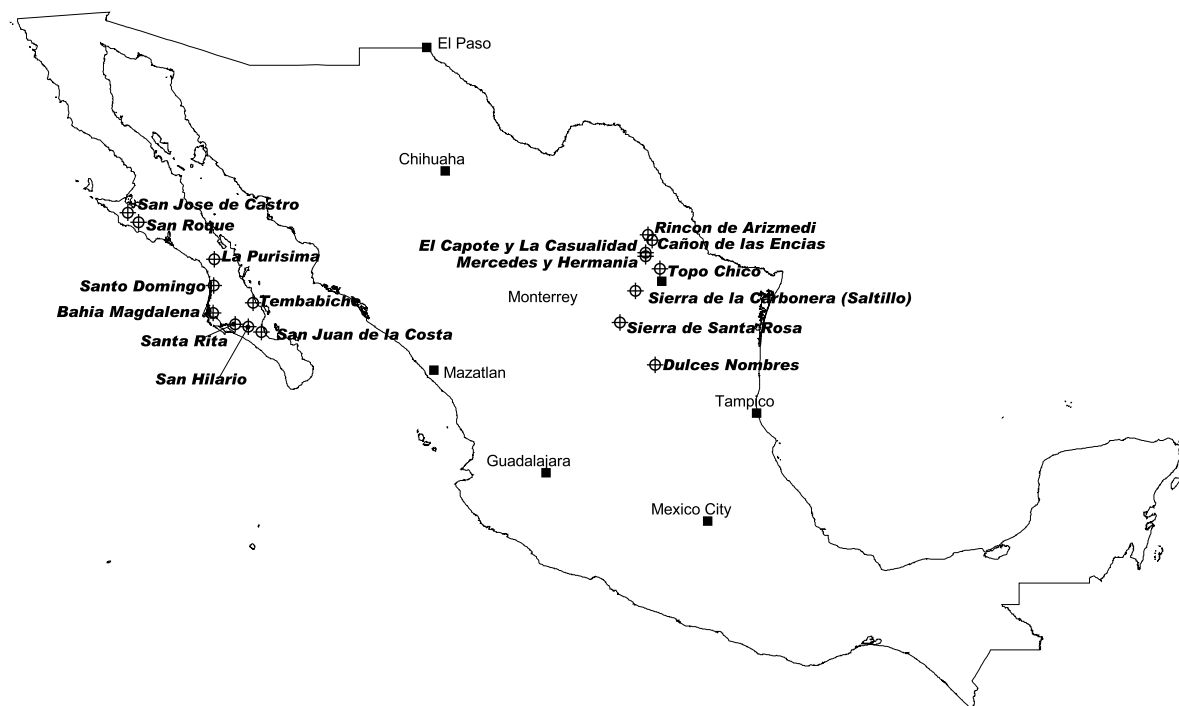
The Grand Connetable deposits in French Guiana were worked between 1884 and 1913 during which time the annual production ranged from 3,000 to 7,000 tons. The phosphate rock material was used in the manufacture of sodium phosphate by a company in New Jersey, and also as a source of alum in France.

*Sources:* (Dahlberg, 1989; De Vletter et al., 1998)

### *Agronomic testing and use*

Pot trials carried out in 1894 showed that the finely ground phosphate from Grand Connetable gave favourable results when applied directly to the soil as fertilizer (Notholt, 1999).

## Mexico



### *Location, Quantity, Quality*

#### Jurassic

Low-grade sedimentary phosphate rock deposits occur in several parts of central and northeastern Mexico, of which some in Nuevo Leon State (e.g. Cañon de las Encias, Dulces Nombres, Mercedes, Hermania, El Capote, La Caulidad, Rincon de Arizmedi and Topo Chico) have been worked on a small scale since the early part of the 20th century. These resources typically contain about 20%  $P_2O_5$ , although they ranged from 7 to 34% (Savage, 1987). Remaining resources in Nuevo Leon are limited, but in the adjacent states of Zacatecas and Coahuila, near Saltillo (Sierra de la Carbonera), phosphate rock in the La Caja Formation (Upper Jurassic) occurs extensively over an area of about 68,000 km<sup>2</sup>. Proven and

probable resources amount to about 77.4 Mt averaging 18%  $P_2O_5$ , with an additional 76.4 Mt containing 13%  $P_2O_5$ . Individual phosphate beds are carbonate-rich, and this, together with their relatively inaccessible location in semi-arid mountainous terrain, has discouraged their economic development (Notholt, 1994a; Notholt, 1999).

### Paleogene-Neogene

On the Baja California Peninsula, deposits of pelletal phosphate rock are contained in the Monterrey Formation that is predominantly fine-grained sediments deposited during a slow marine transgression in late Oligocene to early Miocene times. The formation comprises phosphatic-volcanic conglomerate, tuff containing diatomaceous and phosphatic facies, and siliceous shale containing calcareous and phosphorite facies. The phosphorite facies consists of two to nine beds, each ranging from 0.9 to 2 m in thickness. In the San Juan de la Costa area, the two main beds (Humboldt Superior and Humboldt beds) are 0.6 m and 1.8 m thick respectively and average 19%  $P_2O_5$  (Notholt, 1994a; Notholt, 1999).

Mineable reserves at San Juan de la Costa total about 57.7 Mt (Anon., 2001), with an additional resource of some 16 Mt, which although previously exploited at a rate of about 6000t/day, is now uneconomic because of high overburden to ore ratios, low grades or low recoveries during beneficiation. The marine phosphatic beds of the Monterrey Formation are known to extend for more than 130 km and include the San Hilario deposits located about 100 km WNW of La Paz, which are estimated to contain 841 Mt averaging 14%  $P_2O_5$ . Exploitation of this deposit has also been abandoned (Savage, 1987). Small deposits have been delineated also in the Pliocene Salada Formation at Santa Rita (Notholt, 1994a; Notholt, 1999; Savage, 1987).

### Pleistocene-Recent

Beach deposits occur extensively along the Pacific coast near Santo Domingo in Baja California. The phosphorites are well-sorted sands composed mainly of carbonate fluorapatite in a fine sand to silt matrix. Phosphate particles in the coarser fractions appear to be derived from phosphatic brachiopod shells. The phosphatic sediments extend from the surface to an average depth of nearly 20 m. The Santo Domingo deposits in the Soledad Formation at the northern end of Bahía de Magdalena have been prospected since 1978 and were to be mined to provide about 1.5 Mtpa of phosphate concentrate averaging 24%  $P_2O_5$ . Trenching and drilling delineated an area of about 60 km<sup>2</sup> near Puerto Lopez Mateos, made up of two contiguous zones (Elenas and Prados) which are estimated to contain 434 Mt averaging 4.29%  $P_2O_5$  and 643 Mt with 4.56%  $P_2O_5$ , respectively. Since the investigations relate to only a small proportion of the area over which the phosphatic sands are known to extend, total resources are undoubtedly much larger. Total reserves in the Santo Domingo area were estimated to be equivalent to at least 1,500 Mt  $P_2O_5$ , assuming an average apatite content of 5%, although in some places apatite concentrations of 10 to 12% are common.

Beneficiation studies indicated that a concentrate with 29%  $P_2O_5$  could be produced by subjecting the phosphatic sands to ionic flotation, followed by cationic flotation and magnetic separation. The concentrate is reported to be suitable for superphosphate manufacture. Calcination of the concentrate gave a product grading 31%  $P_2O_5$  or more (Notholt, 1994a; Notholt, 1999).

### Guano

Several thousand tons of phosphatic bird guano was obtained annually from small islands situated in northwestern Mexico close to the Pacific coast of Baja California and within the Gulf of California. The most important sources have been the islands of Elide (28°46'N, 114°12'W) which was first worked in the 19th century, and Pajaros (24°38'N, 112°09'W) in Magdalena Bay, the guano produced generally containing about 11%  $P_2O_5$ . Since 1938 the exploitation of the guano islands in Baja California and elsewhere in Mexico has been under the control of the Mexican Government, which in 1943 formed the *Guanos y Fertilizantes de Mexico, S.A.* to work the deposits. The guano is used in the manufacture of

mixed fertilizers at Guadalajara, Jalisco State. Between 1918 and 1937, some islands were worked by the company G.W. Beermaker Incorporated, San Diego, California. An average of about 615 tons of guano containing 8-13%  $P_2O_5$ , 8-11% N, and 1-2%  $K_2O$  were shipped to California for use as fertilizer (Notholt, 1999).

### *Production*

The San Juan de la Costa mine in Baja California was brought into commercial production in 1981. The beneficiation plant provides for the production of about 1,054,440 tpa of concentrate averaging 31%  $P_2O_5$  from combined open-pit and underground mining operations extracting ore with 18%  $P_2O_5$ . At Santo Domingo, *Roca Fosforica Mexicana SA de CV (Rofomex)* developed a facility with the capacity to produce 1.5 Mt/yr of concentrates by dredge-mining a beach sand deposit grading 4.5%  $P_2O_5$  at a cut-off grade of 3%. It is understood that the project was curtailed due to technical problems caused by hard beds (Savage, 1987). Mexico's phosphate rock production has risen gradually from 622,354t in 1995 to 981,196 t in 2000 all of which comes from the San Juan de la Costa mine operated by *Roca Fosfórica Mexicana* (Anon., 2001).

*Sources:* (Alatorre, 1988; Alvarez, 1989; Alvarez, 1991; Birdsall, 1979; Briones, 1970; Briones, 1978; Carranza et al., 1989; Carreon and Jacques, 1989; Cekinski et al., 1993; Cserna, 1958; Cserna, 1967; Cserna, 1969; Daessle and Carriquiry, 1998; Daessle et al., 2000; De Anglejan, 1962; De Anglejan, 1963; De Anglejan, 1967; Dengo, 1968; Dovalina, 1928; Emery and Dietz, 1950; Espinoza, 1984; Fischer et al., 1995; Flores, 1953; Galli-Olivier et al., 1990; Grimm, 2000; Grimm and Garrison, 1993; Grimm et al., 1991; Harris, 1981; Ibarra et al., 1989; Ledesma et al., 1991; Lopez, 1991; Mathers, 1994; Michalzik and Schumann, 1994; Notholt, 1994a; Overall, 1968; Patron et al., 1999; Perez and Wiggin, 1953; Piper, 1991; Quintus, 1980; Rogers et al., 1961a; Rogers et al., 1961b; Rogers and Ulloa, 1956; Rogers et al., 1953; Savage, 1987; Schuffert et al., 1994; Schuffert et al., 1998; Schwennicke, 1991; Schwennicke and Vazquez, 1996; Sheldon, 1978; Todd, 1984; Weng et al., 1994)

### *Agronomic testing and use*

Núñez and Gavi (1991) studied the agronomic response to phosphate rock in greenhouse and field experiments in four areas of Mexico, ranging from Andisols in the high plains (2600 msnm) to Entisols of the Mexico Gulf Coast. Corn, beans and alfalfa were used as index crops in order to evaluate the residual effect and compare the agronomic effectiveness of ground phosphate rock with different grain sizes. The capacity of TSP, North Carolina phosphate rock (NCPR) and Baja California phosphate rock (BCPR) and mixtures of phosphate rock and sulphur to supply P in soils with pH close to neutral was investigated using crops that acidify the rhizosphere. Demonstrative trials in farmers fields were conducted in several states of Mexico to test (1) the use of direct application phosphate rock applied to soils with pH lower than 6.0; (2) the use of phosphate rocks with 9.4% or higher solubility in citrate; (3) the effects of grinding the PR to <100 mesh; (4) the application of 50% more P than the rate recommended as superphosphate; and (5) phosphate rock mixed with sulphur or manure. The maximum yield obtained with TSP was not achieved with high application rates of PR over the short-term for alfalfa grown in a greenhouse in a Molisol with pH 6.5. However, the differences in agronomic efficiency tended to reduce with time, indicating a residual effect when using ground PR. Over short periods, the agronomic efficiency of North Carolina PR (commercial grain size) tended to be inferior to finely ground (<100 mesh US). However, over a longer period of time, high doses of coarse NCPR tended to produce superior yields than finely ground Baja California PR. Grinding the Baja California PR increased its agronomic efficiency with respect to maize yield by more than 50% in relation to the same material applied at its commercial grain size (<35+100 mesh). The addition of sulphur to Baja California PR increased its agronomic efficiency by about 13% (measured by the quantity of maize stubble) when cultivated in an Andisol, but this effect was not observed for maize grown in a Planosol with higher pH.

The agronomic efficiency of Baja California PR (BCPR) applied at three particle sizes and mixed with sulphur and zeolite (to increase the reactivity of the PR) was compared with North Carolina PR (NCPR) and TSP for *Lolium perenne* (rye grass) cultivated in an Andosol at Michoacán, Mexico (De Gracia et al., 1996). Both phosphate rocks produce similar dry matter yields; fine grinding of the PRs to <100+200

mesh improved yield. The impact obtained through the addition of sulphur or zeolite to ground PR varied with particle size. The addition of 10% sulphur to coarse BCPR increased the yield by 33% compared with S-free BCPR. Yield response for zeolite (12.1 g kg<sup>-1</sup> soil) added to finely ground BCPR was 49% higher compared to zeolite-free BCPR. Coarse BCPR with added sulphur was as effective as coarse NCPR on dry matter yields and P extraction (De Gracia et al., 1996).

*Sources:* (Alvarez et al., 1981; De Gracia et al., 1996; Nuñez and Gavi, 1991)

## Nicaragua

### *Location, Quantity, Quality*

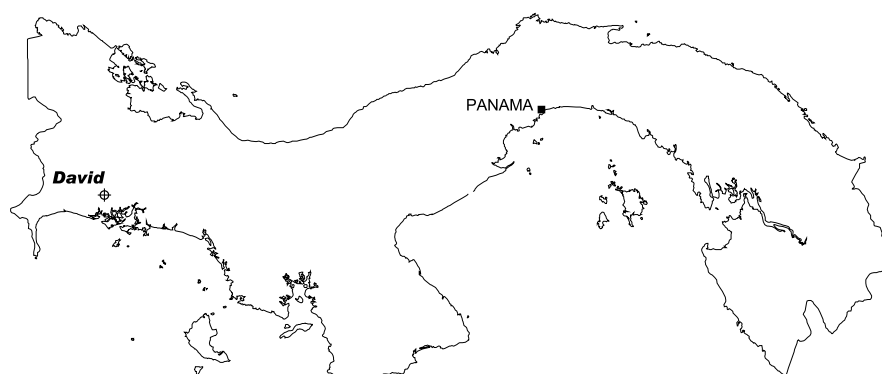
Preliminary surveys for phosphate by the *Servicio Geologico Nacional* in Rivas department of southern Nicaragua to the south-west of Lago de Nicaragua indicated the widespread occurrence of folded and predominantly calcareous sediments of the Upper Cretaceous Rivas Formation and the overlying Brito Formation of Eocene age, the latter formation being well exposed in road cuts through Cerro Papayal, some 5 km from San Juan del Sur on the Pacific coast. However, samples from both formations revealed only traces of phosphate. A more recent report by British Sulphur stated that 27% P<sub>2</sub>O<sub>5</sub> had been recorded in sandstone at the same site. This disparity needs to be resolved (Mathers, 1994).

*Sources:* (Hill, 1994; Mathers, 1994; Zoppis, 1960)

### *Agronomic testing and use*

No records have been encountered of agronomic evaluations of phosphate rock in Nicaragua.

## Panama



### *Location, Quantity, Quality*

Pliocene deposits consisting of flat-lying phosphatic shales and diatomaceous beds up to about 30 m thick occur near David in western Panama. They are geologically similar to the deposits in the Sechura Desert of Peru. Individual beds, which contain up to 20 %  $P_2O_5$ , are poorly exposed (Notholt, 1994a). Sampling showed that phosphate is present throughout the area investigated but the thick overburden of residual soil makes it unlikely that the deposits will prove to be of economic importance (Notholt, 1999).

*Sources:* (Mathers, 1994; Notholt, 1994a; Notholt, 1999; Savage, 1987)

### *Agronomic testing and use*

No records were found of agronomic evaluations of phosphate rock in Panama although Molina et al. (1991) noted that soil Al and Fe fractions in Andisols will cause P-immobilization. Direct application of reactive phosphate rock may well be agronomically effective in high rainfall areas with low pH soils.

## Paraguay

### *Location, Quantity, Quality*

Alkaline igneous complexes are known to occur in the Precambrian Shield areas of Paraguay but their phosphate potential has not been fully assessed even though the complexes represent an extension of the phosphatic carbonatite belt in southern and western Brazil (Notholt, 1994a).

### *Agronomic testing and use*

No record was found of agronomic testing of phosphate rock in Paraguay.

## Peru



### *Location, Quantity, Quality*

#### Jurassic

In central Peru phosphate rock occurs in the Jurassic Aramachay Formation (Pucara Group) between Lake Junin and Huancayo (Grose, 1989; Loughman, 1984; Loughman and Hallam, 1982; Loughman and Hallam, 1983). The sequence of phosphate rock, black bituminous shale or mudstone, chert and limestone is similar to, but thicker than, the Phosphoria Formation of the western USA. There are two main phosphatic zones. The upper zone includes a phosphorite bed 17 m thick containing about 11%  $P_2O_5$ . The other zone ranges from 1 m to 20 m in thickness with 5-20%  $P_2O_5$ . The Aramachay Formation is part of the Pucara Group, which is a thick sequence of marine shelf and miogeosynclinal sediments developed along the western margin of the Brazilian Platform. A similar facies is reported to occur in the Utcubamba Valley area in the Amazonas Department of northern Peru, although no phosphatic deposits have yet been encountered in this area.

#### Cretaceous

Phosphate rock occurrences in the Middle Cretaceous Machay Formation have been identified in the province of Huancané, Puno Department; Yauli, Junín Department; Ica, Ica Department; and Calendín, Cajamarca Department, although none of the deposits is of economic importance. The richest occurrence is located near Ocucaje where a 0.3 and 1.0 m thick conglomeratic bed with phosphatic nodules up to 7 cm in diameter can be traced for a distance of several kilometres. Samples from the village of Estanque are reported to contain up to 14%, averaging 9%  $P_2O_5$ . In the Buenaventura hills, east of the mining town of Morococha, Yauli Province, oolitic phosphate is associated with bituminous and black laminated limestones (Notholt, 1999).

#### Tertiary



Peru possesses the largest resources of sedimentary PR in South America. These are the Middle Miocene deposits discovered in 1955 in the Sechura Desert, Piura Department, in the northwestern part of the country. They lie in a sedimentary basin some 260 km long and 80 km wide along the coast, within which relatively unconsolidated Miocene sediments, dipping very gently to the east or southeast, crop out over large tracts of the desert. In the western part, called the Western Depression, phosphate-bearing marine strata about 200 m thick consist primarily of interbedded friable, light-brown to black phosphorite, and white to black diatomite (McClellan, 1989). The Sechura PR resource, known as the Bayóvar deposit, is one of the tenth largest phosphate deposits in the world.

Three major phosphate zones have been delineated in this area, of which the Diana ore zone in the Lower Diatomite and Phosphorite member is the richest and thickest. It contains an average of 7-8%  $P_2O_5$  and ranges from 35 m to 40 m in thickness. The lower part of the Diana ore zone averages about 21 m in thickness, with 6.4%  $P_2O_5$ . Individual beds are usually less than 1 m thick and grade about 18%  $P_2O_5$ . The richest part of the upper ore zone is about 10 m thick and contains 11.6%  $P_2O_5$ . Phosphate occurs mostly as pellets of carbonate fluorapatite (francolite), mixed with diatom fragments, volcanic glass, soluble Na, K and Mg salts, sponge spicules, gypsum, mica, and organic matter. All the subsurface phosphorites disintegrate in water, cementation being a rare surface feature.

An area of 48 km<sup>2</sup> on the southwestern side of the Sechura Depression delineated as being the most favourable for development has been investigated over the last 45 years since their discovery in 1955. This area has been estimated to contain at least 250 Mt of recoverable concentrate averaging 30.5%  $P_2O_5$ . Reserves to a depth of 30 m are estimated at 58 Mt and 514 Mt in areas designated Area 1 and Area 2 respectively (McClellan, 1989).

Washed phosphate rock contains 26-29%  $P_2O_5$  (5.5-5.8% soluble in citric acid). Calcination increases the  $P_2O_5$  content to 32-34% but reduces the citric acid solubility to 3.5-4.6%  $P_2O_5$  (Notholt, 1999). Lim and Gilkes (2001) confirmed that beneficiation of apatitic PR (including Sechura PR) by calcination will adversely affect the agronomic effectiveness of RP used as a direct application fertilizer.

South of the Sechura Desert, in Ica Province, phosphatic nodules of similar age occur in the Pisco Formation; eleven distinct nodule zones have been identified but their low concentration prevents the occurrences being of commercial interest.

### Guano

Accumulations of bird guano occur on at least 147 islands and 21 mainland locations, located between the island of Lobos de Tierra (6°26'S, 80°05'W) in the north to the border with Chile. Guano accumulates occur where guano birds, including cormorants, pelicans and gannets, congregate in very large numbers. In 1966 the bird population was estimated at 12 million (Notholt, 1999).

### *Production*

#### Sechura

The development of the Sechura deposits was initially investigated in 1961 and agreement was reached with the Peruvian Government for the provision of an initial annual production capacity of about 1 million tons of phosphate concentrate. Mining tests were conducted using a bucket-wheel excavator capable of handling 1,000 m<sup>3</sup> per hour but to date no significant shipments had been made.

Tendering for the private development of the Bayóvar phosphate deposits located in Sechura Province, took place in 2001 but the process was postponed due to political uncertainty. The project involves the exploitation of 816 Mt of accessible reserves of a phosphate ore-body that is equivalent to 262 Mt of rock concentrate at 30% of  $P_2O_5$ . Potential reserves are estimated at 10,000 Mt. The project involves the establishment of a 3 Mt/year mine and beneficiation plant together with the infrastructure and port for rock export and a DAP production unit with a capacity of not less than 1 Mt/y. The Peruvian Government consider that the Bayóvar project will contribute to Peru's economic growth and also encourage the

development of the agriculture, mining, agro-industry, cement, construction, and oil sectors of the economy (Copri, 2001).

### Guano

Beginning in the 1840s, the guano boom, made possible by the droppings from millions of birds, proved to be a bonanza for Peru. By the time that this natural resource had been depleted three decades later, Peru had exported some 12 million tons of the fertilizer to Europe and North America, where it stimulated the commercial agricultural revolution. During this period, the guano trade provided an income of approximately US\$500 million to the State of Peru. Small shipments were made to Germany, the United Kingdom and the U.S.A. in 1804. Large commercial shipments began in 1841 and the production of guano was of primary importance to the agricultural economy of Peru and the country's principal export commodity for many years. The Chincha Islands (13°39'S, 76°25'W) were among the principal sources of supply; others included Isla de Vieja (14°16'S, 76°14'W), Puntas San Juan and San Nicolas (approximately 15°22'S, 75°07'W), Punta Culebras (9°53'S, 78°13'W), Islas Santa Rosa (9°01'S, 78°40'W) and Isla Don Martin (11°03'S, 77°40'W). Exports decreased steadily after 1875 until the end of the century. During this period the guano deposits were worked under a wasteful contract system that threatened the destruction of the guano-bird colonies. Reserves were reduced from an estimated 12 million tons in 1840 to a mere 2 million tons in 1985. Since about 1909, however, production has been strictly controlled by the Peruvian government and because of domestic needs, only a relatively small proportion of the annual output was made available for export. About 7.7 Mt of guano was produced and marketed during the period 1909-1965. The largest single producer was Isla la Vieja with nearly 750,000 tons followed by the neighbouring island of Santa Rosa and the islands of the Guanape group (8°32'S, 78°59'W) with slightly smaller totals. The exploitation of guano declined after the Second World War with the advent of synthetic fertilizers.

Guano was removed from each island at intervals of at least 2 years to permit the accumulation of a rich white guano containing about 15% N, 10-12% P<sub>2</sub>O<sub>5</sub> and 2% K<sub>2</sub>O. A relatively small amount of red or 'fossil' guano similar to that produced in Chile was obtained at one or two localities, containing only a few per cent N but as much as 15% P<sub>2</sub>O<sub>5</sub>. The bulk of the output was sold direct to farmers or pulverised and blended to provide a uniform product. Small shipments of between 8,000 and 12,000 tons were made to the USA, Europe and Japan, where the prices obtained greatly exceeded those in Peru. Demand for guano in Peru greatly exceeded supply mainly because a cheap official sales price was maintained to encourage the use of Peruvian guano for food crops. The price of white guano in 1961 was stated to be about £12 per ton (Notholt, 1999). There has been a recent resurgence of interest in guano for use as a fertilizer in organic food production. Pelletised Peruvian bird guano is marketed in the USA but the quantity currently exported from Peru is not known (Granite Hydroponics Organic Nutrients, 2001).

*Sources:* (Abele, 1957; Allen and Dunbar, 1988; Angeiras et al., 1981; Anon., 1982a; Anon., 1982b; Anon., 1984; Baker and Burnett, 1988; Barrazuela et al., 1995; Baturin, 1999; Burnett, 1974a; Burnett, 1974b; Burnett, 1977; Burnett, 1990; Burnett et al., 1988; Burnett et al., 1982; Burnett and Oas, 1979; Burnett and Soutar, 1979; Burnett and Veeh, 1978; Cabrera, 1962; Caldas et al., 1980; Charter et al., 1995; Chien et al., 1993; Chien et al., 1995; Glenn, 1990; Gonzales, 2000; Granite Hydroponics Organic Nutrients, 2001; Grose, 1989; Hammond, 1991; Jewell, 1994; Kim, 1984; Kim and Burnett, 1985; Kpomblekoua and Tabatabai, 1994; Krajewski et al., 2000; León et al., 1986; León and Hammond, 1983; Loughman, 1984; Loughman and Hallam, 1982; Loughman and Hallam, 1983; McClellan, 1989; Notholt, 1994a; Pardo, 1983; Rajan et al., 1991b; Rude and Aller, 1991; Rueegg, 1957; Sandstrom, 1990; Savage, 1987; Sinclair et al., 1993a; Spillmann, 1952; Stoll, 1961; Suarez et al., 1997; Suess, 1981; Yan et al., 1996)

#### *Agronomic testing and use*

### Annual and perennial crops

Alegre and Chumbimune (1991) conducted agronomic experiments to evaluate phosphorous sources and rates in acid soils using five levels of Bayovar phosphate rock (BPR) and TSP in flooded rice, corn and caupi. The best response of maize was at the rate of between 180 and 200 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>. This application rate was also tested in farmers' fields for annual crops and as a base application in perennial crops (citrus, coffee and cocoa). Caupi and rice showed no response to P fertilization because of their low P

requirements. A residual effect was observed with the BPR at all application rates. It was concluded that the best particle size for phosphate rock used as a direct application fertilizer is 60-140 mesh for low forest soils. Best pH for phosphate rock application was lower than 5.0 and also a good response was obtained in soils high in organic matter. The BPR was most efficient in acid low forest soils and in soils with high contents of organic matter and high P-adsorption capacity.

Chien et al. (1993) studied the effect of a range of three phosphate rock sources (Hahotoe rock, Togo; Tilemsi rock, Mali; and Sechura rock, Peru) in comparison with triple superphosphate (TSP), on soybean seed yield and biological nitrogen fixation by the soybean crop. The greenhouse study was carried out using acid Hartsells slit loam limed to pH 5.2 and incubated with 8.5 mg N kg<sup>-1</sup> as (KNO<sub>3</sub>)-N-15 and sucrose for 2 months prior to planting. Fertilizer P was incorporated into the soil at 12.5, 25, 50, and 100 mg P kg<sup>-1</sup> rates. The relative agronomic effectiveness (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 relative agronomic effectiveness values of the three PRs with respect to TSP (RAE = 100%) in terms of influencing the amount of biological nitrogen fixation were Hahotoe rock (3.0%) > Tilemsi rock (43.4%) > Sechura rock (71.2%).

Chien et al. (1995) evaluated the effect of liming on the agronomic effectiveness of Pesca and Huila PR from Colombia and Sechura PR from Peru as compared with TSP in a greenhouse experiment for an Al-tolerant soybean cultivar grown on an acid Ultisol. On both unlimed (pH 4.4) and limed (pH 5.0) soils, the agronomic effectiveness of P sources in terms of increasing seed yield followed the order of TSP > Sechura PR > Huila PR Pesca PR > check, an order similar to that of solubility of P sources. Liming slightly decreased the effectiveness of Pesca PR, whereas liming had no effect on Huila PR. A significant increase in agronomic effectiveness was observed upon liming for Sechura PR and TSP. On unlimed soil, the relative agronomic effectiveness (RAE) of PRs were: Pesca PR (31%) < Huila PR (42%) < Sechura PR (84%) whereas on the limed soil, the RAE values were Pesca PR (8%) < Huila PR (24%) < Sechura PR (66%). Chien et al (1995) concluded that for soybean cropping, the use of PR with respect to TSP is more favourable in unlimed soil than in limed soil, provided that the soybean plant is relatively Al-tolerant.

## Pasture

Use of rock phosphate for the fertilization of pastures in Peru was first investigated in 1986 (López and Silva del A, 1986). Rajan et al. (1991b) evaluated the agronomic effectiveness of an unground reactive phosphate rock from Sechura (SPR) compared with monocalcium phosphate in a severely P deficient and highly P retentive soil (vitrandepto) over a period of three years using mostly ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*). Soil pHs were adjusted to pH 5.1, 5.3, 5.6 and 6.4. A negative linear relationship was obtained between soil pH and the logarithm of yield in SPR treated plots. The agronomic effectiveness of SPR relative to monocalcium phosphate increased with time at all pHs. Relative agronomic effectiveness at soil pHs 5.1, 5.3, 5.6 and 6.4 were respectively 58, 60, 18, and 5 in year one; 118, 125, 77 and 38 in year three (calculated at fertiliser rates which produced near maximum yields). At pH 5.3, as the rate of application increased the relative agronomic effectiveness of the phosphate rock generally decreased in year one but was enhanced in the intermediate rates in years two and three. The data for ground cover of clover gave a similar trend to that for herbage yield and P uptake. Vela Alvarado (1996) illustrated the potential for reclaiming degraded pasture using SPR and legumes.

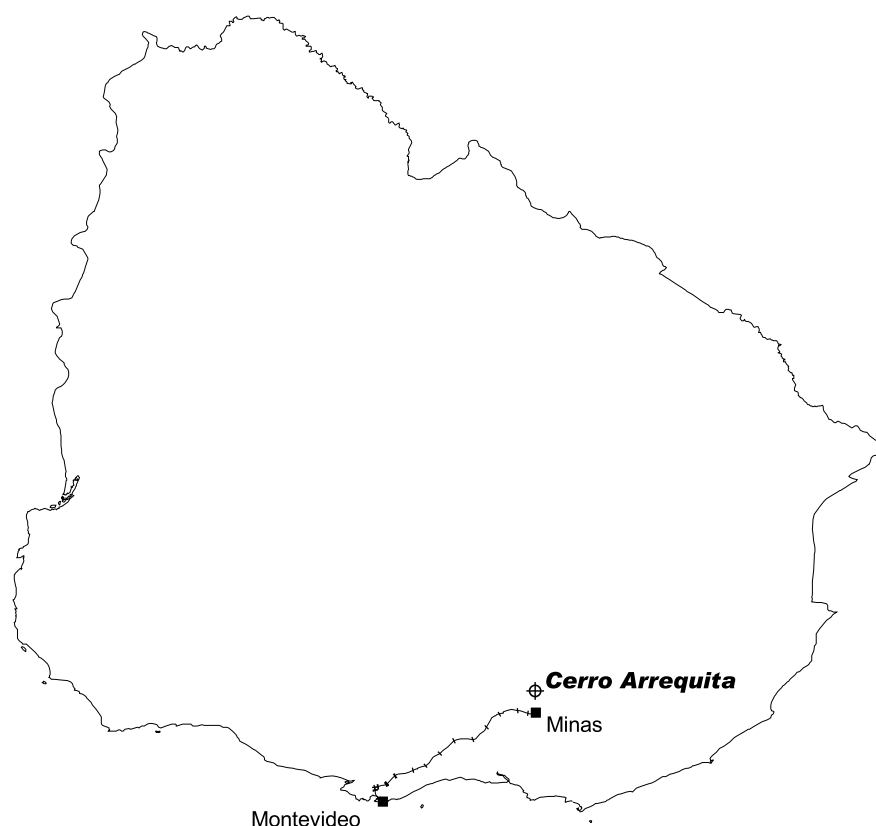
Numerous agronomic evaluations of the use of SPR for pasture fertilization have been carried out in New Zealand and Australia (Bolland and Gilkes, 1997; Gregg et al., 1988; Hedley and Bolan, 1997; Hughes and Gilkes, 1986; Morton et al., 1994; Perrott et al., 1992; Rajan et al., 1992; Rajan et al., 1991a; Roberts et al., 1994; Robinson et al., 1992; Sinclair and Johnstone, 1995; Sinclair et al., 1993a; Sinclair et al., 1993b; Sinclair et al., 1998; Sinclair et al., 1990; Syers and Mackay, 1986). Sinclair et al. (Sinclair et al., 1993b; Sinclair et al., 1998) compared the agronomic efficiency of reactive phosphate rocks (RPRs) from Sechura, Peru (SPR) and North Carolina, USA (NCPR) with triple superphosphate (TSP) as phosphate (P) fertilizers for permanent grass/clover pastures in four field trials in New Zealand. Trial sites ranged in initial pH (in water) from 5.7 to 6.3 and in rainfall from 712 to 1338 mm yr<sup>-1</sup>. SPR and NCPR were used

in the unground 'as-received' state. Fertilizers were applied annually for six years. Pasture was harvested by frequent mowing, and herbage dry matter (DM) yields were measured at each cut. For all sites combined, DM production from RPRs was initially significantly less than from TSP but it improved relative to TSP with time. Herbage P concentrations showed a similar pattern of RPR performance relative to TSP to that shown by DM production except at the highest application rate where TSP always supported much higher herbage P concentrations than RPR. Sinclair et al. (1993b) explained the pattern of DM production from RPR relative to TSP with the hypothesis that P dissolved from RPR entered the plant- available P pool and was used with the same efficiency as P entering by dissolution of TSP. Sinclair et al. (Sinclair et al., 1993b) concluded that the advantage of RPRs in comparison to soluble P fertilizers for permanent pastures was considered to lie in their lower price and not in greater nutrient efficiency. Economic advantage was calculated in terms of the return on investment from establishing and maintaining a pool of RPR in the soil large enough to release the required annual amount of plant-available P compared with the cost of annual applications of soluble P fertilizer.

Sinclair et al. (Sinclair et al., 1998) also evaluated the Sechura (SPR) and another five phosphate rocks (PRs), North Carolina (NCPR), Egypt (EPR), Arad (APR), Zin (ZPR), and Nauru (NPR) by comparison with single superphosphate (SSP) as annually applied P fertilisers for mown ryegrass / white clover swards at two sites, in the central North Island and southern South Island of New Zealand over a period of three years. Overall, responses were in the order SSP>SPR similar to NCPR>APR similar to EPR similar to ZPR similar to NPR. The agronomic performance of PRs was better related to their extractability by formic acid than to extractability by citric acid.

*Sources:* (Alegre and Chumbimune, 1991; Barrazueta et al., 1995; Bolland and Gilkes, 1997; Chien et al., 1993; Chien et al., 1995; Condon et al., 1994; Ghani et al., 1994; Gregg et al., 1988; Hammond, 1991; Hammond et al., 1986; Hedley and Bolan, 1997; Hughes and Gilkes, 1986; León et al., 1986; León and Hammond, 1983; López and Silva del A, 1986; Morton et al., 1994; Perrott et al., 1992; Piccini and Azcon, 1987; Rajan et al., 1992; Rajan et al., 1991a; Rajan et al., 1991b; Roberts et al., 1994; Robinson et al., 1992; Sinclair and Johnstone, 1995; Sinclair et al., 1993a; Sinclair et al., 1993b; Sinclair et al., 1998; Sinclair et al., 1990; Suarez et al., 1997; Syers and Mackay, 1986; Vela Alvarado et al., 1996; Yan et al., 1996)

# Uruguay



## *Location, Quantity, Quality*

Superficial deposits of phosphatized igneous rock occur at Cerro Arrequita, a hill situated some 120 km northeast of Montevideo and about 16 km north of the railway terminus of Minas in the Laralleja Department. The hill is about a 1.5 km wide and about 4 km long, its north-western edge formed by a cliff more than 90 m in height composed of porphyritic felsite. Most of the phosphate occurs in fissures and caves in the lower part of the cliff as well as in the associated talus deposits. It is assumed that the rocks have been altered by the action of phosphatic solutions derived from guano and this produced a soft sponge-like mass a few inches to several feet in thickness. The deposits are reported to extend over an area of 2.5 km<sup>2</sup>. Analysed samples range from 13.0 to 27.92% P<sub>2</sub>O<sub>5</sub>, 3-15% Al<sub>2</sub>O<sub>3</sub> and 4-11% Fe<sub>2</sub>O<sub>3</sub> (Notholt, 1999). The deposit has little commercial significance in view of the fact that most of the phosphate occurs in combination with aluminium and iron as variscite and strengite (Eckel and Milton, 1953)

## *Agronomic testing and use*

No information on agronomic testing was encountered.

# Venezuela



## *Location, Quantity, Quality*

### Cretaceous

Upper Cretaceous phosphorite resources total about 254 Mt and are contained in (i) the black phosphorites of the deep water La Luna Formation in the Tachira, Merida, Trujillo and Lara States, and (ii) the white arenaceous phosphorites of the relatively shallow water Navay Formation in southeastern Tachira State.

The La Luna Formation is one of the most economically important sequences in western Venezuela. It usually comprises thin-bedded, dark grey to black, partially bituminous limestone, interbedded with occasional very thin black shales, black chert and numerous black phosphorite beds. Substantial tonnages of phosphorite have been delineated in central Merida (110 Mt with 18%  $P_2O_5$ ), for example the Chiguara deposit (Casanova and Elizalde, 1988) and, to a lesser extent, in Zulia State (17.8 Mt, grading 16%  $P_2O_5$ ) where several phosphorite beds have been identified. The main bed of the La Molina deposit ranges from 1 to 2.2 m thick and averages 1.8 m thick where it was exploited in the Lobatera mine. As many as 15 individual phosphorite beds have been outlined elsewhere in central Tachira State where the La Luna Formation occurs extensively but has not yet been completely evaluated (Notholt, 1994a). The more recently discovered Monte Fresco deposit, located close to Lobatera, has reported proven reserves of 55 Mt (Romero, 1991).

In southeastern Tachira State, the Navay Formation is the lateral arenaceous (sandy) equivalent of the La Luna Formation. Phosphate is common throughout the formation where it occurs mainly as hard, white to yellowish, sandy phosphorite, characteristically containing 60-80% apatite and more than 16% quartz in a

matrix of fine-grained apatite, quartz, calcite, and minor feldspar. All the phosphorites of the Navay Formation are rich in silica. In the Los Monos area, resources of 80 Mt grading 16% P<sub>2</sub>O<sub>5</sub> have been reported by Notholt (1994a), whereas Romero (1991) reports 96 Mt of proven reserves.

Total proven, probable and inferred reserves in the La Luna and Navay Formations are reported to be 285 Mt and 1557 Mt, respectively (Romero, 1991).

### Tertiary

The Oligocene-Miocene Falcon Basin in northern Venezuela contains substantial resources of phosphate rock, especially on and around Cerro Riecito, which is located about 50 km south east of Jacura, in the eastern part of Falcon State. Phosphorites form thick lenticular beds that vary from a few metres to several hundred metres in length and normally between 2 m to 12 m thick. These occur within the Miocene Capadare Formation, which is sequence of massive limestones and dolomites over 135 m thick. It is thought that the phosphorite may have been formed mainly by redeposition and secondary enrichment. About 25 Mt with 21.6% P<sub>2</sub>O<sub>5</sub> is contained in the Riecito deposit, and about 20 Mt averaging 25.3% P<sub>2</sub>O<sub>5</sub> in the central Lizardo deposit (Notholt, 1994a).

### Recent guano/replacement deposits

Recent guano deposits occur on Gran Roque (11°57'N, 66°41'W) in the Los Roques group of islands, where a replacement deposit has evolved along a steeply dipping shear zone developed in gabbro in the western part of the island. The deposit is nearly 120 m long, 4.5 m wide, and extends to a depth ranging from 2 to 8 m. A surface layer 1.5 m thick contains 33.2% P<sub>2</sub>O<sub>5</sub> or more, but the phosphate content decreases with depth and below 10m the phosphatized rock contains less than 6.7% P<sub>2</sub>O<sub>5</sub>. Proved reserves were estimated in 1938 to be 4,200 tons, with an additional probable reserve of 1,000 tons. The phosphatized rock consists essentially of secondary quartz and dahllite, the latter showing extensive replacement by barrandite. On Los Monjes (12°30'N, 70°55'W) phosphatisation extends to an average depth of about 25 cm with estimated reserves of 2,800 tons, and an additional reserve of 2,200 tons on the other islands of the Los Monjes group. Samples contain a maximum of 31-33% P<sub>2</sub>O<sub>5</sub> in the surface guano and replacement phosphates. Deposits of phosphatic guano also occur on Isla La Orchila (11°48'N, 66°10'W), which was the most important source of guano.

The proven reserves of rock phosphate in Venezuela are greater than 213 million t, which represent on average 23 million t P. These reserves would be adequate to satisfy the annual P demand in Venezuela (49381 t/yr) for the next 236 years (Casanova, 2001).

*Table 11. Rock phosphate reserves (1000t) (Casanova, 2001)*

State	Proven	Probable	Inferred	Total
Tachira	169,314	69,115	1,794,680	2,233,109
Falcon	39,000	1,000	-	40,000
Merida	5,200	57,700	96,700	159,600
Zulia	-	-	17,000	17,000
Bolivar	-	-	200,000	200,000
Total	213,514	327,815	2,108,380	2,649,709

The Riecito and Navay rocks are significantly more reactive than the Monte Fresco phosphate rocks (Casanova and Elizalde, 1988) and also the Lobatera PR.

*Table 12. Chemical and mineralogical composition of Venezuelan phosphate rocks (Casanova, 1991)*

	Monte Fresco II	Monte Fresco II (altered)	Monte Fresco (ground rock)	Riecito	Navay
P <sub>2</sub> O <sub>5</sub> (%)	27.5	33.3	19.5	25.7	19.5- 26.8
CaO (%)	49.5	45.5	40.2	38.3	30.4- 43.8
Al <sub>2</sub> O <sub>3</sub> (%)	0.6	2.0	4.1	3.9	4.5-4.6
Fe <sub>2</sub> O <sub>3</sub> (%)	0.8	1.2	2.5	1.4	1.1-1.2
Cd (ppm)	11	14	15	17	30-32
% of Total P <sub>2</sub> O <sub>5</sub> soluble in 2% citric acid (30 min.)	4.7	16.0	8.0	23.8	21.0- 32.5
% of Total P <sub>2</sub> O <sub>5</sub> soluble in 2% formic acid (30 min.)	9.8	15.2	10.3	26.8	39.8- 53.2
Apatite (%)	61.9	89.4	nd	49.9	37.8
Quartz (%)	3.0	6.4	nd	28.7	53.7
Calcite (%)	29.0	-	nd	7.2	10.9

### *Production*

Venezuela is the third most important phosphate rock producer in Central and South America (Table 2). The Riecito mine operated from 1956 and closed in 1981 for economic reasons but was re-opened in 1986. Mine production capacity is 500,000 tpa but the actual production has fluctuated from 85,000 tonnes in 1988 to 366,000 tonnes in 1999. All the phosphate rock is used for manufacturing fertilizers. Output from the Lobatera mine in Tachira State has been minimal (initially only 100 tonnes per day) and the ground phosphate rock was used as direct application fertilizer either locally or in the neighbouring areas of Colombia (Notholt, 1994a). The ground rock is reported to be effective for the fertilization of coffee, cacao and sugar cane grown on acid soils (Notholt, 1999).

Deposits of phosphatic guano and of phosphatized igneous and coral rock were worked during the latter half of the 19th century on Islas de Aves, Gran Roque, Isla La Orchila and several other islands near the Venezuelan coast. The most important source was Isla La Orchila from which it is estimated that more than 25,000 tons of guano grading between 10 and 32% P<sub>2</sub>O<sub>5</sub> were extracted between 1867 and 1888 when working ceased. It is reported that some of the production from the Islas de Aves was exported to Germany for superphosphate manufacture (Notholt, 1999).

National research institutes, universities, technical assistant companies and producers including FONAIAP, PALMAVEN, PEQUIVEN, INTEVEP, IVIC and CVG have investigated the production of low-cost phosphate fertilizers from the partial acidulation of indigenous rock (PAPRs). The investigations were carried out in collaboration with IFDC (USA), CIRAD and TECHNIFERT (France), IAEA (Austria) and CIAT (Colombia). PAPR was produced in a pilot plant from bulk samples taken from the three major phosphate rock deposits: Monte Fresco and Navay (Tachira state) and Riecito (Falcon state). The success of agronomic trials using the PAPR resulted in PEQUIVEN designing and constructing a plant to produce PAPR from Riecito phosphate rock. The plant has a production capacity of 150,000 t/year via a one-step acidulation and granulation process. The PAPR is commercialised in Venezuela under the name of “Fosfopoder” (Casanova, 2001).

*Sources:* (Aarden et al., 1978; Aguerrevere and Lopez, 1939; Anez, 1984; Barron, 1982; Bellizzia, 1982; Cardenas, 1985; Carmona, 1971; Casanova, 2001; Davey, 1950; Erikson et al., 1996; Erlich et al., 1996; Erlich et al., 1999a; Erlich et al., 2000; Erlich et al., 1999b; Gonzalez, 1980; Lamus et al., 1989; Lorente et al., 1996; Martínez, 1987; Martínez, 1988; Martínez et al., 1987; McConnell, 1941; Notholt, 1994a; Ponte, 1951; Rodriguez, 1985; Rodriguez, 1980; Rodriguez and Anez, 1985; Rodriguez, 1977; Rodriguez, 1981a; Rodriguez, 1981b; Rodriguez, 1989; Rodriguez et al., 1975; Rost, 1938; Sanchez and Cochrane, 1980; Santeliz, 1971; Santeliz, 1972; Savage, 1987; Stoufer and Scherer, 1996; Tiessen et al., 1994; Tiessen et al., 1996; Toro et al., 1996; Urbani, 1996; Useche, 1985; Yoris et al., 1996; Zambrano, 1978)



Most of the agricultural soils of Venezuela are acid, with high P fixation capacity (Casanova, 2001). If a value of 0.2 mg P/l is considered as optimum to reach maximum growth in crops with high P requirements and 0.02 mg P/l for crops with lower P requirements, it is concluded that there was a low P availability in most of the soils studied (Casanova, 2001).

Research on the effect of phosphate rocks on crops growth and yield has been conducted in Venezuela since 1937 with Lobatera phosphate rock. The exploitation of new deposits at Monte Fresco and Navay has produced new research in the last 7 years based on ground and modified phosphate rock for annual, permanent and forestry crops. Research has been conducted since 1987 to assess the agronomic and economic efficiency of Venezuelan phosphate rocks compared with highly soluble, imported phosphate fertilizers. The results indicate the potential of finely ground rock phosphate for annual and perennial crops (pasture, coffee, sugar cane) and forestry. There is also potential for using finely ground PR and acidulated PR for annual crops with higher P requirements (Casanova, 1991).

### Pasture

An agronomic evaluation of phosphate rock and slag on the acid soils of Upata, Bolivar State was conducted to measure their effect on the chemical properties of the soil and growth of *Brachiaria decumbens* (Casanova et al., 1993). The treatments included (i) three sources of phosphate rock (Riecito and Lizardo of Falcon State and Monte Fresco of Tachira State) at four rates of  $P_2O_5$ /ha (0, 50, 100, and 200), (ii) one source of high-solubility P (triple superphosphate (TSP) at the same rates), and (iii) three levels of calcium applied as basic slag from the Orinoco Steel Company (0, 300, and 600 kg Ca/ha). A base fertilizer was applied to all plots (217 kg/ha Urea, 50 kg/ha KCl, and 78 kg/ha magnesium sulphate). The best relative agronomic effectiveness (RAE) values at each sampling time were obtained with the Monte Fresco phosphate rock at the rate of 200 kg  $P_2O_5$ /ha and 600 kg Ca/ha as slag. There was a tendency for the RAE value to improve with each sampling, apparently due to the slow release of phosphorus from the phosphate rock and its residual effect. There are also values of RAE that show better dry matter production than the highly soluble P-source (TSP). Soil available P and Ca increased with phosphate rock and slag application from 5 and 200 mg/kg to 25 and 400 mg/kg, respectively, after 2.5 years of the experiment. Phosphorus uptake changed from 0.1% in the check plot, which is insufficient to supply the P requirement of grazing cattle in the tropics, to a value higher than 0.2%, depending on the sampling time. Soil pH increased slightly from 5.2 to 5.6 with phosphate rock, and to 6.2 when basic slags were applied (Casanova et al., 1993).

A field experiment was carried out on phosphorus deficient Inceptisol located in the Navay cattle-producing zone, in the south of Tachira State. The main objective was to assess the agronomic effectiveness of three sources of phosphorus, including ground Monte Fresco rock phosphate (MF-RP; 24%  $P_2O_5$ ) at the rate of 0-50-100 and 150 kgs of  $P_2O_5$  ha<sup>-1</sup> for forage (*Brachiaria decumbens*). Dry matter decreased in all the treatments and for the four cuts. The residual effect was observed with the MF-RP. Plant tissue phosphorus analyses for the two first cuts were in the range of 0.15 to 0.30 %, which may be considered acceptable. For the third and fourth cuts the tissue phosphorus level decreased significantly, probably due to the dry season (Gamboa and Gamboa, 1991). Gamboa (1991) reported the results of earlier trials (Casanova et al. 1987) that compared the response of *Brachiaria decumbens* in the Puerto Ordaz area, to Monte Fresco II rock phosphate and TSP. The response to the two P sources was more or less similar.

Residual effects of Monte Fresco, layers 1 and 2, and San Joaquín de Navay phosphate rocks, were evaluated compared to TSP using *Brachiaria decumbens* as the test plant. Six consecutive cuttings every 45 days were carried out randomised semi commercial 1 ha plots. Relative production compared of green and dry matter compared to TSP increased with the number of cuttings. Monte Fresco (layer 2) rock was more productive than SFT from the fourth cutting; San Joaquín de Navay rock exceeded SFT from the fifth cutting and Monte Fresco (layer 1) did better than SFT from the sixth cutting. The best response was obtained using 200 kg  $P_2O_5$  ha<sup>-1</sup> for all phosphorus sources. Results showed the following trend: MF-2 > SJN > MF-1. The central hypothesis for semi commercial test was partially demonstrated since the best

response was obtained using Monte Fresco (layer 2) rock and rates of 200 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> (López et al., 1991d).

The effectiveness of natural phosphate rock (NRP) as fertilizer in acid soils cultivated with pastures was measured in two experiments established between 1987 and 1988. The experimental plots were sited on loamy, fine, kaolinitic, isohyperthermic Typic Paleustults in the west of Guárico State and fine, kaolinitic, isohyperthermic Typic Paleustults in the east of Guárico State. Both soils have low natural fertility. The treatments were 0-250-500-750 kg of NPR/ha WITH duplicate treatments combined with triple superphosphate (TSP), zinc and copper. Dry matter yields obtained in the first year were statistically significant between treatments. In west of Guárico State the yield of the control was 49% of the maximum, which was obtained with TSP; in the east of Guárico State this value was 27 % of the treatment with 750 kg of NPR/ha, plus TSP. In the third year, the highest yields in both soils were obtained with the highest NPR rates, demonstrating the residual effect of NPR. Soil P and Ca increased too in parallel with the pasture response, confirming that it is possible to improve fertility of acid soils with the application of NPR. The crop response was at less than 10 ppm P in the soils, indicating that in crops of low requirements, the critical level is less than that established for other crops (López et al., 1994).

An experiment was performed during 1987 in an Oxic Paleustults soil from Cojedes State (Venezuela) in order to assess the use of natural phosphate rock (NPR) as a P fertilizer for pasture cultivated in very acid (pH 4.2), sandy loam, soils with very low fertility and high aluminium saturation. Three levels of NPR were used: 250, 500 and 750 kg/ha; and duplicates of these treatments were combined with TSP, zinc and copper. *Andropogon gayanus* was established with a basic fertilization. The evaluation was based on: dry matter yields, plants number by effective area. Soil analyses were made to determine the impact of the fertilizer treatments on pH, calcium, phosphorus, zinc, and copper levels. Dry matter yields obtained in four years showed the high response of the pasture to P-fertilization. The dry matter yield increased 4000 kg/ha and 2800 kg/ha with phosphorus application (like TSP or NPR) and zinc and copper, respectively. In the last two years, the highest yield was obtained with 750 kg/ha NPR + TSP, but the effect of NPR was more important than the effect of TSP. P and Ca contents increased in the soil and crop indicating that it was possible to improve the mineral nutrition of cattle through improvements in soil fertility. The results suggested that NPR is an appropriate P fertilizer in acid, low pH and low Ca and low P soils (López et al., 1997).

The possible improvement in solubility and potential efficiency of the two main Venezuelan phosphate rocks Monte Fresco (MF) and Riecito (R) treated by acidulation, was evaluated in a series of laboratory and greenhouse experiments conducted using isotopic dilution technique with <sup>32</sup>P. The release of P from these phosphate rocks (PR) and its migration through the soil-plant system was also investigated. Seven P sources were evaluated: the two ground phosphate rocks (MF and R), MF and R at 15 and 40% acidulation with H<sub>2</sub>SO<sub>4</sub> (MF 15%S and R 40%S), MF and R at 40% acidulation with H<sub>2</sub>SO<sub>4</sub> + monoammonium phosphate (MF 40%C and R 40%C) with triple superphosphate (TSP) as the reference fertilizer. Three Venezuelan soils differing in chemical and physical properties were used to evaluate the agronomic efficiency of the fertilizers using *Agrostis communis* as the test plant. L value, which is an index of the amount of isotopically exchangeable P in soil (measured in the plant), was determined and correlated to the PR's solubility in water, neutral ammonium citrate and 2% formic acid. The impact of the quality and residual effect of the PR's on dissolution rate was evaluated through their dissolution patterns obtained by continuous P extraction with 2% formic acid for eight hours. The results indicate that the L value is a good indicator of the agronomic potential and efficiency of phosphate sources. L values obtained in each soil showed a high correlation with the PRs solubility obtained by any of the P extraction methods. The 2% formic acid method showed the highest correlation coefficient. The agronomic efficiency of the evaluated PRs followed the trend: R 40%C >> R 40%S >> MF 40%C >> rough R >> MF 15%S >> rough MF, which corresponds to the trend in PR solubility. Riecito PR appears to produce a better agronomic performance than Monte Fresco PR, and partial acidulation with H<sub>2</sub>SO<sub>4</sub> + monoammonium phosphate a better performance than partial acidulation with H<sub>2</sub>SO<sub>4</sub> alone (Pérez et al., 1995).

Sorghum, soybean, maize (corn)

An agronomic evaluation of phosphate rock (PR) on the acid soils of Guarico and Anzoategui States was conducted to measure the effect on soil available phosphorus (P); grain yields of sorghum (*Sorghum bicolor* (L.) Moench) and soybean (*Glycine max* (L.) Merr), and P absorption by these crops (Casanova and Solorzano, 1994). Treatments used were: triple superphosphate (TSP), North Carolina phosphate rock (NCRPR), compacted NCRPR with TSP at 60-40% and 70-30% (NCRPR 60/40 NCRPR 70/30), compacted Venezuelan Monte Fresco phosphate rock 60-40% and 70-30% (MFPR 60/40, MFPR 70/30), finely ground Monte Fresco phosphate rock (MFPR), finely ground Navay phosphate rock (NPR), and a check plot with no P source added. Five rates were applied (0, 50, 100, 150, and 200 P<sub>2</sub>O<sub>5</sub>/ha) broadcasted and incorporated prior to planting. A basic fertilization of N, K, S, Mg, and Zn was uniformly applied to ensure an adequate supply of these nutrients. Soybean seeds were inoculated with *Bradyrhizobium japonicum*. Maximum yields in all cases were obtained with TSP, however, in most cases there were no statistically significant differences between TSP and NCRPR or compacted (60/40 and 70/30). The compacted Venezuelan phosphate rocks also gave significantly higher yield and relative agronomic effectiveness (RAE) responses demonstrating the potential of these P sources for annual crops. Finely ground Venezuelan PRs increased yields and RAE as compared to the check plot, but they gave the lowest response of all P sources. Soil available P after harvest had a tendency to increase where any source of P was applied or when the application rates were increased. The increase in soil available P was more evident when TSP, NCRPR and compacted NCRPR were used whereas the lowest increments were obtained with finely ground Navay phosphate rock. Leaf P concentration values were within the sufficiency range, except for those treatments where Monte Fresco and Navay finely ground PRs were applied at the rate of 50 kg P<sub>2</sub>O<sub>5</sub>/ha and for the check plot (Casanova and Solorzano, 1994).

About 35% of soils in Venezuela are acid and low in available phosphorus (P). To resolve this problem, farmers would like to lime and apply phosphate fertilizers to the soils, but both lime and fertilizers are expensive. A good alternative to overcome soil acidity is the use of aluminium (Al)-tolerant cultivars. A pot experiment was carried out to test whether sorghum cultivars tolerant to Al toxicity are able to use P from phosphate rock more efficiently than Al-susceptible cultivars (Ramirez and Lopez, 2000). Three sorghum (*Sorghum bicolor* L. Moench) cultivars, Chaguaramas III (Ch), Al-tolerant, Decalb D59 (D59), and Pioneer 8225 (Pi), both Al-susceptible, were grown in the greenhouse for 20 and 35 days in two acid soils fertilized with 0 and 100 mg P kg<sup>-1</sup> as TSP and Riecito phosphate rock (RPR). Santa Maria soil was very low in available P (2 mg kg<sup>-1</sup>) and had a high Al saturation (64.5%) whereas the Pao soil was higher in available P (20 mg kg<sup>-1</sup>) and low in Al saturation (6.5%). Chaguaramas dry matter production, P uptake and root length was higher in the Santa Maria soil as compared with Pi and D59 when grown with both TSP and RPR fertilization. Chaguaramas response to RPR in the Pao soil was not as good as in the Santa Maria soil. The results of the experiment suggest that Al-tolerant Ch is able to utilize P from RPR more efficiently in soils like Santa Maria than the Al-susceptible cultivars Pi and D59 (Ramirez and Lopez, 2000).

The agronomic effectiveness of partially acidulated phosphate from the deposits of Riecito (Falcón State) and Monte Fresco (Táchira State) were evaluated in five experiments conducted at Tierra Buena, El Sombrero and El Tigre in Portuguesa, Guárico and Anzoategui States, respectively. These regions have acid soils with pH values in the range of 5 to 5.3. The crops selected were corn, sorghum and soybean. The P fertilizers were broadcast and ploughed in prior sowing. Preliminary results for the first year of the experiments indicated that Riecito phosphate rock gave better yield responses than Monte Fresco and Riecito partially acidulated at 40% with sulphuric acid and monoammonium phosphate produced similar yields to triple superphosphate (Kadi et al., 1991).

Three phosphate rocks from Táchira State, Venezuela: Monte Fresco (first layer, MF-1), Monte Fresco (second layer, MF-2) and San Joaquín de Navay (SJN), were evaluated in a greenhouse using maize (*Zea mays* L.) as a test plant. Results showed that Monte Fresco (MF-2), is the best source of phosphorus compared to TSP, followed by San Joaquín de Navay PR and finally MF-1 (López et al., 1991a). The residual effect and the agronomic effect of grain size were also evaluated (López et al., 1991b). Aerial and root production and total aerial and root phosphorus showed the following trend: MF-2 > SJN > MF-1. The response increases with increased dose and decreased grain size. The smaller sizes (<100 and <200 mesh) produced similar results. Relative production compared to TSP followed the same trend as the other variables (López et al., 1991b).

The response of Monte Fresco (layer 2) phosphate rock (MF-2) and a mixture of MF-2 with sulphur were evaluated in comparison with TSP in a greenhouse experiment using maize (*Zea mays L.*) as an index crop. Greater yields were obtained with MF-2 than MF-2+S (López et al., 1991e).

The residual effect of phosphate rocks from Monte Fresco (first and second layer), San Joaquín de Navay and biofertilizer PHS, was evaluated in field trials in comparison with TSP using two consecutive crops of maize (*Zea mays L.*) Arichuna variety. Two application methods were used: band and broadcast. Higher yields for both crops were obtained with the band application. Yields varied according to the following trend: MF-2 > SJN > MF-1 > PHS with the best yields obtained with 100 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>. Good residual effects were obtained for all phosphorous sources in the second crop. Yields using Monte Fresco (second layer), PR were higher than those for high solubility fertilizer (TSP) (López et al., 1991f).

The residual effect of the biofertilizer PHS, phosphate rock from Monte Fresco (layer 2, MF-2), and a mixture of MF-2 with sulphur were evaluated in comparison with TSP in a greenhouse experiment using three consecutive crops of maize (*Zea mays L.*) as the index plant. The third crop showed atypical results for all measurements. Aerial and root vegetable material yields for the first and second crops followed the trend: MF-2 > PHS > MF-2+S, whereas the trend for total aerial and root phosphorus was: MF-2 > MF-2+S > PHS. The relative aerial and root production compared to TSP was: MF-2 > PHS = MF-2+S (López et al., 1991g).

The residual effect of the biofertilizer PHS, rock from Monte Fresco, second layer (MF-2), and a mixture of MF-2 with sulphur in the same proportion as in PHS, was agronomically evaluated, in comparison with TSP, in a greenhouse experiment using two different acid soils and three consecutive crops of maize (*Zea mays L.*). Results showed for all crops in soil from Los Mirtos (sandy loam) followed the trend: MF-2 > PHS > MF-2+S whereas the trend for the La Morusca (clay loam) soil was: MF-2 > PHS = MF-2+S. The residual effect of the phosphorus sources increases with increased number of crops (López et al., 1991h).

An experiment was conducted in a greenhouse to evaluate the Relative Agronomic Effectiveness (RAE) for two Venezuelan phosphate rocks from Chirigurá (Ch) and Lobatera (Lo) applied partially acidulated (Pa) at 10% (with H<sub>3</sub>PO<sub>4</sub>), calcinated at 500°C (FC) and phosphocompost (Fcom) in an Ultisol from Uracoa (pH = 4.8) in Monagas state. Sorghum was used as the index crop and TSP with lime as controls. P was added at 0 and 300 kg ha<sup>-1</sup> and 4 seeds were planted in each pot containing 2.5 kg of soil with a basal application of NK. Distilled water was used for daily irrigation. The plant weight was determined 8 weeks after planting and it was found that the best P source was TSP followed by Lobatera Pa, Lobatera Fcom, Lobatera Fc, Chiguará Pa, Chiguará Fcom and Chiguará Fc (Moreno and Mohsin, 1991).

Another experiment was conducted using ground Lobatera phosphate rock (LPR), LoPa at 10% and Fcom at rates of 0, 100, 200, 300, 400 and 500 kg p ha<sup>-1</sup>, to determine the P rate that produced the best sorghum response. TSP with lime was used to calculate the RAE. 9 seeds were planted in each pot and soil available P (Bray-1) and foliar dry matter were measured at 8 and 12 weeks after planting, and panicle dry weight at 12 weeks. The P sources increased soil available P and foliar dry weight and panicle dry weight in both sampling periods. The 3 phosphate rocks increased soil available P although this was higher at 12 weeks and when applied in its acidulated form. The RAE values for foliar dry matter, panicles and PA were 64.6, 88.8 and 89.7 respectively. Sorghum response to rates applied varied according to the P-source although the best response was for 300 to 400 kg P ha<sup>-1</sup> for foliar dry matter and 500 kg p ha<sup>-1</sup> for panicles. The experiments demonstrated that for direct application a small modification of the Venezuelan phosphate rocks at low cost could transform a PR of low quality into an economically profitable P fertilizer when applied to acid soils (Moreno and Mohsin, 1991).

North Carolina Phosphate Rock (NCPR; natural and compacted), Monte Fresco phosphate rock (MFPR; finely ground and compacted), and Navay phosphate rock (NPR; finely ground) were evaluated in comparison with TSP using sorghum (*Sorghum bicolor*) and soybean (*Glycine max*) with the objective of finding alternatives P-sources to reduce P-fertilization costs for annual crops in Venezuela. Field trials were carried out on acid and low available P soils during the rainy season in 1991, at locations in Guarico and Anzoategui States. The best yields were obtained with TSP, but in grain sorghum the response to NCPR was so high that it can be used instead of TSP. Also in grain sorghum, compacted rocks produced relative yields higher than 80%, which indicates their agronomic potential. In contrast MFPR and NPR (finely ground) have a maximum RAE of about 52% indicating that they should not be used as the only P

source for this sorghum. In the case of soybean, the effectiveness of all rocks was lower than in the case of grain sorghum, and NCPR and MFPR (compacted) have a medium effectiveness with relative yields in the range of 70-85%. The study indicated that native Venezuelan phosphate rocks are generally very poor in promoting grain yield in soybean crop. All P sources applied increased the available P levels of the soil, although this effect was greater when TSP and NCPR (both as received and compacted) were incorporated in the soil (Solórzano, 1993).

Phosphogypsum, a by-product of the phosphoric acid industry, has several agronomic applications including use as an amendment for sodic and poor structural soils. Phosphogypsum was evaluated in greenhouse and field experiments at rates of 5-10 mt/ha to assess its potential to improve surface conditions in soils with structural problems and also on the germination, growth, and yield of sesame (*Sesamum indicum* L.). The potential consumption of phosphogypsum in the Turen production zone (Portuguesa State, Venezuela) is approximately 67000 metric tons per year (Shrestha et al., 1995).

### Forestry

In the savannas of the eastern lowlands of Venezuela, 400,000 ha of *Pinus caribaea* var. *hondurensis* plantations have been established. In these alluvial plains, the soils are sandy, strongly acidic, with a low organic matter content and low cation exchange capacity; total phosphate content is extremely low and internal drainage is generally excessive (i.e. the soils have low fertility). A study was carried out to assess whether it was possible to increase the productivity of the pine plantations by fertilization with powdered Monte Fresco rock phosphate (27% P<sub>2</sub>O<sub>5</sub>, 39% CaO) and borax. Both P and B foliar concentrations were very low. The study was executed in one two year-old plantation and another of eleven years of age, established in 1988 and 1979 respectively. Three phosphate rock doses were tried: 0, 200 and 400 kg/ha with 25 g/tree of borax. Twenty months after fertilization, the pine had not apparently responded to the phosphate and borax applications. On the other hand, the effect of reduced competition due to the thinnings (also carried out as part of the study) was reflected in the enhanced growth of the pine trees in the 1979 plantation (Torres and Franco, 1994).

Phosphorous nutritional limitation was studied in teak (*Tectona grandis*) plantations by means of root biomass production, using phosphate rock as P source. Plots of 12, 7 and 2 years old trees were selected upon teak/grass soil covering ratios. Cylinders were filled with surface soil with and without phosphate rocks added for a total of 108 cylinders, 36 for each plot age. They were distributed at random at the soil surface level and sampled at 2, 4 and 6 months, roots were separated, weighed and ground for chemical analysis. The results indicated that for the 2-year old trees there was not P limitation because of the low P requirement of the grass covering most of the surface. However, older trees showed P nutritional limitations where the P from the nutrient cycle has been used in several growth stages, causing low root biomass. Addition of phosphate rocks produced significant differences in the root growth when compared to the check plot (Mothes et al., 1991).

Reports on fertilization research on teca (*Tectona grandis* L.f.) for the western region of Venezuela and on pino caribe (*Pinus caribaea* var. *hondurensis* Barr. y Golf) for the eastern region were presented by Torres (1991). The soil fertility is very low in the western plantations (soil pH 4 to 5.5) and medium to low in the eastern plantations. In general the low foliar nutrient content reflects low soil fertility and this, in turn, is reflected in low productivity. Torres (1991) concluded that there is considerable potential for the use of ground rock phosphate in the forestry sector.

## Summary

Venezuela is working to boost its agro-industrial economy, with plans to bring 46 % more land under cultivation from the year 2001 to 2018. The successful expansion of the country's agroindustrial economy will depend on many factors, the most important of which are: (1) fertilizer requirements to achieve efficiency on permanent crops such as sugar cane, coffee, cocoa, fruits, cassava, improved pastures and forestry (covering more than 6 million ha) as well as annual crops such as maize, sorghum, rice, leguminous grains, oilseeds and cotton on more than 700,000 ha; (2) the high prices of high solubility traditional phosphate fertilizers such as SSP, TSP, NPKs, MAP and DAP; (3) the acidic soils covering 70 % of Venezuela; (4) tropical climatic conditions; and (5) plentiful phosphate deposits (Casanova, 2001).

National research institutes, universities, technical assistant companies and producers including FONAIAP, PALMAVEN, PEQUIVEN, INTEVEP, IVIC and CVG have investigated the production of low-cost phosphate fertilizers from the partial acidulation of indigenous phosphate rock (PAPRs). The investigations were carried out in collaboration with IFDC (USA), CIRAD and TECHNIFERT (France), IAEA (Austria) and CIAT (Colombia). PAPR was produced in a pilot plant from bulk samples taken from the three major phosphate rock deposits: Monte Fresco and Navay (Tachira state) and Riecito (Falcon state). The agronomic yield efficiencies of these PAPRs (20 to 30 %  $P_2O_5$  concentrations and acidulation grades of 40 % and above) were assessed on various crops and soil types using traditional and isotopic techniques. P concentration and availability in the soils increased, whereas P-fixation capacity decreased following the application of PAPR. The P use efficiency obtained in the greenhouse experiments increased with the solubility of the P sources used, although the difference between ground Riecito PR and Riecito-PAPR was marginal (Casanova, 2001). The PAPRs produced increases in yields, compared to the national average, of 29 to 100 % in sorghum, maize, sugar cane, soybean and pasture (Casanova, 2001).

The success of agronomic trials using the PAPR resulted in PEQUIVEN designing and constructing a plant to produce PAPR from Riecito phosphate rock. The plant has a production capacity of 150,000 t/year via a one-step acidulation and granulation process and the PAPR is commercialised in Venezuela under the name of "Fosfopoder"(Casanova, 2001).

*Sources:*(Casanova, 1991; Casanova et al., 1993; Casanova and Solorzano, 1994; Casanova, 2001; Debritto et al., 1992; Gamboa and Gamboa, 1991; Garciamiragaya, 1984; Hammond, 1991; Issa et al., 1991; Kadi et al., 1991; Lamus et al., 1989; León et al., 1986; López et al., 1991a; López et al., 1991b; López et al., 1991c; López et al., 1991d; López et al., 1991e; López et al., 1991f; López et al., 1991g; López et al., 1991h; López et al., 1994; López et al., 1997; Martínez, 1987; Martínez, 1988; Martínez et al., 1987; Moreno and Mohsin, 1991; Mothes et al., 1991; Pérez et al., 1995; Ramirez and Lopez, 2000; Reyes, 1991a; Sanchez and Cochrane, 1980; Shrestha et al., 1995; Solórzano, 1993; Solorzano and Casanova, 1992; Torres and Franco, 1994; Torres et al., 1991; Vassilev et al., 1997; Zapata and Salas, 1991)

# SUMMARY

A summary of the quantity, quality (%P<sub>2</sub>O<sub>5</sub>), past/current production, agronomic testing, use and development potential of the phosphate resources of Central and South America, 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 <sub>2</sub> O <sub>5</sub> (%)	Current (Past) production (tonnes)	Agronomic testing	Current use	Development potential
Argentina	Leones	Guano	Recent			1840-1940 production			low
Argentina	Penguin Island	Guano	Recent	0.015		1840-1940 production			low
Argentina	Las Hayas	Sed	Cretaceous		2-8				low
Argentina	Tres Lagos	Sed	Cretaceous						low
Argentina	Formación Patagonia	Sed	Eocene-Oligocene		2.3-36.5				low
Argentina	Sierra da Vaca Muerta	Sed	Jurassic		1-10				Low grade and unfavourable structural setting
Argentina	Jujuy-Salta	Sed	Ordovician		max. 14.4				Mining not feasible
Argentina	San Juan	Sed	Ordovician	0.023	max. 11				open cast mining possible but ore needs to be upgraded
Argentina	Fmn Río Chico	Sed	Paleocene		15-26				low
Argentina	Zanjón de Lema	Sed	Paleocene		9-29				low
Argentina	Sierra Grande	Sed	Silurian-Devonian		2-3				PR too high in Fe for fertiliser manufacture
Argentina	Cerro Cachueta	Sed	Triassic		max. 36				low
Bolivia	Cerro Manomo	Ign	Cretaceous		4-25				very low (uranium too high, resources too small, inaccessible)
Bolivia	Aguirre	Sed	Ordovician						low
Bolivia	Betanzos	Sed	Ordovician		20	? 1950's			low
Bolivia	Buey Tambo	Sed	Ordovician			? 1950's			low
Bolivia	Camino Nuevo (km 47)	Sed	Ordovician	0.2	25-28	(for agronomic trials)	pasture		Open-cast mining feasible; potential use for pasture, perennial crops, soil amendment for acid soils in tropical lowland areas
Bolivia	Camino Viejo (km 50)	Sed	Ordovician		max. 22				Open-cast mining feasible; potential use for pasture, perennial crops, soil amendment for acid soils in tropical lowland areas

Country	Deposit	Type	Geological age	Quantity of resources (Mt)	Average or range P <sub>2</sub> O <sub>5</sub> (%)	Current (Past) production (tonnes)	Agronomic testing	Current use	Development potential
Bolivia	Capinota	Sed	Ordovician	2.8	25	(for agronomic trials)	pasture, potatoes, carrots, onions, beans, groundnuts, maize, rice		Mining difficult
Bolivia	Caranavi	Sed	Ordovician		5				low
Bolivia	Iluri	Sed	Ordovician						low
Bolivia	Iscayachi	Sed	Ordovician		<2				low
Bolivia	Lagunillas	Sed	Ordovician		17-23	? 1950's			low
Bolivia	Miculpayá	Sed	Ordovician		<8				low
Bolivia	Paloma Pampa	Sed	Ordovician	1.5	22	(for agronomic trials)	pasture, potatoes, carrots, onions, beans, groundnuts, maize, rice		Mining difficult
Bolivia	Quivinchá	Sed	Ordovician			? 1950's			low
Bolivia	Sucre	Sed	Ordovician						low
Bolivia	Umabisa	Sed	Ordovician	0.0037	6.4				low
Bolivia	Villamontes	Sed	Ordovician						low
Bolivia	Cerro Colorado	Sed	Precambrian						more exploration required
Bolivia	Cerro Chapioc	Sed	Pre-Cambrian		10				very low
Bolivia	Laguna Mandiore	Sed	Recent						location of PR not confirmed
Bolivia	Sepulturas	Sed	Recent	0.3	9.3				low
Brazil	Anitapolis	Ign	Cretaceous	300	8				low
Brazil	Araxá	Ign	Cretaceous	500	14	1600000	Perennial crops fertilizer (coffee, citrus), Eucalyptus, soya, rice, beans, cassava, pasture, rubber, wheat	production	major phosphate mine in production
Brazil	Catalão I	Ign	Cretaceous	400	15	800000	rice, bean, wheat	fertilizer production	major phosphate mine in production
Brazil	Ipanema	Ign	Cretaceous	120	6.7				development may occur when other resources exhausted
Brazil	Jacupiranga	Ign	Cretaceous	200	5	(yes - quantity not known)	rice, bean		development may occur when other resources exhausted
Brazil	Patrocínio	Ign	Cretaceous	200	10				development may occur when other resources exhausted
Brazil	Registro	Ign	Cretaceous	18	16				low
Brazil	Tapira	Ign	Cretaceous	750	8.7	1900000	pasture	fertilizer production	major phosphate mine in production



Country	Deposit	Type	Geological age	Quantity of resources (Mt)	Average or range P <sub>2</sub> O <sub>5</sub> (%)	Current (Past) production (tonnes)	Agronomic testing	Current use	Development potential
Brazil	Sume	Pegm		0.25	38				low
Brazil	Cabeceiras	Sed	Pre-Cambrian		10-15				low
Brazil	Campos Belos and Monte Alegre	Sed	Pre-Cambrian		15-17				low
Brazil	Cerro do Abaete	Sed	Pre-Cambrian	1	10-34		rice, bean, wheat		low
Brazil	Formosa	Sed	Pre-Cambrian						low
Brazil	Lagamar	Sed	Pre-Cambrian	5	25-30				former mine
Brazil	Nova Roma	Sed	Pre-Cambrian		max. 22				low
Brazil	Rocinha 1	Sed	Pre-Cambrian	227	14		rice, bean, pasture, wheat		former mine
Brazil	Rocinha 2	Sed	Pre-Cambrian	3.6	11-13				?
Brazil	Maranhao	Sed	Recent		20-30				low
Brazil	Rata	Sed	Recent	0.7	28	(Few shipments exported in 1st World War)			low
Brazil	Paulista (Olinda)	Sed	U Cretaceous	50	21	(for fertilizer manufacture and direct application until ?1995)			former mine
Brazil	Piracicaba	Sed	U Cretaceous						low
Brazil	Santo Amaro	Sed	U Cretaceous						low
Chile	Guanillos	Guano	Recent	1.5 (all Chilean guano deposits)	15	635,000 between 1906-1937 declining to 17,500 in 1942 and 90,000 t in 1948			potential use as 'organic' fertilizer
Chile	Pabellon de Pica	Guano	Recent	ditto	15				potential use as 'organic' fertilizer
Chile	Punta de Lobos	Guano	Recent	ditto	15				potential use as 'organic' fertilizer
Chile	Tarapaca	Guano	Recent	ditto	18-20				potential use as 'organic' fertilizer
Chile	La Serena	Hydro	?	2.5	28-30	(up to 30,000 t/a up to 1966)			High mining and transport costs and loss of subsidy closed mine
Chile	Bahia Inglesa - Caldera	Sed	Tertiary	15	18		wheat, Brassica napus, lentils, rice		resources probably too small for fertilizer manufacture
Chile	Bahia Salado	Sed	Tertiary						low

Country	Deposit	Type	Geological age	Quantity of resources (Mt)	Average or range P <sub>2</sub> O <sub>5</sub> (%)	Current (Past) production (tonnes)	Agronomic testing	Current use	Development potential
Chile	Mejillones	Sed	Tertiary	54	6-7		wheat, Brassica napus, lentils, rice		resources probably too small for fertilizer manufacture
Chile	Tongoy	Sed	Tertiary	15	15-18				resources probably too small for fertilizer manufacture
Chile	Valliant	Sed	Tertiary						low
Colombia	Malpelo Is	Guano	Recent	0.45	25-3-				low
Colombia	Boyaca (Pesca)	Sed	Cretaceous	500	5-27	15000 tpa	corn, sorghum, peanuts, rice, pasture, soybean	direct application pasture, rice, sugar cane, potatoes	resources adequate for ground rock phosphate or PAPR but not for fertilizer complex
Colombia	Huila I (Media Luna)	Sed	Cretaceous	17	27		corn, sorghum, peanuts, rice, pasture, soybean	direct application pasture, rice, sugar cane, potatoes (used for liming effect)	resources adequate for ground rock phosphate or PAPR but not for fertilizer complex
Colombia	Huila II	Sed	Cretaceous						low
Colombia	Huila III	Sed	Cretaceous						low
Colombia	La Juanita - Tesalia	Sed	Cretaceous	?		15000 tpa	corn, sorghum, peanuts, rice, pasture	direct application pasture, rice, sugar cane, potatoes	resources adequate for ground rock phosphate or PAPR but not for fertilizer complex
Colombia	Sardinata (N. Santander)	Sed	Cretaceous	15	22	15000 tpa	corn, sorghum, peanuts, rice, pasture	direct application pasture, rice, sugar cane, potatoes	resources adequate for ground rock phosphate or PAPR but not for fertilizer complex
Colombia	Socha	Sed	Cretaceous						low
Colombia	Yaguara	Sed	Cretaceous						low
Colombia	Soata	Sed							low
Cuba	Guines Pipian	Sed	Miocene		<9.5		sugar cane, pasture, citrics, rice forestry (liming effect of phosphatic limestone may be greater than benefit from phosphate)		resources too deeply buried to be of economic value
Ecuador	El Pelado	Guano	Recent						low
Ecuador	Los Fallaromes	Guano	Recent						low
Ecuador	Santa Clara	Guano	Recent						low
Ecuador	Napo	Sed	Cretaceous	185	25		corn		reserves could be exploited economically

Country	Deposit	Type	Geological age	Quantity of resources (Mt)	Average or range P <sub>2</sub> O <sub>5</sub> (%)	Current (Past) production (tonnes)	Agronomic testing	Current use	Development potential
French Guiana	Grand Connetable	Guano	Recent		35	(3,000 to 7,000 tpa in 1884 to 1913 used for sodium phosphate)	pot trials showed finely ground PR effective		low
Mexico	Dulces Nombres	Sed	?		21-34	exported to US as cattle feed supplement)			low
Mexico	Mercedes y Hermania	Sed	?	0.16	28	(used for superphosphate)			low
Mexico	Sierra de la Carbonera (Saltillo)	Sed	Jurassic	154	19-20	formerly 8000 t/m (now zero)			former mine and plant no longer operating due to economic conditions
Mexico	Sierra de Santa Rosa	Sed	Jurassic	13	16				low
Mexico	San Juan de la Costa	Sed	Late Oligocene	24	18	927000 tpa	corn, beans, alfalfa, rye grass	for fertilizer manufacture	major mine
Mexico	Cañon de las Encias	Sed	Middle Cretaceous		18				low
Mexico	El Capote y La Casualidad	Sed	Middle Cretaceous	0.11	20				low
Mexico	Bahia Magdalena	Sed	Palaeogene-Neogene						low
Mexico	Bahia Magdalena	Guano	Recent			(worked in late 19th century and early 20th century)			low
Mexico	La Purisima	Sed	Palaeogene-Neogene						low
Mexico	San Hilario	Sed	Palaeogene-Neogene	841	11-13				low grade ore, unfavourable location led to abandonment of deposit by Rofomex
Mexico	San Jose de Castro	Sed	Palaeogene-Neogene						low
Mexico	San Roque	Sed	Palaeogene-Neogene						low
Mexico	Santa Rita	Sed	Palaeogene-Neogene		10				low
Mexico	Tembabiche	Sed	Palaeogene-Neogene						low
Mexico	Santo Domingo	Sed	Recent	1077	5				Mining project abandoned due to technical difficulties with dredging
Mexico	Rincon de Arizmedi	Sed			7-33				low
Mexico	Topo Chico	Sed			27-43				low
Nicaragua	San Juan del Sur	Sed	U.Cretaceous		traces				low
Panama	David	Sed	Pliocene		20				unlikely to be of economic value

Country	Deposit	Type	Geological age	Quantity of resources (Mt)	Average or range P <sub>2</sub> O <sub>5</sub> (%)	Current (Past) production (tonnes)	Agronomic testing	Current use	Development potential
Peru	Chincha Islands	Guano	Recent	2 (all guano occurrences)	10-15	(12 Mt exported to Europe and North America in 1800 to 1965) small amount exported to US as 'organic' fertilizer			resources severely depleted due to over-exploitation
Peru	Lobos de Tierra	Guano	Recent	ditto					low
Peru	Other Islands	Guano	Recent	ditto					low
Peru	Aramachay	Sed	Cretaceous						low
Peru	Caledin	Sed	Cretaceous						low
Peru	Huancane	Sed	Cretaceous						low
Peru	Ica-Ocucaje	Sed	Cretaceous						low
Peru	Yauli	Sed	Cretaceous						low
Peru	Muerto Fm	Sed	L. Cretaceous						low
Peru	Pariatambo Fm	Sed	L. Cretaceous						low
Peru	Sechura	Sed	M. Miocene	1500	<23	9000 tpa	annual and perennial crops (citrus, coffee, cacao), pasture, soybean		Major, world-class PR deposit; tendering for private development in 2001
Peru	Offshore	Sed	Recent						low
Surinam	Nickerie River	Meta	Proterozoic		2-14				low
Uruguay	Cerro Arrequita	Guano	Recent		23				little commercial significance due to high Fe and Al
Venezuela	Grano Roque	Guano	Recent						low
Venezuela	Isla La Orchila	Guano	Recent	0.025	10-32	(25,000 tons between 1867 and 1888 - exported to Germany for superphosphate)			low
Venezuela	Lobatera	Sed	Cretaceous	1	23		sorghum		potential use as direct application fertilizer in forestry etc.
Venezuela	Los Monos (Navay)	Sed	Cretaceous	80	0		pasture, soya, sorghum		potential use as direct application fertilizer in forestry etc.
Venezuela	Merida State	Sed	Cretaceous	70	18				potential use as direct application fertilizer in forestry etc.
Venezuela	Monte Fresco	Sed	Cretaceous	300			pasture, coffee, sugar cane, forestry, annual crops including maize, sorghum, soybean		potential use as direct application fertilizer in forestry etc.

Country	Deposit	Type	Geological age	Quantity of resources (Mt)	Average or range P <sub>2</sub> O <sub>5</sub> (%)	Current (Past) production (tonnes)	Agronomic testing	Current use	Development potential
Venezuela	Zulia State	Sed	Cretaceous	18	11				potential use as direct application fertilizer in forestry etc.
Venezuela	Cerro Riecito	Sed	Miocene	20	30	366000 tpa	coffee, sugar cane, cacao, pasture	fertilizer manufacture (including new PAPR plant) and export to Colombia as direct application fertilizer	potential use as direct application fertilizer in forestry etc.
Venezuela	Lizardo	Sed	Miocene	20	0		pasture		potential use as direct application fertilizer in forestry etc.

Deposit Type: Ign = Igneous; Hydro = Hydrothermal; Meta = Metamorphic; Sed = Sedimentary;

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