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U.S. GEOLOGICAL SURVEY CIRCULAR 962

Undiscovered Phosphate Resources in the Caribbean Region and Their Potential Value for Agricultural Development

Prepared as a cooperative effort between the U.S. Geological Survey, East Carolina University, Greenville, North Carolina, and the International Geological Correlation Program Project 156

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By **R. P. Sheldon, D. F. Davidson, S. R. Riggs,** *and* **W. C. Burnett**

ABSTRACT

The countries of the world's humid tropical regions lack the soil fertility necessary for high agricultural productivity. A recently developed agricultural technology that increases soil fertility can make tropical agriculture highly productive, but the technique requires large inputs into the soil of phosphorus and other fertilizers and soil amendments.

Use of fertilizers derived from phosphate rock is increasing greatly throughout the world, and fertilizer raw materials are being produced more and more frequently from phosphate rock deposits close to the areas of use. An increased understanding of the origin of phosphate rock in ancient oceans has enabled exploration geologists to target areas of potential mineral resource value and to search directly for deposits. However, because of the difficulty of prospecting for mineral deposits in forested tropical regions, phosphate rock deposits are not being explored for in the countries of the humid tropics, including most countries of the Caribbean region. As a result, the countries of the Caribbean must import phosphate rock or phosphorus fertilizer products. In the present trade market, imports of phosphate are too low for the initiation of new agricultural technology in the Caribbean and Central American region.

A newly proposed program of discovery and development of undiscovered phosphate rock deposits revolves around reconnaissance studies, prospecting by core drilling, and analysis of bulk samples. The program should increase the chance of discovering economic phosphate rock deposits. The search for and evaluation of phosphate rock resources in the countries of the Caribbean region would take about 5 years and cost an average of $15 million per country. The program is designed to begin with high risk-low cost steps and end with low risk-high cost steps.

A successful program could improve the foreign exchange positions of countries in the Caribbean region by adding earnings from agricultural product exports and by substituting domestically produced phosphate rock and fertilizer products for imported phosphate fertilizers. A successful program also could provide enough domestically produced phosphorus fertilizer products to allow initiation of new agricultural technology in the region and thus increase domestic food production. Finally, a new phosphorus fertilizer industry would create new jobs in the mining, chemical, and transportation industries of the Caribbean region.

INTRODUCTION

The countries of the humid tropical areas of the world, including the countries of the Caribbean region, have two of the three essentials for productive agriculture--water and sunlight--but lack the third essential, fertile soil. In fact, the abundance of water and sunlight in the tropics has caused (1) the leaching of vital nutrients from soil and (2) the breakdown, leaching, and oxidation of the soil minerals. As a result of these processes, the soil is acidic and infertile. Modern agricultural science has developed and demonstrated a technology to give high fertility to such soils by applications of fertilizer and soil amendments and by development of new strains of food plants and rotational crop systems that give high yields under the new soil conditions.

The full potential of tropical agriculture is high but unrealized. Technology that could effectively increase production in the area is not in place, partly because of the newness of the technology and partly because of the lack of raw materials to carry the technology out. Phosphate fertilizers are among the important inputs for this new technology. Because of the difficulty of discovering mineral deposits in forested tropical regions, phosphate rock resources in the tropics often go undiscovered and undeveloped, and, as a result, phosphate in one form or another must be imported.

The agricultural problems of humid tropical countries are compounded by the large populations of the countries and the resulting domestic food needs. The economies of the tropical countries, however, rely substantially, if not primarily, on the export of cereals, sugar, coffee, tea, cocoa, fruits, and other agricultural products. The agricultural land resources must be apportioned between these two uses--production of food for domestic consumption and production of agricultural export products. National policymakers, given the low productivity of the agricultural lands, must make difficult choices between stimulating their national economies and meeting the food requirements of their people. With a growing population, this dilemma becomes increasingly difficult. Improving soil fertility and using new agricultural technology are critical needs.

Availability of phosphate materials is basic to increasing agricultural productivity of the Caribbean region. This report reviews the current world phosphate production and trade situation and the problem of phosphate fertilizer needs versus present levels of consumption. The report discusses the economic implications of phosphate rock resource development and presents data on the phosphate resource potential of the Caribbean region. Finally, the report outlines the essential elements of a phosphate rock resource development program.

WORLD PHOSPHATE SITUATION

HISTORY OF DEMAND AND PRODUCTION

To be fully understood, the phosphate situation of the Caribbean region must be seen in a world context. The world exploitation of phosphate rock has been rising for decades; this increase has been exponential during the last 40 years (fig. 1). Most of this phosphate is used as fertilizer, and the consumption curve is approximately the same as the production curve. The consumption curve, however, demonstrates the cyclic economic nature of the phosphate business more accurately than does the production curve. Over the decades, the increase in demand has caused the exhaustion of smaller deposits, the abandonment of higher cost deposits, and the development of large, low-cost deposits that benefited from the economies-of-scale in mining techniques. As a result, from World War II until a few years ago, three areas dominated world supply and set prices. These areas were (1) Florida and North Carolina, U.S.A., (2) Morocco and Western Sahara, and (3) Khibini in the Kola Peninsula of the U.S.S.R. (fig. 2). The Khibini deposit supplies mainly the U.S.S.R. and eastern Europe; the U.S. and Moroccan deposits supply phosphate rock or fertilizer to the rest of the world. Many other smaller deposits exist (see fig. 2). Because of small size, low grade, remote location, or governmental policies, these other deposits have not contributed greatly to world phosphate trade, although they may be important locally.

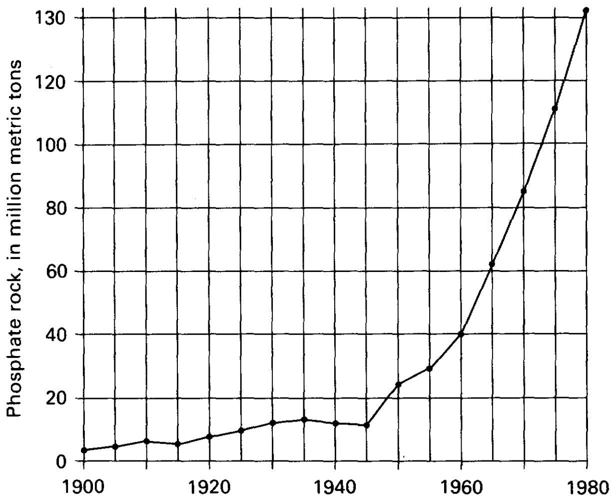


Figure 1.--World phosphate rock production, 1900 to 1980. Data from W. F. Stowasser (written commun., 1981).

HISTORY OF DISCOVERY

Exploration for phosphate rock deposits has increased continually as the demand for fertilizer has increased. No comprehensive history of phosphate rock exploration and discovery has been written. However, an important trend is evident from available information. Most of the early discoveries of marine-origin phosphate rock deposits (the commercially most important type) were made in the process of regional geologic mapping (fig. 3). This mapping was carried out not to explore for phosphate rock but to understand the regional geologic structure and distribution of different rock types. Phosphate rock deposits were found by chance. Occurrence of most of these early-found deposits where rocks are well exposed in desert, glaciated, or mountainous countries is highly significant. Phosphate is still being discovered in this manner, as improved geochemical and geophysical surveying techniques make regional mapping more efficient.

The origin of phosphate rock was the subject of great debate until 1937, when the Russian sedimentary petrologist A.V. Kazakov (1937) developed a hypothesis of the origin of marine phosphorite through upwelling deeper ocean water onto shallow water continental shelf areas. His hypothesis evolved into a generally accepted theory (McKelvey, 1967; Sheldon, 1981). Perhaps more than any other factor, Kazakov's theory allowed exploration geologists to develop theoretical targets and search directly for phosphate deposits. As a result, an era of discovery began in the mid-20th century and continues today (fig. 3). At the same time, recognition of the likely geologic environment in which to find marine phosphate has allowed significant extensions of previously known phosphorite provinces (fig. 3).

Exploration for phosphate rocks, however, has been remarkably unsuccessful in the tropical regions of the world, primarily because of the poor exposure of the rocks. This climate-biased exploration history is a major factor in the present distribution of phosphate mining districts of the world.

PHOSPHATE ROCK QUALITY REQUIREMENTS FOR FERTILIZER PRODUCTION

Once a phosphate rock deposit has been discovered and measured, the quality of the deposit must be evaluated for its potential as a raw material for agricultural use. The quality of the phosphate rock is as important a factor as the minability, size, and accessibility of a deposit in evaluating the deposit. The quality evaluation requires extensive physical and chemical testing to (1) determine the best method for beneficiating the rock and removing detrimental minerals and (2) select the best process for fertilizer manufacture.

The present technology for manufacturing phosphorus fertilizer uses dissolution of phosphate rock in sulfuric acid. The products are then processed in several ways to produce one of a number of phosphorus fertilizers.

A number of contaminants in phosphate rock can interfere with fertilizer production processes and make the processes more costly or less efficient. Perhaps the most damaging contaminants are calcium and magnesium carbonates, which are also dissolved by sulfuric acid. The pres-

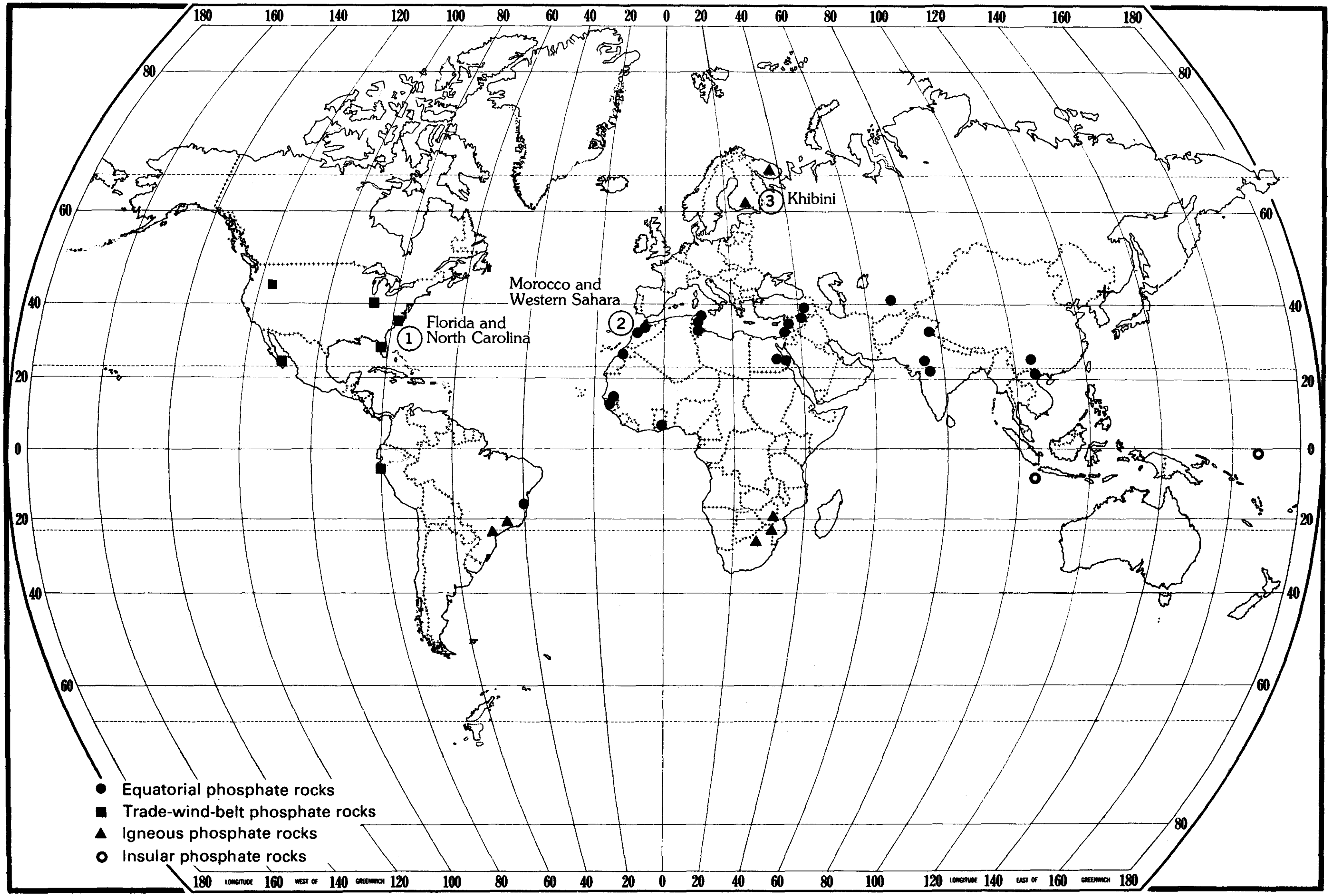
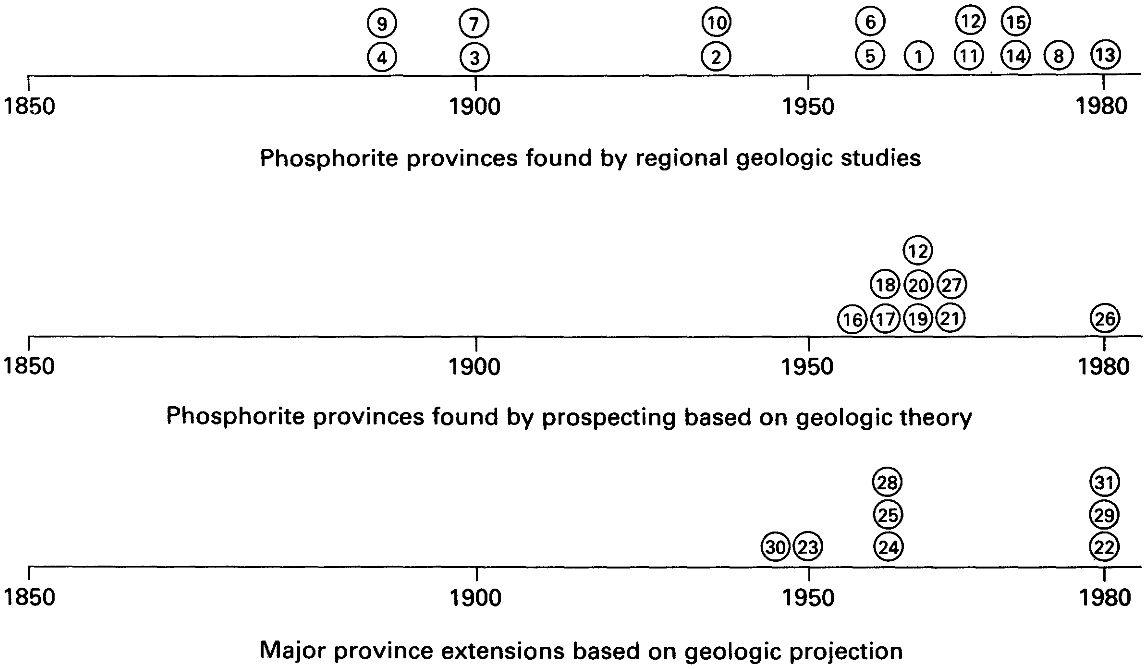


Figure 2.--Major phosphate rock mining districts of the world in 1980. See text (p. 19-22) for explanation of phosphate rock types. Data from Stowasser (1981) and Sheldon (1982).



Phosphate rock deposits

Regional geologic studies

1. Miocene, North Carolina
2. Miocene, California
3. Cretaceous-Eocene, North Africa
4. Cretaceous-Eocene, Middle East
5. Jurassic, Mexico
6. Triassic, Alaska
7. Permian, Utah
8. Precambrian, Liberia
9. Pliocene, Florida
10. Cambrian, China
11. Cambrian, Mongolia
12. Cambrian, Australia*
13. Precambrian, Surinam
14. Lower Proterozoic, India
15. Lower Proterozoic, Michigan

Geologic theory

16. Holocene, Baja California
17. Miocene, Peru
18. Jurassic, Peru
19. Devonian, Iran
20. Cambrian, India
21. Upper Proterozoic, India
12. Cambrian, Australia*
26. Cambrian, Spain
27. Precambrian, Benin

Province extensions

22. Miocene, offshore North Carolina
23. Cretaceous-Eocene, Israel
24. Cretaceous, Turkey
25. Cretaceous-Eocene, Saudi Arabia
28. Cretaceous, Colombia
29. Cretaceous, Ecuador
30. Cambrian, China
31. Precambrian, Nepal

*Australian phosphorite found simultaneously by two different techniques.

Figure 3.--History of discovery of phosphorite mining provinces and province extensions, age of deposition, and location.

ence of calcium and magnesium carbonates increases the amount of acid required to dissolve the total rock and thereby increases the processing cost. Iron and aluminum oxides and magnesium carbonates or silicates interfere with the manufacturing of phosphorus fertilizer by forming sludges that clog filters and form scale on phosphoric acid production equipment. Excessive amounts of chlorine, fluorine, and some minor elements are also deleterious to fertilizer manufacturing processes and the resulting fertilizer. McClellan (1980) has given an excellent account of these problems.

For the acid soils of the humid tropics, adding crushed raw phosphate rock to the soil commonly improves agricultural productivity; therefore, in some conditions and for some crops, processing phosphate requires nothing more than crushing the rock. When using crushed raw phosphate rock as an additive, the presence of calcium and magnesium carbonates is not as serious a problem as when using rock processed by the sulfuric acid procedure. In fact, the carbonates in crushed phosphate rock help to reduce the acidity of the soil, and the magnesium in the rock is a valuable nutrient.

Discerning the quality of undiscovered phosphate rock is impossible. With the deep leaching typical of rocks in the humid tropics, phosphate rock originally rich in calcium and magnesium carbonates may be leached free of these contaminants in some parts of the deposit, thus increasing the deposit's value (Altschuler, 1973). Conversely, leaching can spoil a phosphate rock deposit by forming calcium aluminum phosphate or aluminum phosphate minerals in the leached zone from the original phosphate rock (calcium phosphate). The resulting aluminum-bearing phosphate minerals are more insoluble than the original calcium phosphate and are more difficult and expensive to process into phosphorous fertilizer.

After the quality of a discovered phosphate rock deposit is ascertained, the best process to use in beneficiating and in making phosphorus fertilizer from the concentrate can be determined, and the deposit can be fully evaluated. Even the lowest grade phosphate deposit sometimes can be used if a suitable process is selected.

The phosphate rock from the new deposits is commonly less pure or more difficult to mine or beneficiate than is the phosphate rock of the southeastern United States and of Morocco and Western Sahara, but the new deposits have the economic advantage of shorter distances to local markets. The increasing cost of ocean transportation, as well as a shortage of hard currency in many countries, increasingly has caused the world phosphate market to take into account the numerous smaller and poorer deposits of the world. The general trade patterns generated by this situation are shown in figure 4. The dominance of the southeastern United States and Morocco and Western Sahara is clearly illustrated in the pie diagram (fig. 4) that shows the major phosphate rock exporters. Phosphate rock is often shipped halfway around the globe from these two areas to ports in western Europe, South America, and Asia. Other trade occurs from the Soviet Union to eastern Europe and from Christmas Island and Nauru to Australia and New Zealand. As can be seen in figure 4, economically developed countries form the majority of importers of phosphate rock.

PRESENT WORLD PHOSPHATE PRODUCTION AND TRADE

World production of phosphate by country is shown in table 1. The top six producers of phosphate rock in 1980 produced 85 percent of the phosphate rock, and the bottom 16 produced 15 percent. Table 1 lists the reserve base of each of these producer countries and indicates a potential for increased production, particularly in South Africa, Brazil, Syria, Algeria, Mexico, and Finland (see Glossary for definition of resource terms). Phosphate rock mines in India, Syria, Brazil, Australia, Finland, Turkey, Peru, and Mexico have opened up in the last decade, and additional mines in Iraq, Egypt, and Mongolia are reported to be opening soon. In contrast, in the last 10 years, the mines on Ocean Island and Curacao have closed because of exhaustion of the resource.

The map in figure 4 shows that phosphate rock trade is a major international enterprise. The major phosphate rock and fertilizer sales are by large companies (which, outside the U.S., are primarily national companies) to the major cash crop farming areas. Moreover, developing countries have received relatively little international assistance with respect to phosphate imports. The trade barriers around the centrally planned economies are apparent also on this map; that is, the region that includes the Eastern Europe Bloc countries and northern Asia is isolated from the rest of the world as far as phosphate trade is concerned, except for minor phosphate rock imports from Jordan. A vigorous phosphate trade is going on within the bloc of countries with centrally planned economies, and, generally speaking, the phosphate resources are more fully developed in these countries.

Table 1.--Phosphate rock production and estimated reserve base by country

[In millions of metric tons of phosphate rock]

Country	1980 production	Reserve base[1]
U.S.A.	54.4	8,000
U.S.S.R.	26.1	6,300
Morocco and Western Sahara	18.8	44,000
China	6.7	10,000
Tunisia	4.6	500
Jordan	4.2	1,100
South Africa	3.3	700
Togo	2.9	110
Brazil	2.9	800
Israel	2.6	150
Nauru	2.1	20
Christmas Island	1.7	62
Senegal	1.4	75
Syria	1.3	883
Algeria	1.0	1,000
North Korea	.5	90
India	.4	108
Vietnam	.4	100
Mexico	.3	1,034
Zimbabwe	.1	50
Finland	.1	565

[1]Reserve base is phosphate rock in the ground that can be mined under existing economic conditions. Data from Stowasser (1981).

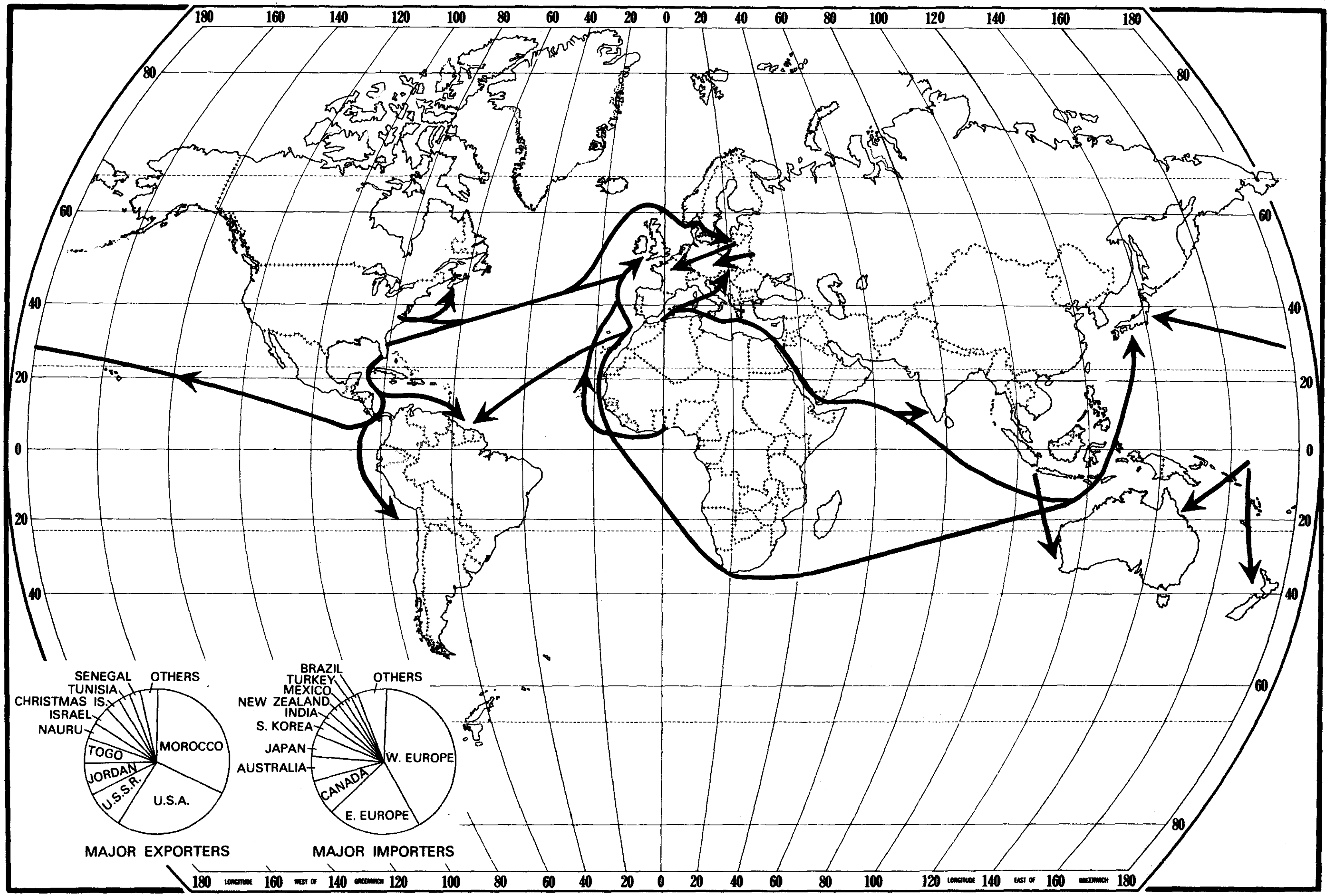


Figure 4.--Import-export trade of phosphate rock. Trade routes are shown on map, and market shares of major exporters and major importers are shown in pie diagrams. Data from Stowasser (1979).

PRESENT APPLICATION RATES

Application rates of phosphate fertilizer to arable land correlates with the per capita gross national product (GNP) in many countries (fig. 5). The higher the per capita GNP, the larger the application per hectare of phosphorus pentoxide (P_2O_5). One probable cause for this relation is the richer countries' ability to buy needed phosphate fertilizer. Another cause may be the dependence of the productivity of the agricultural sector of the economy on efficient agricultural technology and, by implication, effective fertilization programs. The resulting increase in productivity tends to raise the per capita GNP of a country. Phosphate fertilizer application rates, however, are only one part, although an essential part, of agricultural productivity. Other factors include application rates of other fertilizers, the type of crop and crop varieties raised, water availability, length of growing seasons, and agricultural technology.

If the relation between per capita GNP and P_2O_5 per hectare is examined in more detail for the higher application rate countries, an interesting phenomenon surfaces (fig. 6). Geographically related groups of countries show unique ranges of these combined values. Most clear is the relation in the western Europe group (Belgium and Luxembourg, Switzerland, Netherlands, West Germany, and France), with high per capita GNP and high phosphate application rates. The poorer central and southern European countries (East Germany, Hungary, Poland, Bulgaria, Czechoslovakia, Romania, Italy, Greece, Spain, Portugal, and Yugoslavia) use less phosphate; this suggests that perhaps with more money they would consume more phosphate. Consumption of phosphate, however, is dictated by more than economic conditions. Climate, soil conditions, and different crops influence phosphate use. Because cold, temperate soils tend to have relatively high mineral contents, Scandinavian countries (Sweden, Norway, Denmark, and Finland) use less phosphate than do the western European countries just to the south, although they have similar per capita GNP's. Soils in desert areas also have high mineral contents; therefore, in desert countries such as Australia, Libya, and Saudi Arabia, the rate or use of phosphate is relatively low, although these countries have few financial constraints. The United States, Canada, and the Soviet Union also use relatively small amounts of phosphate per hectare, possibly because of their wide variety of soils and climate.

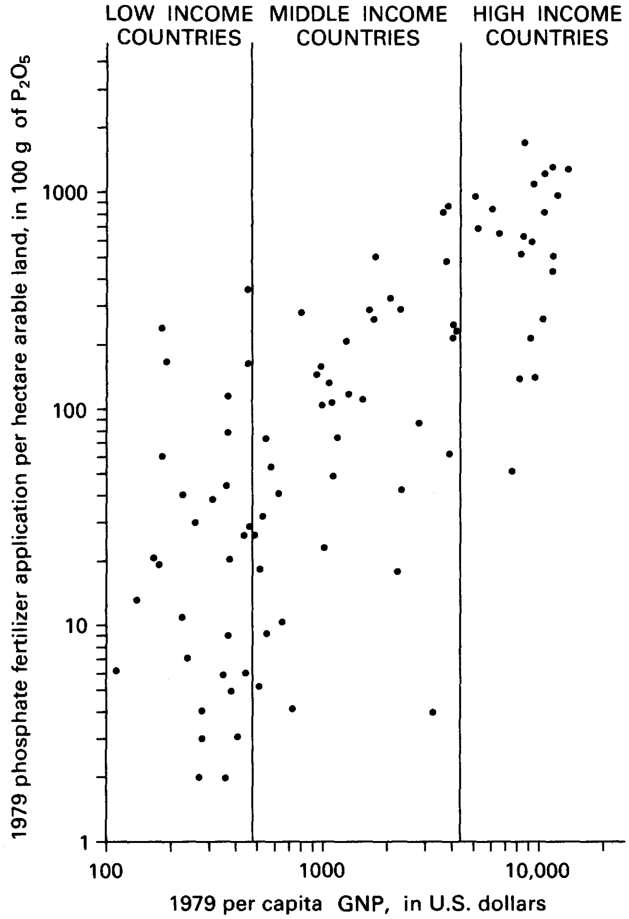


Figure 5.--Phosphate fertilizer use on arable lands in relation to per capita gross national product. Data from Food and Agricultural Organization (1980) and World Bank (1980). Note logarithmic scale.

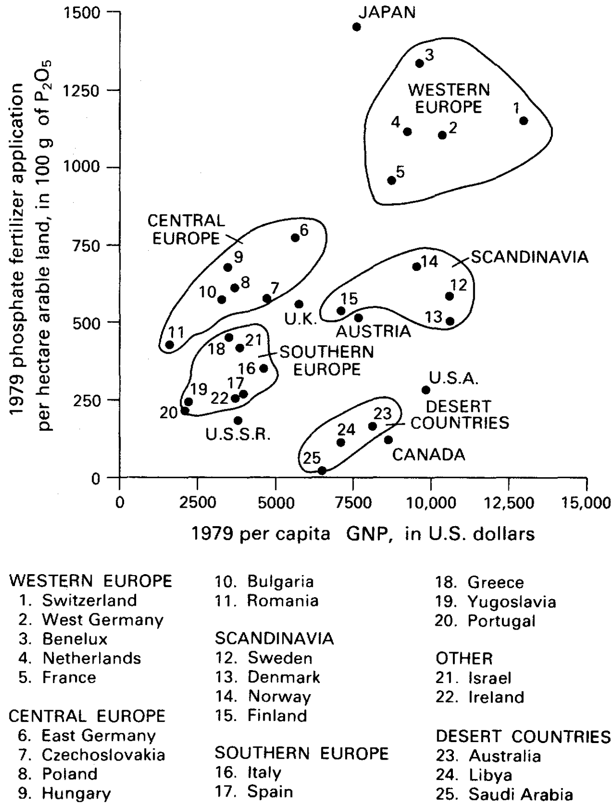


Figure 6.--Phosphate fertilizer use on arable lands in relation to income and geographical area. Data from Food and Agricultural Organization (1980) and World Bank (1980). Note arithmetic scale.

The countries that use less than 15 kilograms of phosphate per hectare have a combined population of 2.75 billion people--65 percent of the world's population (fig. 7). These low-use countries are largely in the humid or arid tropics, where the soils not dedicated to plantation crops for export are too wet, too leached, too dry, or too salty to allow anything other than subsistence-level farming. The subsistence-level farmer generally does not grow sufficient cash crops to allow him to buy fertilizer. As a result, except for plantation farming, no significant economic demand for phosphate arises from these countries.

NEED FOR PHOSPHATE FERTILIZER IN THE CARIBBEAN REGION

Except for the mountainous areas, the Caribbean region has low-latitude, humid or wet-and-dry climates and low agricultural productivity. Production of cereal, sugarcane, and paddy rice in the Caribbean region and, for comparison, production of the same crops in Asia, Africa, South America, Europe, the United States, and Japan are shown in table 2. The productivity of arable land for any given crop varies according to many factors, only one of which is soil fertility. The latitude factor, which influences the length of the day during the growing season, is fundamental (fig. 8 and table 2). In the humid tropics, however, yearlong multiple cropping is possible and can overcome the latitude factor if satisfactory agricultural technology is used.

Soil studies at the School of Tropical Agriculture of the University of Hawaii show that soils of humid and wet-and-dry tropical climates are broken down by leaching and oxidation to form low-productivity soils called ultisols and oxisols (Fox and Yost, 1980; Uehara, 1980). As a result of this leaching and oxidation process, the fixation of phosphorous in the soil is greatly increased because phosphate from fertilizer is absorbed or fixed by the degraded clay minerals of the soil and is not available as plant nutrient. Sanchez and others (1982) of the Department of Soil Science, North Carolina State University, studied the soils of the Amazon Basin and found that 75 percent of the soils are acidic, infertile oxisols and ultisols, 90 percent are phosphorous deficient, and 16 percent have a high phosphorus fixation.

Fox and Yost (1980) calculated that 540 million metric tons of P_2O_5, the equivalent of about 1.7 billion metric tons of high-grade phosphate rock, would have to be added to the currently cultivated soils of the world (mostly in the tropical regions) to bring the soils up to a moderate level of fertility. Thereafter, the fertility level could be maintained with annual applications of 20 million metric tons of P_2O_5, or about half of the 1980 world consumption.

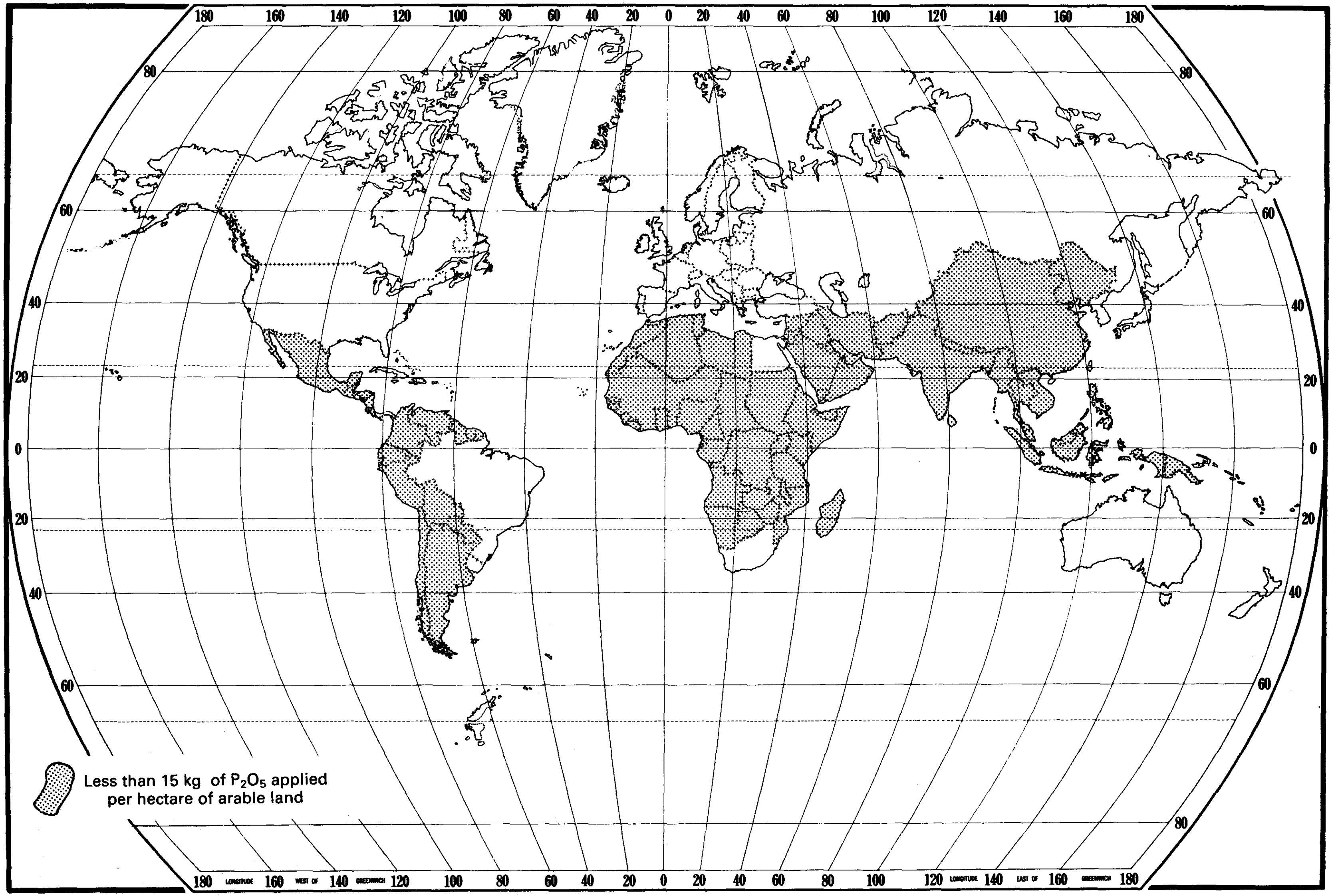


Figure 7.--Countries of the world with application rates of less than 15 kilograms of P_2O_5 per hectare of arable land. Data from Food and Agricultural Organization (1980).

Table 2.--1981-82 grain production in Caribbean Basin countries and other countries and regions

[Production figures in kilograms per hectare. Data from Food and Agricultural Organization (1982a)]

Country	Cereals	Sugarcane	Paddy rice
Belize	2,015	37,096	2,364
Costa Rica	2,250	49,020	2,571
Cuba	2,531	48,387	3,200
Dominican Republic	3,559	56,084	3,840
El Salvador	1,713	76,014	3,166
Guatemala	1,395	76,398	3,200
Haiti	902	37,500	2,100
Honduras	1,107	33,684	1,957
Jamaica	1,633	52,858	2,000
Nicaragua	1,414	76,923	3,191
Panama	1,291	54,902	1,667
Asia	2,199	54,707	2,923
Africa	970	71,499	1,752
South America	1,906	60,594	2,022
Europe	3,796	62,407	4,928
U.S.A.	4,409	88,595	5,315
Japan	5,308	63,333	5,688
Amazon Basin	7,800	--	--

The field studies of Sanchez and others (1982) in the Amazon Basin region of Yurimaguas, Peru, showed that an annual application of 172 kilograms of P_2O_5 per hectare to fields of a test project of continuous cropping allowed annual yields of 7.8 metric tons of grain (rice, corn, soybeans, and peanuts) per hectare (table 2). Applications of lime, nitrogen, potassium, magnesium, and trace metals also were required. These tests were carried out over 9 years on 3 fields with 88 harvests; however, the yield from test plots in agricultural experiments are generally higher than those of farmer-operated fields. To evaluate this factor, eight farmers of the region planted three crop rotations on a number of demonstration plots and increased their yields six- to tenfold over slash and burn agricultural yields. The economic analysis by Sanchez and others (1982) shows that continuous cropping technology is viable over a wide range of crop and fertilizer prices, capital levels, and labor force composition. Sanchez and others carefully state

> * * *It would be unwise to assume that continuous cultivation technology is directly applicable to the millions of hectares of ultisols and oxisols in the humid tropics. Our work has concentrated on nearly level soils, thereby avoiding the erosion hazard of cultivating sloping lands. Landscape adaptations, including terracing such as is practiced in parts of humid tropical Asia, would be needed for continuous cultivation on sloping lands.

Sanchez and others (1982) also point out that weed, insect, and disease attacks are likely to increase above the levels reached in their 9-year study. Also, variability in socioeconomic conditions is a limitation. Finally, they believe that the new technology must be tested locally to determine any necessary modifications.

Despite the early stage of development of the continuous cropping technology, appropriate variations adapted to local conditions clearly can have a major impact on tropical agricultural productivity. If the

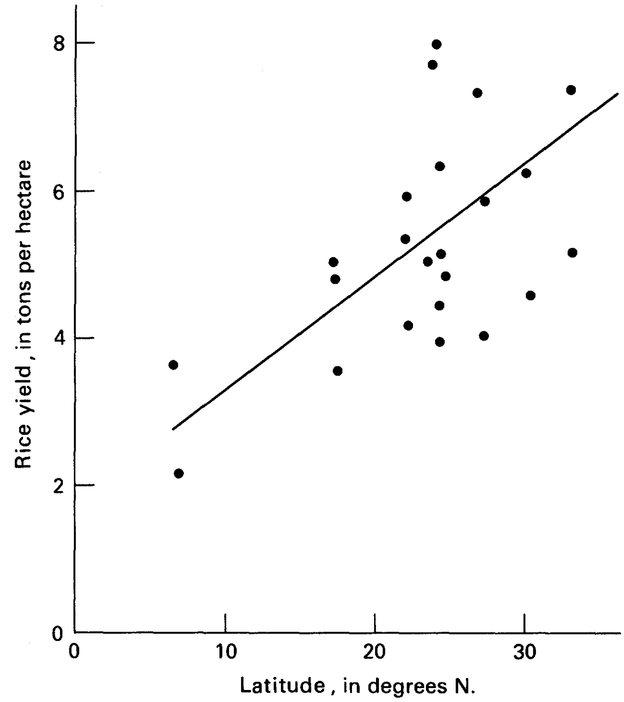


Figure 8.--Relation between rice yields of the INPUTS (Increased Production Under Tight Supplies) experimental sites and latitude. From Uehara (1979).

area presently under cereal cultivation in the Caribbean region were farmed under the new continuous cropping technology and yielded only 5 metric tons of cereal per hectare (instead of the 7.8 metric tons in the experiment), the region's cereal production would more than double (table 3).

Applying this technology to agricultural production in the Caribbean region at present unsubsidized, free-market prices for phosphate fertilizer (about \$650 per metric ton of P_2O_5 in 1980) would cost about \$978 million per year (table 4). The total cost of the technology also will include expenditures for other inputs. The value added of the projected additional 8.6 million metric tons of cereals produced (table 3) (not including increased production of other crops), at \$350 per metric ton, would be more than \$3 billion. These figures are based on current international prices and, as such, are unrealistic in that

Table 3.--1982 cereal production statistics and projected cereal production statistics for new agricultural technology in the Caribbean Basin countries

[Data from Food and Agricultural Organization (1982a)]

Country	1982 yield, in kg/ha	1982 production, in 1,000 t	Value,[1] in million dollars	Projected production, in 1,000 t	Value, in million dollars
Belize	2,015	29	10	70	24
Cuba	2,531	577	202	1,140	399
Dominican Republic	3,559	484	170	680	238
El Salvador	1,713	651	228	1,900	665
Guatemala	1,395	1,397	489	5,005	1,751
Haiti	902	415	145	2,300	805
Honduras	1,107	466	163	2,105	737
Jamaica	1,633	8	3	25	9
Nicaragua	1,414	499	175	1,765	618
Panama	1,291	213	75	825	289
Total	19,810	7,893	2,764	16,515	5,780

[1]Cereal average value taken as $350 per metric ton.

great increases of cereal supply inevitably would affect the world market price of cereals. Despite this effect, the new cropping technology could greatly increase agricultural supply at cost-benefit ratios that would support use of the technology. Annual application of 172 kilograms of phosphate per hectare, as used in the Sanchez field test, is 5 to 10 times the application rates in countries of the Caribbean region but only slightly higher than the 1979 P_2O_5 application rate of Japan (table 4).

Such application rates require large amounts of phosphate. For example, the rate of yearly application of 172 kilograms of phosphate per hectare to all of the arable land in the Caribbean region (9.7 million hectares as of 1982) would require

Table 4.--1982 phosphate fertilizer consumption in the Caribbean Basin countries, Amazon Basin, and Japan and projected consumption and cost for new agricultural technology in the Caribbean Basin countries
[Data from Food and Agricultural Organization (1982b)]

Country	Arable land, in 1,000 ha	1982 P_2O_5 consumption per 1,000 ha of arable land, in kg/ha	1982 P_2O_5 consumption, in 1,000 t	Projected P_2O_5 requirements, in 1,000 t	Projected P_2O_5 cost at $650/t, in millions of dollars
Belize	46	12.0	0.556	8	5
Costa Rica	283	42.4	1.200	49	32
Cuba	2,535	31.6	8.010	436	283
Dominican Republic	885	12.4	11.000	152	99
El Salvador	560	35.9	20.086	96	62
Guatemala	1,485	18.7	27.800	225	146
Haiti	548	2.6	1.400	94	61
Honduras	1,563	2.7	4.200	269	175
Jamaica	205	14.2	2.910	32	21
Nicaragua	1,085	6.9	7.500	187	121
Panama	462	13.6	6.300	79	51
Amazon Basin experiment	--	171.8	--	--	--
Japan (1979)	--	169.0	--	--	--
Total	9,657	533.8	90.962	1,627	1.04 billion

1.63 million metric tons P_2O_5 per year at a cost of $1.06 billion, assuming a price of $650 per metric ton of P_2O_5 (table 4).

In summary, if the agricultural potential of the Caribbean region is to be realized, substantial amounts of phosphate fertilizer will be needed, along with other fertilizers and soil amendments. The value of the increase in agricultural products is expected to readily exceed the cost of phosphate fertilizer and other agricultural inputs.

ECONOMIC IMPLICATIONS OF PHOSPHATE ROCK RESOURCE DEVELOPMENT

The successful development of minable phosphate rock deposits could impact the economies of the Caribbean countries in four ways: (1) Foreign exchange earnings could be increased by the export of either raw phosphate rock or manufactured phosphate fertilizer. (2) Domestically produced phosphate rock could be a direct substitute for current phosphate rock imports into the region. (3) Application of optimal quantities of phosphate fertilizer to lands used for production of export crops could result in greater agricultural exports and higher foreign exchange earnings. (4) Application of phosphate to lands used for production of food crops for domestic consumption could increase the domestic supply of food crops for the region and reduce food imports into the region. These possible impacts are discussed below.

PHOSPHATE EXPORTATION

The discovery and development in the Caribbean Basin of a large phosphate rock deposit that could be mined and beneficiated competitively with the deposits of the southeastern United States would allow entry of the Caribbean Basin countries into the international phosphate market. Such a discovery, however, is unlikely.

The deposits of Florida and North Carolina are large, uniform, flat lying, and close to the surface, all of which allow intensive surface mining by large pieces of equipment at low cost. The deposits are beneficiated easily and provide a high-grade, high-quality concentrate. Because the deposits are close to ports, transportation costs are low. These deposits are nearly unique, matched only by the deposits of Morocco. As a result of these deposits, the United States and Morocco set the competitive price floor for the world phosphate rock market. These two countries supply over 60 percent of the world's phosphate exports.

Although unlikely, another such deposit may exist in the Caribbean region. If such a deposit were found, it would have to compete in the same local market area as the southeastern United States deposits. Although the discovery of a world-class deposit in the Caribbean region is remote, the chance of such a discovery should not be totally discounted.

SUBSTITUTION FOR PHOSPHATE IMPORTS

In 1982, imports of phosphate rock to the Caribbean Basin countries amounted to 90,000 metric tons of P_2O_5 in the form of phosphorus fertilizer. The total value was about $60 million. The resulting trade deficit could be avoided by substituting domestically produced phosphorus fertilizer for that now imported. Savings could be large and would be determined largely by the increase in phosphorus fertilizer use, as well as by future energy prices. For example, transportation costs, which are a part of the import cost of phosphate rock, are sensitive to bunker fuel costs. Also, a significant percentage of mining and processing costs is sensitive to energy costs. Thus, the future prices of imported phosphorus fertilizer will increase as energy costs increase, and the savings created by substituting domestic phosphorus fertilizer for imported fertilizer products will increase accordingly.

AGRICULTURAL PRODUCT EXPORTATION

The economies of the tropical countries of the Caribbean region rely substantially, if not primarily, on the export of cereals, sugar, coffee, tea, cocoa, fruits, and other agricultural products. The field studies of Sanchez and others (1982) (see p. 13) demonstrated that an annual application of phosphate fertilizer to fields increased agricultural productivity in a continuous cropping test project in Peru. Despite the early stage of development of this technique, appropriate variations adapted to local conditions clearly can have a positive impact on tropical agriculture. Applying phosphate fertilizer to lands used for production of export crops, along with other soil amendments, can result in increased agricultural exports and higher foreign exchange earnings.

INCREASED FOOD PRODUCTION

Finally, applying phosphate to agricultural land would increase production of food crops for domestic consumption. Because of anticipated population growth, additional food supplies must be produced to avoid a decrease of food supplies for per capita consumption. Food shortages can be prevented by an increased application of phosphorus and other fertilizers to the lands currently used for production of food crops and by the adoption of new agricultural technologies to improve and sustain the soil fertility. If domestic food production is not increased, food imports must increase--with a resulting increase in trade deficits.

BENEFITS OF SUCCESSFUL DEVELOPMENT OF PHOSPHATE ROCK RESOURCES

In summary, the implication of successful development of phosphate rock resources in the Caribbean region is an improved foreign exchange position for the countries of the region because of foreign exchange earnings from exports and savings from import substitution. The availability of Caribbean-region-produced phosphorus fertilizer would facilitate adopting new agricultural techniques for tropical soils and result in new lands being brought into productive cultivation. An additional benefit of a new phosphorus fertilizer industry would be the creation of jobs in the mining, chemical, and transportation sectors associated with the industry.

UNDISCOVERED PHOSPHATE ROCK RESOURCE POTENTIAL OF THE CARIBBEAN REGION

The undiscovered phosphate rock resource potential of the Caribbean region has never been assessed systematically. As a result, areas for prospecting cannot be targeted systematically, and the resource potential cannot be estimated. Indications are, however, that a considerable potential exists in the Caribbean region.

COMPARATIVE ANALYSIS OF THE PHOSPHATE RESOURCE POTENTIAL OF THE TROPICS

The humid tropical areas of the world constitute 22 percent of the total land area, yet they contain only 2 percent of the presently known phosphate rock reserve base (shown by country in table 1). The combined cold, temperate, and arid climate regions of the world have a phosphate rock reserve base of about 7 metric tons per hectare, whereas the humid tropics contain only 0.4 metric tons per hectare. If the tropical regions had the same phosphate-rock-per-hectare reserve base as the rest of the world has, the tropics would contain about 20 billion tons, rather than the present estimate of 1.25 billion tons, of phosphate rock reserve base. Even this estimate is inaccurate, however, because the reserve base of countries now producing phosphate rock excludes many of the world's known phosphate deposits that are not currently being mined but have commercial potential.

Another factor contributing to the underestimate of phosphate resources by the reserve base comparison is that many of the present commercial deposits are not well defined, and reserve base estimates predicted on these deposits commonly represent minimum estimates. Even more important, these estimates exclude undiscovered phosphate rock deposits. For example, recent estimates of the identified recoverable phosphate rock resources of the United States are placed at 45 billion metric tons (Cathcart, Sheldon, and Gulbrandsen, in press). The undiscovered phosphate rock resources of the United States are estimated to be an additional 13 billion tons. Thus, the total resource is estimated as 58 billion tons. Earlier estimates had prospected only 8 billion tons of reserve base for the United States (see table 1).

Finally, the area used in the calculation of reserve base for areas of the world other than the humid tropics includes much cold-climate land that has not been prospected for phosphate rock. Thus, we consider the 7 metric tons of phosphate rock per hectare figure used as a basis for comparison with the humid tropics to be too low.

Despite its limitations, this type of comparative analysis can be used with some degree of validity for very large regions of the world. When large areas are considered, their geologic histories can be assumed to have been comparable. As a result, their average mineral contents can be assumed to be comparable. In general, the geologic history of the tropics does not seem to differ greatly from that of the rest of the world. The primary reason for this similarity is the movement of the continental masses over the globe throughout geologic time. In the past, continental areas that are now in the tropics were in other climate zones, and present nontropical areas have at times been in the tropics. Consequently, the distribution of different rock types is not geologically biased by the present climate areas of the world.

A bias does exist, however, between the humid tropics and the rest of the world for the amount of rock outcrop. The presence of dense tropical forests and thick soil cover over deeply weathered rocks makes direct observation of underlying fresh rocks very difficult, particularly for the more soluble rocks such as phosphate rock and carbonate rock. Alirio Bellizzia, Secretary-General of the Association of Geoscientists for International Development, in 1977 wrote in the foreword to "Hidden Wealth: Mineral Exploration Techniques in Tropical Forest Areas" (Laming and Gibbs, 1982):

> The vast areas of the world covered by tropical rain forests, consisting largely of Precambrian rocks, include geological environments whose mineral and energy potential is very great; but, due to climatic and geographic conditions, most of the countries which form part of this belt are not capable of undertaking discovery of these resources utilizing modern methods. Modern exploration techniques have largely been developed in temperate regions and these, especially geochemical and geophysical techniques, which can give excellent results in temperate areas, present problems of application and interpretation when used in tropical rain forests.

In the same book, Vicente Mendoza (p. 6) summarized technical papers presented on the topic "Mineral Exploration Strategies in Tropical Forest Areas," as follows:

> Faced with an area covered with tropical rain forest, the exploration geologist requires a coherent exploration strategy, more than in any other type of terrain. The difficulties, both the obvious ones and those revealed only by experience, make such exploration more expensive and less fruitful. However, we must suppose that the rocks beneath tropical forests are as

well mineralized as comparable geological terrains that are well exposed. The problems of exploration in the jungle cannot be solved by reading books or using powerful geophysical formulae: The practical experience of geologists long familiar with the terrain must be combined with appropriate technical methods in an exploration strategy, a properly managed sequence of operations, if an efficient and effective mineral search is to be undertaken.

The lack of rock outcrops in the humid tropics probably is the controlling factor in the scarcity of known phosphate rock deposits. Phosphate rock deposits in the tropics are covered and therefore difficult to find and so have not been efficiently and effectively prospected.

The present-day approach to assessing the phosphate rock resource potential of the Caribbean region is to apply knowledge of the origin of marine phosphorite to Caribbean geology and then determine whether reason to suspect the occurrence of undiscovered phosphate rock deposits exists. When such an assessment is made for the Caribbean tropics, reason to suspect undiscovered phosphate deposits clearly exists. Exploration for suspected phosphate deposits must take into account both the area's complex geology and the deep soil weathering, and prospecting strategies used must be both cost and production effective.

ORIGIN OF MARINE PHOSPHATE ROCK

Marine phosphorite is formed within narrowly defined environments. Its formation requires phosphorus deposition in shallow water (Burnett, 1980; Sheldon, 1981). Second, the deposition must take place at low latitudes where the shallow seas are warm enough to provide a physical-chemical environment in which phosphorite can form (Sheldon, 1964; Cook and McElhinny, 1979). Deposition of phosphorus is theorized to occur by upwelling of phosphorus-rich deep-ocean waters onto shallow continental shelf areas that causes high surface-water productivity and subsequent settling of phosphorus-bearing oceanic plant and animal remains on the shallow ocean floor.

The formation of large phosphorite deposits has not been continuous over geologic time but has occurred at 11 different intervals (fig. 9). During each of these intervals, deposits were formed in shallow seas at low latitudes in many sites around the world. At times other than these 11 intervals, deposition was limited, rare, or nonexistent. Although the phosphorite formed during these 11 intervals is similar, the global distribution is not similar, and two major families of phosphorite deposits can be discerned (Sheldon, 1980, 1982) (figs. 2 and 9). The first occurs along the western coasts of the continents on shallow marine shelves in the trade wind belt zone, where deeper phosphate-rich ocean water is brought to the surface by upwelling currents. The best understood example of this family is the young deposits that are about 5 to 15 million years old (of Neogene age; fig. 9). This type of phosphorite deposition is ongoing, although the amount of phosphorite being deposited is very small (Baturin, 1982). This and other examples of the family are indicated by the notation "TW" (for trade wind) in figure 9. The second family of phosphate rock deposits is distributed around the ancient shallow seas of the Earth in a circumglobal, low latitude belt centered around the equator and in figure 9 is noted "E" (for equatorial). The oceanographic conditions that cause the formation of deposits of the equatorial family are not well understood and continue to be the subject of discussion and research, but the existence of the family is clear.

GEOLOGY OF THE CARIBBEAN REGION

The continents have been in constant motion over the Earth through geologic time, due to the process of plate tectonics. As the result of this movement, ancient continental shelf areas are now

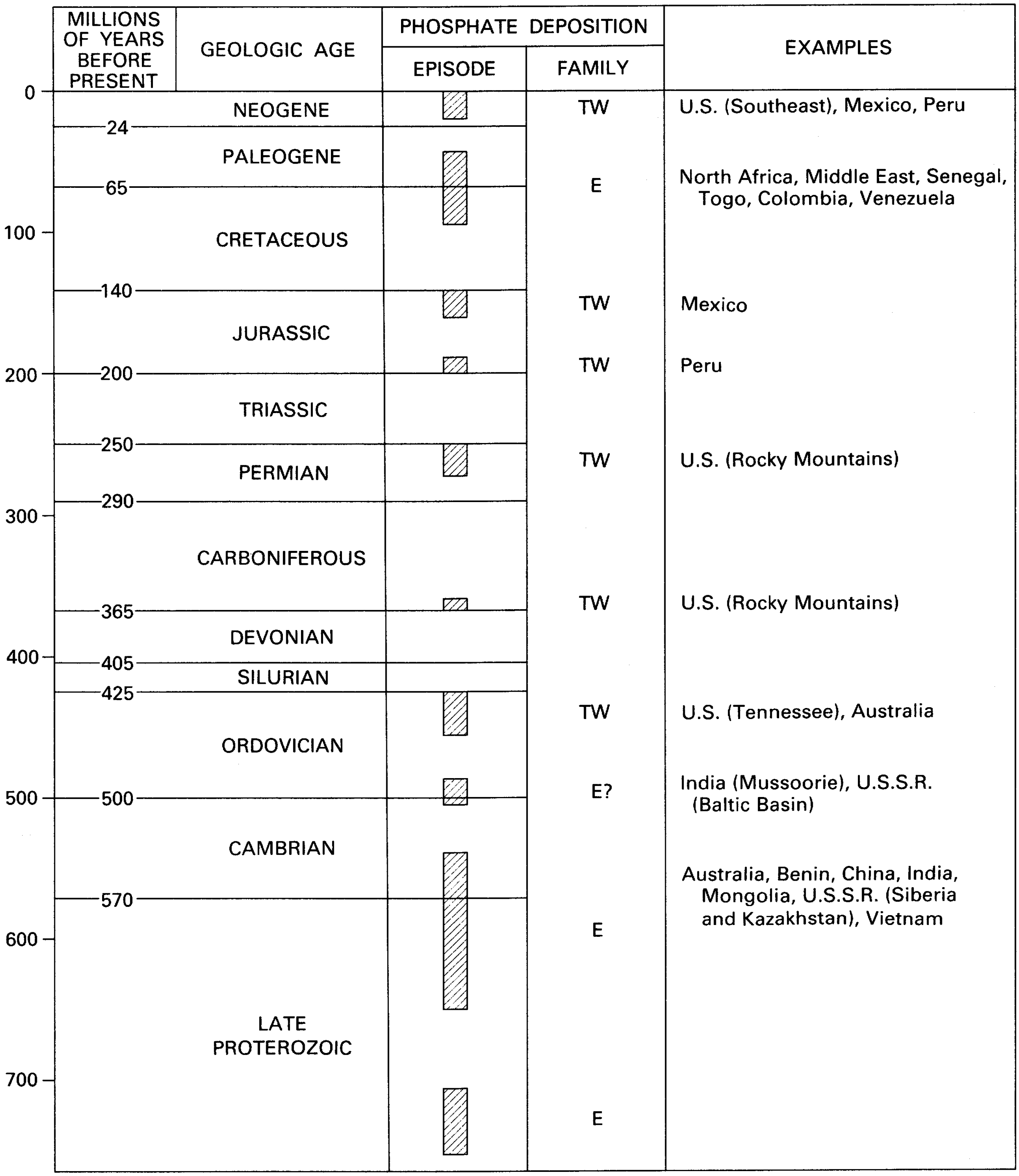


Figure 9.--Geologic episodes of phosphate rock deposition. An additional episode of phosphate rock deposition occurred in the Middle Proterozoic but is not shown. TW, trade wind family; E, equatorial family.

found at latitudes different from those at which they formed. Also, because plate tectonic processes have both split ancient continents into pieces and welded the pieces together in different combinations to form new continents, ancient continental shelves commonly are found in the middle of the present continents (for example, the Mongolian and Siberian Continental Shelf phosphorites of Precambrian age in central Asia). These processes make understanding the Caribbean region's geologic history quite difficult (Case and Holcombe, 1980).

For land areas that have been formed by the welding together of pieces of ancient continents, unraveling geologic history is especially difficult because the rocks tend to be deformed and metamorphosed by the welding process and because volcanoes are common in such areas. Another complicating factor is that continental shelves tend to be short lived in areas where such active plate tectonic processes are ongoing. Although the geologic environments of such areas may not appear favorable for the formation of phosphorites because of deposition of volcanic rocks and the short life of continental shelves, many important phosphate deposits of the world have formed in this environment. Areas of major deposits include northwestern South America, western North America, Turkey and Iran, and Kazakhstan, Siberia, and Mongolia.

PHOSPHATE RESOURCE POTENTIAL OF THE CARIBBEAN REGION

Two major phosphate rock provinces occur in the Caribbean region, one of Miocene age and the other of Late Cretaceous age. Both provinces are being mined, and the Miocene phosphate deposits of the southeastern United States are a major world source of phosphate rock. Neither of these provinces has been explored to its original sedimentary edges.

The Miocene phosphate province in the southeastern United States was the subject of much research during the early 20th century; recent research by S.R. Riggs and his colleagues in North Carolina has greatly advanced the understanding of the origin of the area's phosphate rock (Riggs, 1984).

The Caribbean region also contains Miocene deposits. A Miocene phosphate deposit occurs in Cuba (Pokrishkin, 1967). On Mona Island, between Puerto Rico and the Dominican Republic, a Miocene-Pliocene phosphate rock, which possibly is a marine phosphorite, occurs above an unconformity (Kaye, 1959). A Miocene phosphate deposit, which has been in part altered, exists in Falcon State in northern Venezuela (Rodriguez, 1984). These deposits indicate that the Miocene age province extends over the eastern Caribbean region. Phosphorite sedimentation in this province was controlled by the ancestral Gulf Stream (Riggs, 1984), which flowed from south to north from the northeastern South American Continental Shelf, through the Caribbean Sea, and along the eastern U.S. Continental Shelf. Many parts of the province have not been explored for phosphate, particularly the larger Caribbean islands and the eastern parts of Central America and northern South America. Miocene rocks have been mapped on the coastal plains of Puerto Rico, the Dominican Republic, Haiti, Jamaica, Venezuela, and the eastern Continental Shelves of Central American countries. Miocene marine sediments probably occur extensively offshore of these areas and possibly are phosphatic.

The second province is made up of late Cretaceous age phosphorites of Venezuela, Colombia, and Ecuador. A recently discovered potentially minable phosphate deposit in Tachira, Venezuela (Rodriguez, 1984), enhances the potential of this province. The resource potential of the area is already being exploited on a small scale in Colombia (Cathcart and Zambrano, 1967). The Cretaceous phosphorite beds occur in cyclic, laminated sequences deposited on the northern Continental Shelf of South America. Much postdepositional tectonic movement has disturbed these phosphate rock beds, so that exploration and exploitation are difficult, but the potential of the deposits is significant. Other Continental

Shelf areas of the Caribbean region, some of which were rifted off the South American craton and now form parts of the Caribbean islands, also may contain phosphate deposits. Descriptions of the Late Cretaceous age rocks of these areas indicate that sedimentary environments possibly suitable for phosphorite deposition occurred.

The extension of the Late Cretaceous age episode of phosphate sedimentation into early Tertiary time in other parts of the world, particularly North Africa and the Middle East, suggests that rocks of these ages in the Caribbean region may be prospective. Geologic mapping of the Caribbean region has shown that Upper Cretaceous and early Tertiary age rocks are widespread in both the Caribbean island countries and Central American countries.

In general, this region has been underexplored for phosphate deposits. Modern geologic knowledge and tools should be applied to further investigate possible extensions of the known phosphate provinces of the region.

DISCOVERY AND DEVELOPMENT PROGRAM FOR UNDISCOVERED PHOSPHATE ROCK RESOURCES OF THE CARIBBEAN REGION

Discovery and development of undiscovered resources of phosphate rock will require two main programs, a prefeasibility program and a feasibility program. The objective of the prefeasibility program is to discover phosphate rock deposits and measure the inferred reserve base; the feasibility program assesses the possibility of economically producing the phosphate rock. The relation of these two programs is shown in table 5, and the definitions of phosphate resource terms are given in the Glossary (p. 24).

The prefeasibility project consists of two phases. The first is a reconnaissance study. Previously collected data on the geologic structure and distribution of rock types are assembled by the project team from libraries and government files and analyzed with respect to the geology of phosphate rock. On the basis of this analysis, a field reconnaissance project is planned and carried out by geologists in each country, guided by phosphate resource specialists. This reconnaissance includes examination of outcrops and soil geochemical sampling. Resource assessment reports are prepared jointly by the resource specialists and the geologists of each country. Target areas that may contain phosphate deposits are identified by additional reconnaissance geologic mapping and by stratigraphic studies to determine the areal distribution and depth of potential phosphate-bearing rocks and their relations to surrounding rocks.

The second phase of a prefeasibility program is initiated when positive results of the reconnaissance phase are obtained. This phase consists of prospecting by reconnaissance core drilling and estimating the inferred reserve base by detailed core drilling to collect samples of phosphate rock to measure its thickness, quality, depth, and lateral extent. This part of the program is undertaken by geologists of each country under the guidance of phosphate resource specialists.

If a significant inferred reserve base of phosphate rock is established, bulk samples are collected for chemical and mineralogical analysis to determine the quality of the rocks for making phosphate fertilizer. A study of the rocks to establish appropriate mineral technology is necessary. This study ends the prefeasibility phase.

At this point, the feasibility program begins. The phosphate inferred reserve base of the participating countries of the Caribbean region is established, and studies initiated to establish the feasibility of economic development. The studies should include a detailed analysis of mining and beneficiation of the most promising phosphate rock deposits and should require the delineation of demonstrated reserves. Phosphate fertilizer manufacture and market studies also must be designed, and corresponding cost analyses performed.

Table 5.--Programs for developing a phosphate rock mining and phosphate fertilizer production industry

Prefeasibility program
First phase--Reconnaissance study
A. Collection and review of available data relevant to geologic environment of phosphate rock. Identification of target areas.
B. Field reconnaissance. Evaluation of target areas.
Second phase--Discovery
A. Prospecting by core drilling.
B. Measurement of inferred reserves of phosphate rock by development core drilling.

Feasibility program
A. Design and cost analysis of mining and beneficiation of phosphate rock deposit.
B. Design and cost analysis of phosphate fertilizer manufacture.

COST OF A PHOSPHATE RESOURCE DEVELOPMENT PROGRAM

Whether a country should invest money in the high-risk venture of mineral exploration depends on the cost of the program weighed against the value of the resource gained if the venture is successful. To take geologic uncertainty and cost into account, the development program can be designed in steps that start as low cost-high risk and escalate at each stage in cost but decrease in risk. The risk of economic loss is thereby reduced in each step.

The first phase, the identification of target areas, has a low geologic certainty but is quite inexpensive because it consists of a phosphate resource assessment that lasts only a few months and primarily uses data already collected. The cost is projected to be less than $100,000 for each country. The more expensive field reconnaissance phase should be undertaken only if the results of the target area identification are encouraging. The field reconnaissance to evaluate target areas should include established geochemical prospecting techniques, stratigraphic studies of sedimentary rocks, and geologic structural studies. The program would cost between $0.5 million and $1 million (U.S.) and last 1 to 3 years. Most of the work would be carried on by geologists of each country. Phosphate rock deposits may be discovered in the field reconnaissance phase, but, because of the deep weathering of rocks and dense vegetation cover, probably only promising areas would be located.

If field reconnaissance shows that one or more of the target areas is highly promising, the second phase, prospecting by core drilling and hand and bulldozer trenching, is started. This discovery phase would cost $1 million to $4 million per country and last 2 or 3 years. The goal of this phase of exploration is the discovery of phosphate deposits. Development exploration, to delineate the deposit after discovery by core drilling and trenching, would cost $4 million to $8 million and should define inferred reserves of phosphate rock in terms of quality, quantity, and minability.

At the conclusion of the second phase of the prefeasibility program, the feasibility studies begin. Each country should be able to complete a successful program of discovery and prefeasibility development of phosphate resources in 5 years at a cost of less than $15 million. Because of the staged approach, less than $2 million of this total would be at high economic risk, with subsequent expenditures at decreasing economic risk.

GLOSSARY OF PHOSPHATE RESOURCE TERMS

Taken from the sedimentary resource classification system of the U.S. Bureau of Mines and the U.S. Geological Survey (U.S. Geological Survey, 1982).

Identified resources. Phosphate resources whose location, grade, quality, and quantity are known or estimated from specific geologic evidence. To reflect varying degrees of geologic certainty, identified phosphate resources can be subdivided into demonstrated and inferred resources.

Demonstrated resources. A term for the sum of measured plus indicated resources.

Measured resources. Quantity is computed from dimensions revealed by outcrops, trenches, workings, or drill holes; grade and (or) quality are computed from the results of detailed sampling. The sites for inspection, sampling, and measurement are spaced so closely and the geologic character is so well defined that size, shape, depth, and phosphate content of the resource are well established.

Indicated resources. Quantity and grade and (or) quality are computed from information similar to that used for measured resources, but the sites for inspection, sampling, and measurement are farther apart or are otherwise less usefully spaced. The degree of assurance, although lower than that for measured resources, is high enough to assume continuity between points of observation.

Inferred resources. Estimates are based on an assumed continuity beyond measured and (or) indicated resources for which there is geologic evidence. Inferred resources may or may not be supported by samples or measurements.

Undiscovered resources. Phosphate resources whose existence is only postulated.

Economic resources. Those phosphate resources for which profitable extraction or production under defined investment assumptions has been established, analytically demonstrated, or assumed with reasonable certainty. Economic resources include reserves, inferred reserves, and economic undiscovered resources.

Reserves. That part of the demonstrated resources that can be economically extracted or produced at the time of determination. Reserves include only recoverable materials.

Inferred reserves. That part of the inferred resources that can be economically extracted or produced at the time of determination; otherwise similar to phosphate reserves.

Marginally economic resources. Those phosphate resources that, at the time of determination, border on being economically producible. Their essential characteristic is economic uncertainty.

Reserve base. That part of an identified phosphate resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. The reserve base is the in-place demonstrated (measured plus indicated) resource from which reserves are estimated.

Inferred reserve base. The in-place part of an identified resource from which inferred reserves are estimated.

Subeconomic resources. That part of identified resources that does not meet the economic criteria of reserves and marginal reserves.

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