

Sources of Fertilizer Minerals in South America A Preliminary Study

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By J. F. HARRINGTON, D. E. WARD, and V. E. McKELVEY

G E O L O G I C A L S U R V E Y B U L L E T I N 1 2 4 0

*Geology and technology of fertilizer-
mineral deposits of phosphates, potash,
and sulfur and suggestions for further
exploration in South America*



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SOURCES OF FERTILIZER MINERALS IN SOUTH AMERICA—A PRELIMINARY STUDY

By J. F. HARRINGTON, D. E. WARD, and V. E. McKELVEY

ABSTRACT

People in many South American countries are largely dependent for food upon their own agricultural output. Diminishing crop productivity from worn-out depleted soils is serious. Essential fertilizers needed to rejuvenate depleted soils are phosphates, nitrogen, potash, sulfur, and lime, together with minor amounts of such elements as manganese and boron.

South America's consumption of fertilizer minerals is in large part met by imports. Needs are far above combined imports and domestic production and are in part reflected in the large food imports. Requirements for fertilizer minerals by 1970 will likely be at least five times the consumption in 1965. Developing South America's potential for fertilizer-mineral production will go far toward meeting needs. This survey describes principal indigenous deposits of phosphate, potash, and sulfur in South America.

Resources are substantial and prospects bright for increased production of phosphate, potash, and sulfur in South America. The newly discovered Sechura Desert phosphate deposits and potash brines in northern Peru rank among the world's major reserves. As they come into production, phosphate and potash supplies for the western part of South America will be vastly increased. Needs for sulfuric acid on the west coast can be met from huge sulfide-ore deposits and copper and zinc smelters in Chile and Peru. Guano, apatite, high-phosphate iron ores, and small sulfur mines are of great importance as local sources of fertilizers in western South America. Chile produces a limited amount of sodium and potassium nitrate from coastal desert deposits. Prospects for substantial increases of guano production are not encouraging.

In the eastern part of South America, Brazil and Venezuela both mine phosphorites from marine sedimentary formations and have possibilities for developing further ore reserves. In addition, Brazil also has large igneous apatite deposits, some producing and others being developed. In Argentina several large areas of marine sedimentary rocks are being explored for petroleum; these formations may also be possible areas of exploration for phosphates and potash. Salars in Argentina should be thoroughly investigated for potash salts or brines. Igneous apatites similar to those of Brazil may be found in Argentina. A possible major source of potash salts in Brazil is being explored in Sergipe Province in northeast Brazil.

Available sulfur in the eastern part of South America is deficient in relation to needs. Argentina mines some elemental sulfur in the high Andes, and sulfuric acid is made from smelter gases at a lead smelter. Brazil uses pyrite from coal-

processing plants to manufacture acid; other possible sources are oil shales and gypsum. Venezuela has one area of petroleum reserves high in sulfur.

Known deposits or prospects and areas of favorable geologic environment will serve as starting points for the expanded exploration programs that are necessary to meet mounting demands for fertilizer minerals in the South American countries. New technologies and concepts in exploration, mining, and mineral beneficiation should be useful in exploring for new deposits and also in re-evaluating known deposits and prospects. Of particular interest are new methods of phosphate exploration based on recognition of regular lithologic sequences and changes in facies of phosphate-bearing marine strata. These sequences are now recognized as common to many marine phosphate deposits of the world and indicate the need for detailed exploration in favorable environments, such as those found in South America. In recent exploration of continental shelves and river mouths in North America, large phosphate and potash reserves of offshore phosphatic and potassium minerals were found. Probably similar deposits occur off the coasts of South America, particularly Chile and Peru.

Mineral beneficiation techniques, including fine grinding, classification, and flotation are making possible the recovery of a high-grade product from low-grade igneous apatite ores such as those found in Brazil. Solution mining of potash salts now being attempted in a Canadian deposit may be applicable for a deep deposit in the province of Sergipe, Brazil, provided that sufficient ore reserves are found.

Transportation costs of fertilizers from the coast to the interior in many countries, such as Brazil, Colombia, Ecuador, and Bolivia, may be prohibitive. In such places, lower grade material found near the consumer may be the only practical source. Potassic feldspar, potassium-rich volcanic rocks, muscovite, glauconite, and high-potash black shales all may become important for local use, either as finely ground material for direct application or perhaps for beneficiation and upgrading.

Exploration for fertilizer minerals in South America indicates a need for a long-term continuing effort. Utilization of all available geological information from all sources, such as geological mapping, petroleum exploration, ground-water work and mining-company investigations, may furnish clues to fertilizer-mineral deposits.

INTRODUCTION

A May 6, 1965, Washington press release of the Agency for International Development expressed the concern of the Inter-American Committee on the Alliance for Progress (CIAP) over the increasing disparity between the 2.5 percent rate of growth of the population of South America and the relative decline in per capita food production for the population. CIAP urged the immediate establishment of research programs in the alliance countries to bolster food production. A means of substantially increasing agricultural productivity lies in the widespread application of fertilizers, plant nutrients, and soil conditioners to the generally depleted soils of the region. Two important questions must be resolved in promoting the use of fertilizers for agricultural development: what is the availability and distribution of indigenous resources, and how can their use be made economically feasible for South American farmers?

To study these questions, CIAP established a Working Group on Fertilizers, and early in June 1965 the first meeting of this group was held in Washington to discuss ways and means of stimulating the development and utilization of fertilizers in the alliance countries. Included in the group were representatives of the Agency for International Development (AID), the Latin American Association for Free Trade (ALALC), the Inter-American Development Bank (IDB), the International Bank for Reconstruction and Development (IBRD), the Economic Committee for Latin America (CEPAL), the Inter-American Committee for Agricultural Development (CIDA), the United Nations Food and Agricultural Organization (FAO), and the Committee for Central American Economic Integration (CIEGA).

As a result of these activities, the Office of Institutional Development of the U.S. Agency for International Development (US-AID) requested the U.S. Geological Survey to undertake a rapid survey of information available on the phosphate, potassium, and sulfur resources of South America.

The present report was prepared in response to the request by US-AID, through funding by that agency, during the period September 1–November 20, 1965, from published reports and from unpublished information obtained from geological and mining agencies of various countries of South America.

Although the survey is comprehensive enough in regional coverage to indicate the potential for fertilizer-mineral exploration and development in South America, several countries—the Guianas, Uruguay, and Paraguay—were not included, partly because of the lack of time but mainly because of the lack of information on their geology and mineral potential. This rapid survey considers only phosphate, potash, and sulfur; nitrates are excluded because they can be made synthetically. Lime, which is needed for many of South America's acid soils, and other secondary plant nutrients, soil amendments, and soil conditioners are not considered because of the short time available for the survey.

ANALYSIS OF THE GEOLOGIC ENVIRONMENT

Specific minerals occur in characteristic geologic environments; hence exploration for fertilizer minerals can be narrowed down to areas of host rocks where these minerals are most likely to be found. Previous detailed geological studies of major known deposits of phosphates, potash, and sulfur provide keys or criteria that are of tremendous help in finding and evaluating new mineralized areas. For example, the recent work on phosphates in the Western United States by the U.S. Geological Survey led to recognition of regular lithologic

sequences and lithofacies relationships in the phosphate-bearing strata; this recognition of strata characteristics has been instrumental in discovering similar phosphorites in Peru, Turkey, Saudi Arabia, and India and also offers a basis for prospecting in other areas (McKelvey, Swanson, and Sheldon, 1953; McKelvey and others, 1959; Sheldon, 1963; McKelvey, 1963; Sheldon, 1964a).

Although such aids are valuable in identifying favorable provinces, lack of knowledge of the local geology hinders both preliminary appraisal and prospecting. Unfortunately, there are very few large areas of South America in which the geology is well known. These few, such as the Maracaibo and Barinas Basins in Venezuela and parts of Minas Gerais in Brazil, have been mapped and examined in detail because of their petroleum and ferrous metal deposits. Other vast areas of the major river basins, including the Amazon, and regions such as Patagonia, are geologically unknown.

Even in mapped areas the fertilizer minerals may have gone unnoticed if exploration were oriented only toward metallic minerals or petroleum. Phosphates are dull earthy minerals easily overlooked in outcrop and drill samples. Potash salts are soluble and may be leached from outcrops or not noticed in drill cuttings unless special coring equipment is used. Full exploration and development of South America's fertilizer-mineral potential may require many years—as it does, in fact, in other areas also—but there are now specific prospects that can serve as starting points in exploration, and the general knowledge available on the geology of South America helps to define some of the regions broadly favorable for further prospecting.

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Chile: Chilean Ministry of Mines; Gran Minería Association.

Colombia: Ministerio de Minas y Petróleos; Departamento Administrativo, Nacional de Estadística.

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Venezuela: Ministério de Agricultura y Cría; Ministério de Minas y Hidrocarburos; British Sulfur Corporation; Shell Foundation; Venezuela Petrochemical Institute.

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PHOSPHATE DEPOSITS

Many countries with low crop yields have phosphorus-deficient soils incapable of supporting adequate crop yields. Before man upset the cycle by farming, phosphorus in the soil was absorbed by plants and animals, then returned to the soil as plants decayed and as animals died and their bones decomposed. Now man grows crops which he removes from the land, and the soil is starved for necessary mineral nutrients. Bone as a source of phosphate was used early in the 18th century but the supply was inadequate. With the discovery of large mineral deposits of phosphates, the chemical fertilizer industry was born. Large increases in the use of phosphate fertilizers by the undeveloped nations are expected to help revitalize soils that have been long neglected.

MINERALOGY

"Phosphate rock" is a blanket term for rocks containing phosphate minerals that are used in production of fertilizers or other chemical

compounds. The term "phosphorite" is generally applied to sedimentary rocks made up largely of phosphorus minerals, but it is sometimes used interchangeably with phosphate rock. The principal mineral in phosphate rock is fluorapatite, represented by the general formula $\text{Ca}_{10}(\text{PO}_4)_6\text{F}_2$, or some other member of the apatite mineral family. In chemical analysis, the phosphorus is usually reported either as phosphorus pentoxide, P_2O_5 , or tricalcium phosphate, $\text{Ca}_3(\text{PO}_4)_2$, which contains 45.8 percent P_2O_5 and is known under the trade name "bone phosphate of lime" ("B.P.L.").

Apatite may contain many minor elements—vanadium, arsenic, silicon, sulfur, rare earths, uranium, and others. Fluorine content in phosphate rock may be as high as 4 percent and may present a serious problem in the form of noxious gases that may be released during the manufacture of fertilizers. Some of the elements that occur in very small amounts are beneficial to plant life, and some (vanadium and uranium, for example) have at times been recovered as byproducts in the manufacture of phosphoric acid. Uranium, which may be present in amounts of 0.1—0.4 pound of uranium per ton of ore, makes some phosphate rocks sufficiently radioactive to be detectable by gamma-ray techniques.

Most sedimentary phosphorites contain small pellets, oolites, nodules, or pebbles of phosphate which commonly are irregular in shape and may have another mineral grain or a fossil fragment as a nucleus.

GEOLOGY

Most phosphate deposits can be classified under one of six broad categories (see table 1; McKelvey, Cathcart, Altschuler, Swanson, and Buck, 1953):

1. Igneous apatites
2. Marine phosphates
3. Residual phosphorite
4. River-pebble deposits
5. Phosphatized rock
6. Guano

IGNEOUS APATITES

Apatite deposits occur as intrusive masses, hydrothermal veins, disseminated replacement bodies, and marginal differentiation deposits near boundaries of intrusives and pegmatites.

The largest of these deposits are in intrusive sheets or sills associated with syenite, pyroxenite, amphibolite, and, in some places, carbonatite, ilmenite, magnetite, or nelsonite. The sheets may be interleaved around a core. Near São Paulo, Brazil, large carbonatite deposits contain an estimated 90 million tons of low-grade rock which can be beneficiated to a product that is 40 percent P_2O_5 .

Apatite-rich intrusive layers, which may range in thickness from tens to hundreds of feet, have been traced for several miles. They may contain as much as 35 percent P_2O_5 . Reserves may be measured in millions of tons. Lower grade rock (5–25 percent P_2O_5) can be beneficiated by grinding, screening, flotation, or magnetic separation. The smelting of apatite-rich iron ores yields a high-phosphorus slag which is a valued phosphate fertilizer in Germany and elsewhere.

Vein-type, disseminated replacement, and marginal differentiation deposits near pegmatites are usually of low grade and small size.

MARINE PHOSPHATES

Marine phosphates are of primary importance, reserves in individual deposits generally being in the range of millions to billions of tons. Therefore, an understanding of the depositional environment of this type of deposit can be most rewarding.

Marine phosphates are precipitated along the continental flanks in places where deep phosphorus-rich cold water upwells toward the surface. Phosphates precipitate as the temperature and pH of the water increase near the surface; biological agents may also cause precipitation in the same environment. A typical assemblage of rocks is commonly associated with such deposits, which are found in many places in a regular lateral and vertical sequence that reflects a transition from one environment to another and a shift of environments with time as a result of elevation or depression of the sea bottom. For example, in the direction toward land, the lateral sequence in the Pacific Ocean phosphate field of the United States consists of dark carbonaceous shale, dark phosphatic shale, phosphorite and dolomite, chert, fossiliferous limestone, anhydrite, and light-colored and red shale. Most marine phosphates consist of small pellets or oolites associated with carbonaceous matter, argillaceous minerals, chert, or sand. Phosphate-rich zones may be several feet or more in thickness, contain as much as 35 percent P_2O_5 (generally as fluorapatite), and extend over thousands of square miles. Some deposits consist of large nodules or pebbles sparsely disseminated in a matrix of limestone, glauconitic sandstone, sandstone, and clay, and a few deposits are associated with manganese oxide and iron-ore deposits. Many are a basal conglomerate which may have been concentrated by submarine reworking of older phosphatic formations. These nodular deposits are generally thinner and lower grade; in fact, the pebbles themselves may contain only 15–25 percent P_2O_5 .

The distribution of phosphate deposits on the present sea bottom and the present distribution of upwelling waters provide clues to the occurrence of phosphorites in coastal plain sediments, and the identification of typically associated rocks (for example, black shale and chert)

TABLE 1.—*Characteristics of principal types of phosphate deposits*

[From McKelvey, Cathcart, Altschuler, Swanson, and Buck (1953, p. 349)]

Type (and example)	Origin	Associated rocks	Shape and structure of deposits	Principal phosphate minerals	Common minor metals	Range of reserves in individual fields, in tons of rock
1. Igneous apatites:						
a. Apatite intrusions (Kola Peninsula, U.S.S.R.; eastern Uganda; Palabora, East Transvaal).	Differentiation from cooling basic magma.	Nepheline syenite, ijolite carbonatite, pyroxenite, magnetite.	Inclined sheets in some places interleaved with other rocks around a circular core.	Fluorapatite ($\text{Ca}_{10}(\text{PO}_4)_6\text{F}_2$).....	Sr, rare earths.....	10^4 – 10^{10}
b. Apatite marginal differentiations (eastern Adirondacks).	Metasomatic differentiation along contacts of alaskite intrusions.	Alaskite, magnetite...	Steeply inclined irregular masses.	Fluorapatite.....	-----	10^3 – 10^6
c. Apatite pegmatite (southern Ontario).	Late-stage differentiation from cooling basic magma.	Pyroxenite, syenite, calcite, phlogopite, titanite.	Steeply inclined tabular masses.	Fluorapatite.....	Sr, rare earths.....	10^3 – 10^5
d. Hydrothermal veins, disseminations and replacements (Norwegian apatite veins, Virginia nelsonite).	Late-stage emanation from basic magma, generally cutting or partly replacing earlier differentiates.	Ilmenite, nelsonite, anorthosite.	Steeply inclined tabular masses or irregular disseminated bodies.	Fluorapatite; chlorapatite ($\text{Ca}_{10}(\text{PO}_4)_6\text{Cl}_2$); hydroxylapatite ($\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$).	-----	10^4 – 10^7
2. Marine phosphates:						
a. Geosynclinal phosphorites (Western United States; north Africa; Kara Tau (U.S.S.R.)).	Organic or inorganic precipitation on margins of oceanic basins.	Carbonaceous mudstone, chert.	Widespread blanket, folded to varying degrees.	Carbonate-fluorapatite ($\text{Ca}_{10}(\text{PO}_4\text{CO}_3)_6\text{F}_{2-3}$).	V, Cr, rare earths, Co, Ni, Mo, U, Zn, Ag, As, Cd, Cu, Tm, Be.	10^6 – 10^{11}

b. Platform phosphorites (Cretaceous glauconite marls of Gulf Coastal Plain; Tennessee blue rock).	Organic or inorganic precipitation in epicontinental seas; often reworked from older phosphatic formations.	Limestone, dolomite, quartz, sandstone, glauconite, carbonaceous mudstone	Widespread blanket, locally moderately warped.	Carbonate-fluorapatite	V, Cr, rare earths, Co, Ni, Mo, U, Zn, Ag, As, Cd, Cu, Tm, Be.	10 ⁶ -10 ¹⁰
3. Residual phosphorite (Tennessee brown-rock deposits).	Insoluble residuum remaining after decomposition of phosphatic limestone in humid climate.	Limestone, clay, quartz sand.	Near-surface blanket lying on irregular etched bedrock surface.	Carbonate-fluorapatite	As, U	10 ⁴ -10 ⁸
4. River pebble (Florida, South Carolina river-pebble fields).	Fluvial transport of weathered-out phosphatic particles in humid or subtropical regions of low relief.	Quartz sand	River bars, channel fillings and terraces.	Carbonate-fluorapatite		10 ⁴ -10 ⁷
5. Phosphatized rock: a. Calcareous terrane (Florida hard rock, Tennessee white rock, Nauru and Ocean Islands).	Replacement of limestone or clay in tropical or subtropical climate by phosphate derived from overlying phosphatic rocks or guano.	Limestone, dolomite, clay, quartz sand.	Near-surface irregular blanket.	Carbonate-hydroxyl-fluorapatite (Ca ₁₀ (PO ₄ CO ₂) ₆ (OH, F) ₂₋₃); hydroxylapatite (Ca ₁₀ (PO ₄) ₆ (OH) ₂); whitlockite (Ca ₃ (PO ₄) ₂); brushite (H ₂ CaPO ₄ ·2H ₂ O); monetite (H ₂ CaPO ₄); wavellite (Al ₃ (OH) ₃ (PO ₄) ₂ 5H ₂ O); randallite (CaAl ₃ (PO ₄) ₂ (OH) ₅ ·H ₂ O); taranakite (K ₂ Al ₆ (PO ₄) ₆ (OH) ₂ ·18H ₂ O).	Zn, Ag, Cd, Ga	10 ⁴ -10 ⁹
b. Igneous terrane (Daito Jima, Malpelo, Brand Connetable islands).	Replacement of igneous rock or clay by phosphate derived from guano.	Trachyte, andesite, basalt, granite, gabbro.	Near-surface irregular blanket.	((Al,Fe)PO ₄ ·2H ₂ O.) High-aluminum member occurs in acid igneous rocks, high-iron member in intermediate and basic rocks. Orthorhombic series: Variscite (AlPO ₄ ·2H ₂ O); barrandite ((Al,Fe)PO ₄ ·2H ₂ O); strengite (FePO ₄ ·2H ₂ O). Monoclinic series: Metavariscite, clinobarrandite, metastrengite.		10 ⁴ -10 ⁶
6. Guano (islands along Peruvian and Chilean coasts).	Accumulation of sea-fowl or bat excreta.	All varieties (no genetic relationship).	Surficial irregular blanket.	Carbonate-hydroxylapatite, hydroxylapatite, whitlockite, brushite, monetite.		10-10 ⁶

5a Metals listed are those present in amounts greater than five times their average concentration in the earth's crust, exclusive of detrital impurities.

5b No information available.

gives useful clues in prospecting in older rocks. A study by Sheldon (1964b) shows that geologically young phosphorites occur at warm latitudes between the equator and the 40th parallel; analysis of paleogeography and paleomagnetic data may therefore prove helpful in defining environments favorable for phosphate deposition.

RESIDUAL PROSPHORITE

Residual phosphorites are concentrated as relatively insoluble fluorapatite pellets or nodules by the weathering of marine phosphatic limestones in humid areas. Most such deposits are near the surface and occur on irregular deeply eroded bedrock surfaces. Deposits of this type may contain 15–35 percent P_2O_5 and have reserves of thousands or millions of tons. The phosphate deposits of Tennessee are typical examples.

RIVER-PEBBLE DEPOSITS

River-pebble deposits are placer concentrations of clastic phosphate minerals derived from erosion of phosphatic rocks and concentrated by stream action. Known deposits are mainly in the Southeastern United States. They are not of much economic interest now, partly because the P_2O_5 content of the leached nodules in the streams is low and partly because the deposits are not extensive.

PHOSPHATIZED ROCK

Phosphatized rock consists of phosphate minerals deposited by meteoric waters in joints or as tabular bodies which have replaced certain favored zones of the bedrock. Low-pH meteoric waters in hot humid regions dissolve phosphate minerals from phosphatic limestone or guano and transport it short distances. Where the bedrock consists of limestone, the deposits are calcium phosphates; where the bedrock consists of silicates (as in volcanic rocks or clays), the phosphates consist of one or another variety of aluminum silicate mineral, such as variscite or metavariscite, and crandallite. Tennessee and Florida have large deposits of this type. Ocean, Nauru, Angaur, and other islands in the south-central Pacific have been an important producer of phosphate from deposits derived from leaching of guano. Deposits of this origin may contain 35 percent or more P_2O_5 and have reserves of thousands or millions of tons.

GUANO

Guano from sea birds or bats is a rich nitrogenous phosphorus material which gains in phosphate concentration as the more soluble nitrates are dissolved. The largest guano deposits are found in the vicinity of the same phosphorus-rich upwelling-cold-water environment that produces many of the marine phosphates.

A dry hot climate in low latitudes is the most favorable environment for the preservation of guano. These conditions exist along the west coasts of South America, Lower California, and Africa. The P_2O_5 content seldom exceeds 20 percent but is readily available. Guano also contains other nutrients, particularly nitrogen except where decomposition has removed it. Most guano deposits are not large, but some still being formed can be harvested at regular intervals.

OTHER TYPES

Other types of phosphates may be important locally. Phosphatic iron ores, when smelted, may yield a basic slag, called Thomas meal, which contains 8 percent or more P_2O_5 that is readily available. Reserves are large, but the slag is a byproduct, and output depends on iron production. Such iron ores occur in Colombia and Brazil.

Glauconite, or greensand, is basically a hydrous silicate of iron and potassium, but it may also contain 1–5 percent P_2O_5 . Reserves are very large and constitute a possible future source of potash and phosphate. At present, however, there is no feasible economic method of treatment.

Phosphate produced from bones is no longer a major source, but a small amount, as a side product of slaughter houses, could be locally important in some countries remote from other sources of phosphate.

TECHNOLOGY OF PHOSPHATE

TREATMENT METHODS

Phosphate rock as mined contains 15–30 percent P_2O_5 and generally must be upgraded by some beneficiation process. Because in places phosphate rocks are fine-grained intimate mixtures of several minerals, some phosphate may be lost in milling operations. Rocks containing considerable amounts of carbonate minerals present difficult ore-dressing problems, but those in which the impurities are mainly sand and clay generally respond to beneficiation. Flotation techniques have much improved recovery from many deposits. Apatite deposits of igneous origin, such as those found in Brazil with carbonatite intrusives, may be beneficiated by grinding, screening, and flotation to yield a high-grade product.

The washed concentrates generally contain 28–34 percent P_2O_5 . Raw rock and concentrates are relatively insoluble when applied directly on most soils, but if finely ground they can be used on acid soils such as those found in parts of Brazil.

PHOSPHATE-FERTILIZER MANUFACTURE

In general there are three methods of treating phosphate concentrates or phosphate rock to make the contained phosphorus available as a plant nutrient: acid treatment, thermal fusion with magnesium silicate, such as olivine or serpentine, or thermal reduction with coke and a flux.

The oldest and commonest process is simple decomposition of the rock (generally beneficiated to contain at least 31 percent P_2O_5) with sulfuric or other acid to produce soluble monocalcium phosphate containing 16–20 percent P_2O_5 . Phosphoric acid is made by completely dissolving the rock with sulfuric acid and filtering out the $CaSO_4$. Triple superphosphate is obtained by acidulating phosphate rock with phosphoric acid; the product contains 42–48 percent P_2O_5 .

Thermally fused phosphate is made with phosphate rock and a basic magnesium silicate mineral fused together in a furnace; the product, termed “fused phosphate,” is a favored phosphate fertilizer in Japan. Thermal reduction of phosphate rock in an electric furnace with a siliceous flux volatilizes the phosphorus, after which it is condensed and collected as elemental phosphorus. Slags produced as a side product from smelting high-phosphorus iron ores may also be used as a phosphate fertilizer. Argentina has substantial reserves of such ores, and Colombia already uses high-phosphorus slag as a fertilizer.

TRANSPORTATION

Phosphate rock is a low-priced mineral commodity (about \$7.00 per ton f.o.b. at the mine in the United States). Transportation, therefore, is a big factor in calculating the unit cost of the P_2O_5 delivered to the consumer. For many years it has been customary to ship the phosphate rock or concentrates (containing about 31 percent P_2O_5) to the acid plant to make an ordinary water-soluble monocalcium superphosphate (20 percent P_2O_5). Higher grade phosphate fertilizers can be transported at lower cost per unit of P_2O_5 , and the market now demands triple superphosphate and ammonium phosphate. Elemental phosphorus manufactured near the mine for export may meet the increasing needs of countries like Japan, which are on the end of a long transportation route. A concentrated product will probably become more important to many South American countries such as Brazil, where internal transportation costs are high. A concentrated product may also become important in Peru for the export market.

FACTORS IN APPRAISING EXPLOITABILITY

In general, in a feasibility study of the exploitability of any phosphate deposit, the following must be considered:

1. Size and grade of the deposit.
2. Geology: thickness and strike and dip of beds, faults, overburden, and strength of wallrocks.
3. Mining method: surface, dredging, or underground.
4. Beneficiation process: gravity methods (washing, screening classifications, cyclones), flotation, or fluosolid calcining.
5. Market availability and transport costs: local and export.
6. Available power: thermal or hydroelectric.
7. Availability of materials necessary for manufacturing marketable fertilizers: cheap acid, cheap power and silica for elemental phosphorus, and serpentine or olivine for fused phosphates.

MINING METHODS

Mining of phosphate rock can be classified under one of three general methods: surface mining, underground mining, and dredging. The method selected for any given deposit is largely controlled by geologic factors such as thickness of overburden, thickness of beds, strike and dip of beds, competence of hanging wall and footwall, and faults and other characteristics of the deposit. Water and weak hanging walls may also present problems in some underground mines. Underground mining is usually accomplished by room-and-pillar methods in flat beds and by open stopes in inclined beds where wallrocks will stand. It is generally undertaken only where the rock is high grade (31 percent or more P_2O_5).

Most phosphate is mined by open-pit methods with large-capacity equipment. Much of the phosphate deposit of the western Sechura Desert in Peru is reported to have a low stripping ratio of overburden to phosphate rock, and open-pit methods will be applicable.

In North Carolina, preliminary experiments in deep dredging of phosphates at a river mouth are reported to be successful, and experimental dredging on the California Continental Shelf is also reported to be encouraging.

A big problem at many phosphate beneficiation plants is waste and tailings disposal. In Florida much of the ore contains a large amount of fine material (200 mesh and finer). The phosphate in this fine component is not recovered in the beneficiation process and goes with the slime tailings to disposal ponds. Losses may reach 40 percent of the phosphate in some plants.

POTASH DEPOSITS

Potash is a term derived from the early practice of leaching wood ashes in iron pots and evaporating resultant brines to obtain pearlsh. There are many compounds and minerals of potash, but the noun

"potash" has come to denote the K_2O equivalent in a salt, although no such compound exists in nature or is manufactured commercially. There is no substitute for soluble potash-salt compounds in fertilizers.

In 1843 potash was discovered in a well at Stassfurt, Germany, and thereafter potash salts came into wide use as fertilizer. During World War I, exports from Germany were no longer available to many countries, and other sources had to be found. England obtained a small amount of potash by burning seaweed. Japan used orthoclase feldspar and jarosite for a limited amount of high-cost fertilizer. In the United States and Canada, an intensive geological search and drilling campaign was successful in finding salt beds fully equal to those in Europe.

MINERALOGY

Although there are many other potash minerals, the most noteworthy are as follows:

	Percent K_2O
Sylvite, KCl	63.2
Langbeinite, $2MgSO_4 \cdot K_2SO_4$	27.7
Polyhalite, $K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$	15.6
Carnallite, $KCl \cdot MgCl_2 \cdot 6H_2O$	16.9
Kainite, $MgSO_4 \cdot KCl \cdot 3H_2O$	18.9
Niter, saltpeter KNO_3 , cave or caliche.....	46.5
Alunite, $K_2O \cdot 3Al_2O_3 \cdot 4SO_3 \cdot 6H_2O$	11.4
Orthoclase, $K_2O \cdot Al_2O_3 \cdot 6SiO_2$	16.9
Leucite, $KAl(SiO_3)_2$, lava-type deposits.....	21.5

Sylvite is commercially by far the most important potash mineral. Others, such as carnallite, niter, kainite, and langbeinite, are also of economic importance. Polyhalite, leucite, alunite, and glauconite are of potential value but are not of commercial interest at present.

GEOLOGY

BEDDED POTASH DEPOSITS

Sea water contains an estimated 0.05 percent K_2O , and certain lakes also contain substantial amounts. Evaporation in a blocked arm of the sea, bay, or large inland saline lake, under arid climatic conditions, concentrates the brines and may selectively precipitate the various salts. In Utah, California, Chile, Peru, Israel, and many other places, this process is actively going on today. Recent brine basins are a major source of potash salts.

Potash is obtained commercially both from brines and bedded salt deposits. These have a common genetic relationship inasmuch as both result from evaporation cycles.

In the United States, central Europe, and the U.S.S.R., sylvite and

other potash minerals occur in marine sedimentary beds of Permian age. Similar deposits in Canada are of Devonian age. The bedded potash formations of Sergipe, northeast Brazil, are said to be Cretaceous in age, but their mineralogy, grade, and size are not yet known. On the west coast of South America in Peru and Chile, brines contain substantial potash reserves. A brief description of principal known Western Hemisphere potash deposits is pertinent for exploration and evaluation criteria in lesser known areas.

In the Permian basin the salt deposits that underlie parts of New Mexico, Texas, Colorado, Oklahoma, and Kansas formed about 250 million years ago. A hot arid climate prevailed at that time, and salts were slowly deposited on the edges of this huge evaporation basin. As salt precipitated and the area sank, the seaward bars were breached periodically and the brines were replenished with sea water. The cycle was repeated many times and finally the gradual retreat of the Permian sea to the southwest left enriched brines on the southern flanks of the basin. These last evaporation cycles probably deposited the younger, richer potash deposits near Carlsbad, N. Mex. The salt-bearing Salado Formation containing the potash strata is about 1,200 feet thick; it is covered by the younger Rustler Formation and Recent sedimentary rocks.

In this large Permian basin, commercial deposits of potash have been found in an area of 1,000 square miles known as the Carlsbad potash district east of Carlsbad. The deposits consist of many thin beds of sylvite, halite, carnallite, and langbeinite which occur in about the middle of the thick salt-bearing Salado Formation. The strata of economic importance range from 4 to 14 feet in thickness and average about 18 percent K_2O equivalent. Individual beds are not constant in lithology or thickness owing to abrupt facies change. Halite ($NaCl$) horizons are common, and results based on one wildcat drill hole may be inconclusive.

In southeast Utah and southwest Colorado, the Paradox basin series of Pennsylvanian age contains a saline Paradox Member of the Hermosa Formation which occupies an area of more than 8,000 square miles. About 30 cycles of evaporation are represented in the salt facies. The member lies at depths of 1,400 feet on anticlinal structures and at greater depths in the synclinal structures of the basin.

Very little is known of a recent potash discovery in the Sergipe-Alagoas basin in Brazil. Salt deposits containing potash were reported at depths ranging from 457, to 2,799 meters in 29 holes drilled late in 1964. Many other holes were drilled without finding salt; however, at that time, the principal objective was petroleum rather than potash, so incomplete information on potash was obtained from

these drill cuttings, chemical analyses, and gamma-ray logs. In recent work in 1966, cores have been recovered that are said to contain both potash and magnesium salts. More detailed geological work and additional drilling are needed to evaluate this discovery. Minalable potash deposits in this area could be of greater economic significance than oil.

Large deposits similar to those in New Mexico and Utah are worked in Saskatchewan, Canada. The beds are 3-10 feet thick and contain about 25 percent K_2O . Quicksand above the potash beds makes shaft sinking expensive, but an alternative, discussed in the "Mining Methods" section, is being developed.

BRINES AND SALT CRUSTS

Another major source of potash is naturally occurring brines, formed by long periods of evaporation in inland seas or lakes. Chemically, most of the brines are very complex and represent saturated solutions, the principal components corresponding to sea-water bitterns. The salts in the brines commonly average 30 percent of the brine weight. Iodine, bromine, and boron are valuable byproducts from some solar operations.

In northern Chile, high-grade KNO_3 and KCl were produced from potassium salts at Salar de Bella-vista, as side products in the solution treatment of caliche and salt crusts. In the Provincia de Tarapaca, total reserves of low-grade caliche are estimated to be 1,000 million tons containing 200,000-600,000 tons of $KClO_4$. Salar Grande and other similar deposits have appreciable amounts of potash salts; the highest grade potash crusts contain about 3-4 percent K. Potassium nitrate is made by dissolving the crusts, which then undergo simple chemical purification.

All these deposits are formed in closed arid valleys or basins with little or no drainage to the sea. The water of solution is from ground water seeping downslope from the Andes, or from condensation of heavy fogs that sweep in from the sea and provide water for surface leaching in the desert. There are many closed basins in southwestern Bolivia, Peru, northwestern Argentina, and northern Chile. Some are basins surrounded entirely by volcanic rocks; little is known about the higher Andean valleys.

OTHER POTASH SOURCES

Alunite, which occurs mainly as veins and disseminations resulting from hydrothermal alteration, has been used as a commercial raw material in the production of potash alum and sulphate of potash through a calcination process. In recent years Japan has been a leading producer of potash from alunite (Johnstone and Johnstone,

1961, p. 27). Glauconite has long been used in its raw state as a slow-acting potash plant nutrient, and attempts have been made to utilize it as a source of potash salts. This has not been successful to date because of the high cost of production. One process consists of heating the glauconite with lime and recovering caustic potash by leaching (Johnstone and Johnstone, 1961, p. 235). Some marine black shales—for example, the alun shale in Sweden—contain a few percent potash and have been used as a source of potash alum. Leucite has been used in Italy to produce potash alum (Johnstone and Johnstone, p. 476). Granite, syenite, and other igneous rocks rich in potassium-bearing minerals, such as orthoclase, microcline, and some of the micas, constitute a large potential world reserve of potash; however, an economical process for producing the potash must be developed. A rhyolitic tuff very rich in potassic feldspar has recently been discovered in the Mohave Desert region of California (Sheppard and Gude, 1965); therefore other occurrences of this type may be worth prospecting. A readily available source of potassium minerals are the tailings and wastes from some of the milling operations of major porphyry copper mines.

TECHNOLOGY

TREATMENT METHODS

Brines.—Solar evaporation is an economical method of recovering potash from some natural brines or bittrens that contain appreciable amounts of K_2O and small amounts of sulfate; however, a low narrow temperature range is necessary, roughly between 18° and $45^{\circ}C$, evaporation and selective precipitation cycles being accomplished at the daily highs and lows. Potash is recovered under these favorable conditions only from the Dead Sea and from Great Salt Lake at Wendover, Utah. Artificial evaporation, with heat supplied from thermal plants, is economical for separation of various major products when the brines also contain elements such as iodine, bromine, and boron, which are recovered as valuable side products. Recovery by this means is carried out at Trona, Calif. Many simple solar salt industries recover salt from sea water without attempting to separate the various components. A major salt producer in northeastern Brazil is currently studying the possibility of recovering several thousand tons of potassium chloride as a side product of the regular sodium chloride recovery. A solar brine concentrate from Macau in northeast Brazil shows the following analysis, in weight percent: 8.7 percent $NaCl$, 2.1 percent KCl , 11.7 percent $MgCl_2$, 7.7 percent $MgSO_4$, and 30.2 percent total solids.

Bedded deposits.—For fertilizers, potassium chloride is most widely used, followed by potassium sulfate and potassium magnesium sulfate. Two grades of chloride are produced, 60 percent K_2O muriate and 22 percent K_2O (manure salts). The sulfate contains 50 percent K_2O equivalent, and the double sulfate contains 22 percent K_2O equivalent and 18 percent MgO . In the potash deposits sylvite and other potash minerals are generally intimately mixed with halite and impurities such as clay and shale. Two general methods of beneficiation are used, flotation and selective crystallization. In the flotation process, sylvite is floated away from halite in a saturated brine of sodium and potassium chlorides, the flotation reagent being amine chloride or amine acetate. The halite is then obtained as a separate product from the sink part of the flotation circuit.

Selective crystallization is dependent on differences in solubilities of sylvite and halite in saturated solutions at controlled temperatures. Ore is crushed and selectively dissolved in warm sodium-chloride-saturated brine. The potassium chloride is dissolved, then recovered as a separate pure salt when the brine is cooled.

Potassium salts in brines may be recovered by evaporation, either by solar heat or by applied thermal heat.

MINING METHODS

Mining of bedded potash deposits is generally accomplished by modern large-scale highly mechanized production methods, somewhat similar to those used in large coal mines. The room-and-pillar method is most used; the pillars are recovered in subsequent retreat mining. Both drilling jumbos and continuous mining equipment are used at the face, and shuttle cars or belt conveyors transport broken ore to gathering pockets at the shaft.

Owing to pressures generated at depths below 3,500 feet, it is not feasible to mine salt beds much beyond this depth. The salt formations have inherent structural limitations, but other factors, such as strength of formations enclosing the salt deposit, must also be considered.

In deeply buried potash-salt deposits, like many of those in the United States, Canada, and possibly Brazil, the capital required for shaft sinking and mine development is a large proportion of the initial investment, especially if difficult ground must be penetrated to reach minable beds, as in Saskatchewan. For this reason, a new method of mining potash salts at depth without shaft sinking is being observed with great interest by the industry. The Kalium Chemical Ltd. in Saskatchewan is drilling deep wells to the salt bed. It plans on pumping water to carefully controlled areas in the bed to form a brine that will be raised to the surface in a manner somewhat similar

to the Frasch method of producing sulfur. A disadvantage is the costly brine treatment that is required.

Problems in deep solution mining are generally twofold. One difficulty is to maintain the solvent capacity of the solution pumped down the hole to dissolve the salt beds. As the underground cavity in the salt beds grows larger, the velocity of the solution moving through the cavity becomes less, and the solution loses its effectiveness as it flows at a slower rate across the salt walls. As velocity decreases, insolubles, such as sand grains, tend to drop out of the moving stream and deposit on the sloping walls of salt beds to further lower the solution rate. Premature collapse of roof rock may also occur as cavity size increases, but to some extent this can be avoided through higher pressures in the chamber. Oil is usually floated on top of the chamber solutions to protect the roof rock. Success in overcoming the problems outlined here could be very beneficial to countries such as Brazil that have deep potash-salt deposits.

SULFUR SOURCES, GEOLOGY, AND TECHNOLOGY

Sulfur is itself an essential plant and animal nutrient, but its principal use and value in the fertilizer industry is in the manufacture of the superphosphates and phosphoric acid. Approximately 40 per cent of the world production of sulfur is used for this purpose. The following diagram outlines the present economic sources of sulfur:

Elemental	Native	Salt domes Other
	Recovered	Natural gas Refinery gas Coke ovens
Other forms		Pyrites Sulfur dioxide Sulfate minerals

FRASCH-PRODUCED SULFUR FROM SALT DOMES

Salt domes with associated sulfur are the type of deposit yielding the most sulfur. They commonly are found in areas of flat-lying or gently dipping sedimentary rocks. Low mounds in some places mark the surface expression of intrusive salt plugs or domes. They generally form in areas where the weight of thick sediments deposited on underlying salt-bearing beds forces salt plugs up into the overlying sediments.

In Texas and Louisiana, sulfur generally occurs in the cap of the salt intrusive, impregnated in porous limestone in the lower part of the caprock. This sulfur-bearing layer overlies anhydrite, which in turn is in contact with the main salt-plug mass beneath. The main salt-plug mass may extend to great depths; it has been postulated that the source of the intrusive salt is deeply buried Permian sedimentary rocks. The top limestone member of the plug, or dome, is a dense compact limestone. There is some evidence that the sulfur was derived from the anhydrite. The average thickness of sulfur-bearing formations is about 100 feet; the sulfur content is 30 percent.

Sulfur from dome-type deposits is called Frasch sulfur, after the method used to extract the sulfur from the cap. Hot water and steam are forced into the porous sulfur formation to melt the sulfur and force it up the drill hole to the surface. The Frasch method of extraction is extremely economical.

Although at present the only salt domes commercially producing sulfur are those in the United States and Mexico, others are known in the U.S.S.R., Iran, Romania, and Germany. Those in Mexico on the Isthmus of Tehuante have been rapidly developed; they yielded in 1964 an estimated 1.5 million tons of elemental sulfur. Salt basins in the Gulf of Mexico area extend about 350 miles inland and also are found offshore. The Freeport Sulfur Co. is presently producing sulfur from an offshore dome.

Geophysical surveys are used to detect salt domes and to delineate the hard cap area. When a salt dome is found, systematic drilling and sampling establish the character and extent of the deposit. Sulfur requires special sampling techniques because of the friable nature of the sulfur. A special core barrel is required. Sulfur, like phosphate, may be easily overlooked in drill cuttings.

Every consideration should be given to detection of sulfur-bearing domes in salt basins. Study of petroleum drill logs for the sequence of compact barren limestone, porous limestone with sulfur, anhydrite or gypsum, and deep salt can lead to discovery of a sulfur salt dome. The area of a salt dome may be small, perhaps only 75-1,200 acres. This presents a much smaller discovery target than phosphate or potash beds; phosphate beds may extend over hundreds or thousands of square miles.

SULFUR IN RECENT VOLCANIC ROCKS

Along the spine of the Andes in areas of late volcanic activity, many sulfur deposits similar to those in the famous Matsuo mine in Japan occur as impregnations in porous volcanic material such as tuffs and vesicular andesite. Unfortunately, they are generally found at high

altitudes, remote from markets and fuel for extraction. Individual deposits are generally small, but the aggregate reserve is large; they are important for local consumption, and some may yield enough sulfur for export—for example, Bolivia exports such sulfur to Chile.

It is necessary to produce elemental sulfur at the mine, because of the high cost of transportation to market. Mining and processing costs are high, and the autoclave or reduction-kiln recovery methods are slow and expensive.

PYRITES

Pyrite (53.4 percent S) and pyrrhotite (38.4 percent S) are both used for sulfuric acid manufacture. Pyrites (an inclusive term for iron sulfides) may be produced from massive sulfide deposits or as a byproduct from beneficiation processes of other minerals. Massive sulfide deposits are broadly associated with ultramafic rocks and pillow lavas of the great Circumpacific belt. High-sulfur coals may also yield pyrites during cleaning operations. Expense of transporting pyrites to the acid plant is a large cost factor because they contain only about half as much sulfur per ton of material as sulfur derived from sour gases and salt-dome deposits. Generally, production is feasible only where mining and extraction costs are very low.

Pyrites can be of great economic importance, however, for sulfuric acid manufacture in a country or an area remote from other sources. Much of Europe's sulfuric acid is derived from pyrites, and in Japan more than 2.5 million tons of pyrite and pyrrhotite, much of it from massive sulfide deposits like the Yanahara mine, is used in acid plants. A valuable side product is iron cinder. Other massive sulfide deposits around the Great Pacific Arc are in Taiwan, the Philippines, western Canada, and northern California. No comparable deposits are known along the Andes, and the environment there does not seem favorable for them because of the absence of ultramafics and associated mafic lavas. A more favorable zone for massive sulfides may be the east-trending eugeosynclinal belt in Venezuela.

SMELTER GAS

Smelter gases from copper, lead, or zinc smelters are used for acid production where there is a local market for the sulfuric acid. Enriched hot smelter gases can be used for fertilizer production if the economics of transportation and market are favorable. There has been experimental work on production of liquid sulfur dioxide from smelter gases for transportation to local acid plants. Consideration of alternatives depends on local costs, transportation usually being a big factor.

GYPSUM AND ANHYDRITE

The largest concentrated accumulations of sulfur over the world are in sedimentary beds of gypsum, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, and anhydrite, CaSO_4 , but unfortunately the recovery processes are costly. Great Britain produces some sulfur from gypsum, and several plants have been built for production of ammonium sulfate, utilizing gypsum in a wet chemical process. Gypsum and anhydrite will become increasingly important sources of sulfur as technology advances and as demands and prices increase.

COAL

On a worldwide basis there is more sulfur in coal than in any other source except gypsum and anhydrite. Sulfur occurs as iron sulfides (pyrite or marcasite) and in amorphous forms. Average minable coal containing 2.5 percent sulfur as pyrite may require uneconomically fine grinding to recover the sulfur. However, some high-sulfur coals like those of Brazil and Ecuador are possible sources, and research to develop means of recovering sulfur from them may be worthwhile. Usually sulfur is removed from coal only if the sulfur dioxide is objectionable in urban areas.

OTHER SEDIMENTARY DEPOSITS

Sedimentary sulfur deposits may form in basins by bacterial action on soluble sulfates where reducing conditions existed during deposition. The sulfur is amorphous and was deposited as colloidal sulfur; this is the probable genesis of the sulfur-bearing coal deposits near Cuenca, Ecuador. In Sicily, sulfur deposits in clay shales at the top of the Miocene sequence are important producers. The sulfur-bearing beds are accompanied by calcite, gypsum, and bituminous matter and contain as much as 30 percent S; they are irregular in thickness and commonly are associated with a succession of muds and gypsum. Similar deposits of Permian and Late Tertiary age occur in the U.S.S.R.

Black shales, particularly oil shales containing distillable hydrocarbons, may also contain as much as several percent sulfur, both as sulfides and in amorphous form. Sweden obtains a substantial part of her requirements as a byproduct from the processing of black shale for recovery of vanadium and oil.

PETROLEUM, NATURAL GAS, AND BITUMINOUS ROCKS

Refineries treating petroleum from high-sulfur crude oil and gas producers using sour gases must take out the sulfur before their product is usable. The side-product sulfur has become a significant and

cheap source of sulfur. Western Canada and France have become major producers of sulfur from this source.

Tar sands and other bituminous rocks also contain substantial amounts of sulfur that must be removed in the recovery of petroleum. Some of these deposits are of tremendous size, and although they are not being exploited much at present, they are certain to be large sources in the future.

SURVEY OF FERTILIZER MINERALS IN SOUTH AMERICA

Known deposits of phosphates, potash, and sulfur in South America are described briefly in the following sections, and their locations are shown on plate 1. Potential occurrences, as judged from available information on the regional geology, are also discussed. It should be emphasized, however, that the geology of most of South America is as yet poorly known, and subsequent studies may reveal prospects in areas now not suspected to contain them. The striking correlation shown on plate 1 between the location of known fertilizer minerals in South America and the more heavily populated coastal regions suggests that further exploration will show a much larger resource potential than can be documented on the basis of presently available knowledge.

ARGENTINA

Argentina, containing huge areas of pasture and rangeland, mostly below lat 25° S., is in a temperate zone where rains do not leach the soils of their valuable mineral nutrients as rapidly as in more tropical countries. Feldspars, apatite, and other minerals containing fertilizer elements are leached at a moderate rate, and grasses and plants obtain sufficient nutrients if the cropping pressure is not severe. Until lately the farmer or rancher has not felt the need for chemical fertilizers. This is reflected both in past low production and in import taxes on fertilizers.

A poor crop in 1963, partly due to drought and lack of fertilizer use, worsened production for the following year. The Government took immediate steps to reduce fertilizer costs to the farmer by eliminating import taxes and by allowing the farmer to deduct fertilizer costs from income taxes.

Consumption of fertilizers during the 1963 crop year totaled 54,500 metric tons, a decline from the previous year. Imports totaled 33,718 tons, nitrates being the major item. Domestic production was 8,551 tons of nitrogen, 2,576 tons of P_2O_5 , and 2,230 tons of potash. Much of this was derived from organic slaughterhouse products, guano, and oilseed cake.

There are plans to construct a fertilizer plant at Campana by local and foreign interests at a cost of \$20 million (U.S.) to make the following fertilizers:

	<i>Thousands of metric tons annually</i>
Ammonia	55
Urea	55
Sulfuric acid.....	39
Ammonium sulfate.....	50
Superphosphate	50
Mixed fertilizers.....	30

The raw-material requirements will be met from local resources as far as possible. Ammonia and nitrates will be no problem as they can be made synthetically. Argentina has substantial sulfur resources, but phosphate rock and potash deposits sufficient to meet the demand have not been discovered. There appear to be some prospects for these materials, however, and further geological reconnaissance and exploration are needed.

SULFUR

In 1963, Argentina produced 22,500 metric tons of refined sulfur and 166,130 metric tons of gypsum; volcanic-type deposits were the source for all local production of refined sulfur. In addition to elemental sulfur, sulfuric acid is made as a byproduct from the smelter gas of a lead-zinc refinery, and some from hydrogen sulfide gas is recovered from coke ovens of the Government-owned steel plant. Imports of sulfur amounted to 14,000 metric tons.

VOLCANIC TYPE

Along the east slope of the Andes are extensive deposits of sulfur-impregnated layers or beds of volcanic ash or tuffs on the slopes of volcanoes, generally at high altitudes (10,000 ft or higher). Owing to heavy storms during the winter months, mining operations are restricted to about 7 months of the year. Mining, transportation, and treatment costs are high, but in some places ore reserves are said to be sufficient to justify modern equipment, particularly at the Minera Argentina and the Volcán Overo mines, both owned by the same company.

The volcanic-type sulfur deposits, as mined, assay from 30 to 60 per cent S, and the sulfur content varies widely in short distances. The heterogeneous nature of these deposits makes it difficult to estimate reserves without extensive costly sampling. However, the amount of sulfur-bearing rock in this volcanic belt is undoubtedly very large; the question is what can be classified as sulfur ore within the present economic framework. Altitude and transportation are big factors.

In 1962, proved reserves in seven deposits, including three now worked, were reported to be 3,250,000 tons of sulfur, with an additional several million tons in the probable and possible categories. Total sulfur resources along this belt are undoubtedly many times these amounts.

Among the principal volcanic sulfur deposits is the Volcán Overo mine, in Mendoza Province (lat $34^{\circ}40'$ S., long $70^{\circ}05'$ W.). Its altitude, 14,500 feet, restricts mining operations to only 4 months in the year. The average grade of the ore is about 40 percent S. Ore reserves in 1964 were estimated as 265,000 tons proved and 365,000 tons probable in three of the principal areas. The ore is mined in an open pit and trucked to a loading bin on the top end of an aerial tramway. The ore is lowered by the tramway to the sulfur refining plant near the Atuel River, at an altitude of 7,000 feet. Treatment of the crushed ore is by autoclave and by flotation of the undersized material discharged from the autoclave. Overall recovery at this modern plant is 90 percent.

The Hilda Mary mine is in the territory of Neuquén, on Cerro Bayo 60 kilometers northwest of Trincão (lat $36^{\circ}40'$ S., long $70^{\circ}45'$ W.). From exploration in two sections of the mine during 1962, the sulfur content is estimated to be 23 percent. Reserve estimates are 38,700 tons probable and 13,300 tons possible. There is a small production of sulfur by autoclave. Exploration work is continuing.

The Julia mine is in Salta Province, on Cerro Estrella, almost on the Chilean border, 16 km from the Casualidad mine (lat $25^{\circ}00'$ S., long $68^{\circ}25'$ W.). A cableway provides means of transportation of ore to the Casualidad autoclave refinery. Reserves are estimated as 2,700,000 tons of ore that is 23 percent S, with probable and possible reserves of 10 million tons or more. Some sections of the mine contain masses of pure sulfur. Fabricaciones Militares refines the ore, and production is about 18,000 tons of refined sulfur per season.

Other mines are under exploration or are worked on a very low scale. The Orcoyurac mine is in the Territory of Neuquén near Corrida Río Grande and has been explored in part by Fabricaciones Militares. The grade of the ore is reported to be 23 percent S, but no reserve estimates are available. The Hwayracoya mine is also in the Territory of Neuquén; the ore assays 26 percent sulfur, but reserves have not been determined. The Rey Mago mine in San Juan Province contains 20 percent sulfur ore, but its reserves are also unknown. The La Betty mine in Jujuy Province, containing ore that is 26 percent S in the richest parts, is said to have an extensive area of tuff impregnated with sulfur.

SULFURIC ACID

At San Lorenzo in Jujuy Province, Sulfacid S. A. and St. Joseph Lead Co. operate a lead-zinc smelter that has a sulfuric acid capacity of 110 tons a day. The lead-zinc ores are from the mine at El Aguilar (lat $23^{\circ}15'$ S., long $65^{\circ}40'$ W.). A government-operated plant at Río Tercero in Córdoba Province has a daily capacity of 100 tons of acid. Sulfide ores for the smelter come from San Juan Province. A wet-contact sulfuric acid plant (78 percent H_2SO_4) produces about 23 tons of acid per day from the coke ovens at San Nicolas Steelworks. Other acid plants use elemental sulfur. Zarate Sulfurico S. A. has a capacity of 100 tons a day, and Industrias Químicas is rated at 225 tons a day. Yacimientos Petrolíferos de Fomento operates a hydrogen sulfide extraction plant and sulfur recovery unit to produce 42 tons of sulfur per day from oil refinery operations.

Until now, most of the demand for sulfur has been for industrial uses other than fertilizers, but the manufacture of fertilizers will increase in the future.

POTASH

Salts and brines.—No potash salts have been found to date (1965) in Argentina. There has been some investigation for potash in the large salinas of the northwestern part of the country where borax is mined in sufficient quantities to be an export commodity. Principal sources of common salt (halite) are the salt crusts in shallow salinas of Papa and Buenos Aires Provinces. Systematic investigation for potash salts in salinas and in closed basins may find potash salts or brines. Oil-well logs and samples also should be carefully investigated where salt beds are penetrated.

Alunite.—In the vicinity of Camarones, lat $44^{\circ}48'$ S. and long $65^{\circ}42'$ W., in Chubut Province, an alunite deposit is being considered as a possible source of potash with side products of aluminum oxide and sulfuric acid. Analysis shows that the alunite contains 4–7 percent K_2O , 22–35 percent Al_2O_3 , and 25–35 percent SO_3 .

PHOSPHATE**PHOSPHORITE**

No phosphate rock is produced in Argentina, but marine sedimentary rocks of Mesozoic and Cretaceous age are perhaps favorable for its occurrence. A belt of marine rocks of Jurassic and Cretaceous age that are also worthy of investigation for phosphates are exposed on the eastern slope of the Andes.

A phosphate occurrence in Departamento o Jujan (lat $33^{\circ}03'$ S., long $69^{\circ}10'$ W.), near Cacheuta in Mendoza Province, was investigated in 1963. This deposit consists of sedimentary carbonaceous and

bituminous rocks of Middle to Late Triassic age. Few samples showed more than 1 percent P, but further reconnaissance probably would be justified.

APATITE

Pegmatites containing some apatite are found in the mountains of San Luis, Mendoza, Córdoba, La Rioja, and Catamarca Provinces and the Territory of Neuquén. To date (1965), none of the pegmatites investigated contain enough apatite to be of interest as a source of fertilizer. Intrusive carbonatites similar to those found in Brazil may also occur in Argentina.

THOMAS SLAG

Basic slags from high-phosphorus iron ores contain 15–18 percent P_2O_5 and are a very desirable fertilizer for most soils. Such slags supply Germany with half of its phosphate fertilizer requirements.

High-phosphorus iron ores contain the largest known reserves of phosphate in Argentina. At the Zapla mine in Jujuy Province (lat $24^{\circ}15' S.$, long $63^{\circ}05' W.$), iron ore contains 0.7 percent P. Basic slag from this ore assays 15–19 percent P_2O_5 ; production was 20,000 tons in 1965. There are plans to increase production to 30,000 tons.

At Sierra Grande (lat $41^{\circ}37' S.$, long $65^{\circ}23' W.$), iron ore assays 1.13 percent P and 55 percent Fe. Reserves are said to be 63 million tons of ore. Planned production is 1,500,000 tons of ore which will be converted into pellets containing 68 percent Fe. Phosphate will be recovered as a marketable basic slag containing 15 percent P_2O_5 .

A deposit of marine phosphate was recently discovered by geologists of Yacimientos Petrolíferos Fiscales (YPF) in the Comodoro Rivadavia region of southern Argentina (oral commun., E. O. Roller, chief geologist, YPF). The deposit will be investigated by the Instituto Nacional de Geología y Minería.

BOLIVIA

Bolivia uses very little fertilizer of any type. Import records for 1963 show total imports of 2,000 tons of all types of fertilizers. No potash or phosphate is produced locally, and there are no known potash deposits. Sulfur was mined from high-grade volcanic deposits in the Departamento Potosí at a rate of 10,800 tons for 1963 and was exported to Chile. Smelters treating sulfides discharge the sulfur gases into the air, and some sulfides also are discarded in mill tailings and dumps.

Large reserves of gas and petroleum are sufficient to supply all local requirements for ammonium fertilizers and probably to supply some

for export, when a market is developed to justify the capital cost of a small ammonia plant at the refineries.

The Brazilian Shield covers much of the eastern part of Bolivia, including much of Departamento Santa Cruz; Precambrian alluvial sedimentary rocks fill the Beni and Chaco sedimentary troughs. The zone is composed of thick beds of Paleozoic sedimentary rocks.

SULFUR

Bolivia has many volcanic-type sulfur deposits similar to those of Ecuador, Peru, Chile, and Argentina. They all occur at high altitudes and are usually high-cost producers. Total sulfur reserves are probably very high but are difficult to estimate because the sulfur-impregnated tuff and ash are very irregular and have no uniform deposition pattern. All Bolivia's present sulfur production comes from these volcanic sulfur deposits. Principal sulfur deposits are as follows:

San Pablo de Napa is in Nor Lipez Province, Departamento Potosí (lat $22^{\circ}29'$ S., long $68^{\circ}39'$ W.), and near a railroad. The ore is reported to contain 70 percent S and to yield an autoclave product of 99.5 percent S. Reserves are 1.5–5.5 million tons of inferred ore. Size of the deposit is 1,300 meters in length, 600 m in width, and 6 m in thickness.

El Desierto Concepción is about 8 km south of San Pablo de Napa in Nor Lipez Province (lat $20^{\circ}23'$ S., long $68^{\circ}36'$ W.). The grade of the ore is 55–60 percent S which produces a 99.5 percent S product after treatment. Inferred reserves in the open pit are 560,000 tons of ore.

Sillayhuay is in Nor Lipez Province (lat $19^{\circ}45'$ S., long $68^{\circ}42'$ W.). Reserves are estimated to be 1,200,000 tons of 69 percent inferred ore.

Canapa is in Nor Lipez Province (lat $21^{\circ}28'$ S., long $68^{\circ}07'$ W.) and near a railroad. Reserves are estimated to be 1,250 tons of ore that is 91.5 percent S. A beneficiated product assays 99.5 percent S.

Ocana is in Nor Lipez Province (lat $20^{\circ}36'$ S., long $68^{\circ}27'$ W.) and near a railroad. Inferred reserves are 80,000 tons containing 40–60 percent S. The ore body is 500 m long, 150 m wide, and about 6 m thick. A lava flow 3–4 m thick covers the deposit.

PHOSPHATES

Although no phosphates are mined in Bolivia, there are favorable marine formations which are worthy of investigation. Thick sections of Cretaceous strata crop out in the vicinity of Lake Titicaca and to the south, where they contain petroleum.

Chacorilla farm in Cornelio Saavedra Province (lat $19^{\circ}34'$ S., long $65^{\circ}27'$ W.) is in an area of folded Ordovician sandstone and shales.

Here a thin-bedded layer of phosphorite 20 centimeters thick has been traced for 900 m along the outcrop; it contains 20 percent P_2O_5 .

Samuel Rosenblum (written commun., November 1965), U.S. Geological Survey, reported phosphate float in a streambed 100 km east of La Paz on the east slope of the Andes. The samples are oolitic collopheane and shell fragments. A search will be made for the source of this material.

Alkaline igneous rocks of Permian age form part of the Andean mountain zone. Margins of these intrusives may be worth prospecting for igneous apatite deposits.

BRAZIL

Brazil is fortunate in having fairly large known reserves of phosphate, mostly in the form of igneous apatite. There are also promising areas likely to contain potash in Sergipe State.

PHOSPHATES

With the exception of Olinda and possibly Araxa, very little of the phosphate reserves of Brazil can be classified as measured. Indicated and inferred reserves from known deposits total about 300 million tons, as follows:

Name	Location	Reserves (million tons)	Grade (percent P_2O_5)
Olinda.....	Pernambuco.....	30-40	24-35
Araxa.....	Minas Gerais.....	42	22
Araxa.....	do.....	49	10-20
Jacupiranga.....	São Paulo.....	150	6, 5
Serrote.....	do.....	1	20
Guariruvá.....	do.....	5	20
Ipanema.....	do.....	1	20
Pirocoá.....	Maranhão.....	10	26, 9
Trauíra.....	do.....	6	32, 4
Guano deposits.....	Coastal islands.....	6	18
Total (rounded).....		300	

Agri Research Incorporated (1964) estimated that, by 1970, production of soluble P_2O_5 will be 232,000 tons per year soluble from about 700,000 tons of rock or concentrates. Agri Research further stated,

If the consumption of P_2O_5 follows a steeper trend than indicated by the linear projection of past consumption there should be no problem in providing facilities for soluble P_2O_5 , but the national phosphate rock supply will be more of a problem.

The best solution to the problem of future phosphate reserves for Brazil would be a strong program of geological exploration to find and develop additional reserves, hopefully in reasonable accessible locations. The only other reasonable alternate is importation of phosphate rock with the resultant drain on hard currency exchange.

OLINDA PHOSPHORITE DEPOSITS

The Olinda phosphate deposits contain the largest known reserves of marine phosphate rock in Brazil. They are about 7 km northeast

of Recife, State of Pernambuco, in northeast Brazil, and are conveniently located adjacent to a good deep-water harbor at Recife. However, shipping costs are very high between Brazilian ports owing to local port and shipping charges. Olinda rock is thus handicapped in competition with imported phosphate rock in Santos or any part of Brazil other than the northeast. Fortunately several local fertilizer plants are in the construction or planning stage at Recife, so in a few years the mines should not have to seek distant markets for either their high-grade (35 percent P_2O_5) or their low-grade (24 percent P_2O_5) rock.

Estimates of reserves range from 30 to 50 million tons of phosphate rock, about 4 million tons of which is considered suitable for strip mining. At a rate of 200,000 tons per year of concentrating-plant product and a ratio of 3.4 tons of rock to 1 ton of concentrate, the open-pit rock is sufficient for 5 years of operation. On the basis of the total-reserve figure of 30 million tons, reserves are sufficient to last for 35 years at the planned output. Demand probably will increase rapidly, and it would be desirable to undertake exploration to develop additional reserves.

The phosphate formation at Olinda occurs at the base of a gray argillaceous limestone which is called the Gramame Formation; it is Late Cretaceous in age (M. G. White, written commun., 1957). Underlying the Gramame Formation is the Itamaraca Formation, also Late Cretaceous, which is probably more than 200 m thick and overlies Precambrian crystalline rocks. It is composed of layers of hard yellow to gray calcareous marine sandstone interlayered with friable fresh-water sandstone. The friable continental sandstone is locally conglomeratic and contains carbonized plant remains.

The phosphate bed at the base of the Gramame Formation varies in thickness, but it rarely exceeds 4 m and in some places may be as thin as 20 cm. Production is from the parts of the layer that exceed 1 m in thickness.

The phosphate is gray and yellowish white. The gray phosphate rock is compact and hard, and the lighter colored rock is more granular. The phosphorite occurs as small nodules and fills the interior of fossils, including foraminifers and coprolites. The rock averages about 25 percent P_2O_5 and is high in SiO_2 , Fe, and Al. White stated (written commun., 1957) that this phosphate is radioactive; individual samples contains as much as 0.03 percent U_3O_8 , and the average is probably 0.02 percent U_3O_8 .

A modern beneficiation plant with a capacity of 200,000 tons per year operates at a rate of only 50,000 tons per year; this is largely due to the high shipping costs previously mentioned. Two plant

products are obtained. One, 50 percent of the output, is a high-grade concentrate containing 33–34 percent P_2O_5 and is sold for normal superphosphate manufacture. The fines make up the remaining plant output and assay about 24–25 percent P_2O_5 ; the fines are combined with some of the high-grade material to make a direct-soil-application product of 28–30 percent P_2O_5 . Agri Research Incorporated (1964) estimated that a production of 140,000 tons of Olinda phosphate rock will soon be required for local fertilizer plants and direct soil application in the northeast. The low-grade-concentrate plant product is not suitable for making superphosphate or phosphoric acid (H_3PO_4).

Mining is now by open-pit methods; but reserves are limited, and as overburden increases, underground methods will have to be employed. Water and hanging-wall support will present problems. Ground-water geologists say the beds overlying the phosphate formations are aquifers producing a fairly strong hydrostatic head in the mine area, and they estimate that the amount of water involved is sufficient to supply the cities of Recife and Olinda.

The marine Tertiary sedimentary rocks unconformably overlying the Cretaceous sequence are called the Barreiras Formation; this formation extends for hundreds of kilometers along the coast, both north and south of Olinda. To the north it is found as far as João Pessoa, a distance of 104 km. The width of this sedimentary belt ranges between 11 and 16 km, and the thickness of the beds also changes along the strike. The Barreiras Formation conceals the phosphate deposits, and it is difficult to determine their extent except by drilling.

Some exploratory drilling has been done along this belt in the course of petroleum exploration, and some low-grade phosphatic rock has been found in Rio Grande do Norte several hundred kilometers to the northeast of Olinda. More work on these Tertiary and Cretaceous sedimentary rocks is needed; geological study of facies changes should be a major factor in the search for new marine phosphate deposits.

Phosphate nodules have been dredged from the sea bottom off the coasts of Bahia and São Paulo, but their extent and potential have not been explored.

ARAXA APATITE DEPOSIT

The apatite deposit at Araxa, Minas Gerais, is one of the two largest known apatite deposits in Brazil. It is in the central region, but transportation facilities to supply São Paulo and agricultural areas in the State of Goiás are poor.

A recent drilling program by the Brazilian Government has revealed an ore body of which 42 million tons is more than 22 percent P_2O_5 and 49 million tons is 12–20 percent P_2O_5 . However, the Brazilian Government also reported that at least 32 million tons of the

higher grade material contains 15 percent Fe_2O_3 , which would require removal. The amount of low-grade iron-rich apatite rock is unknown. Because some blocks of iron-free apatite are unmapped, total reserves are not known with any exactitude.

This deposit also contains one of the world's large reserves of pyrochlore, said to be 120 million tons assaying 3.48 percent Nb_2O_5 , 0.114 percent ThO_2 , and 0.05 percent U_2O_8 . Samples of the apatite averaged 29.9 percent P_2O_5 , 12.45 percent Fe_2O_3 , 0.20 percent Al_2O_3 , 0.05 percent TiO_2 , and 3 percent F.

The Araxa deposit is associated with a carbonatite mass, 6.5 km in diameter, intruded into crystalline limestones of the Minas Series. Magnetite, barite, and calcite are associated with the apatite. The iron-apatite ore is an intimate mixture of small shattered grains of apatite, with secondary limonite in the cracks. Treatment of this type of material presents a difficult ore-dressing problem.

The present ore-dressing plant upgrades the run-of-mine ore by washing, grinding to 48 mesh, removal of magnetic iron by electromagnets, and fine grinding to 200 mesh to obtain a direct-soil-application product. In 1963, production of this direct-application product was 30,000 tons containing 8,700 tons of P_2O_5 .

Much of the deposit is high in iron and therefore not suitable for acid treatment to make a normal superphosphate. The company plans to build three thermophosphate furnaces which will produce 150,000 tons per year of fused phosphate (magnesium silicate-tricalcium phosphate). Agri Research Incorporated, in its 1964 report, stated that according to findings of thermophosphate manufacturers in Japan, the high iron content will not be detrimental in this process. The material will contain 20 percent P_2O_5 . Similar material has proved to be a highly effective phosphate fertilizer in Japan, where tests on acid soils show that the fused phosphate gives superior rice yields compared to superphosphate additives. Magnesium silicate can be obtained from a deposit of serpentine near Araxa. Cheap power is also available.

JACUPIRANGA APATITE DEPOSIT

The Jacupiranga deposit is in southern São Paulo State near the Atlantic coast (pl. 1). It is in the center of the southern farming region, which consumes 90 percent of the fertilizers used in Brazil and has the highest agricultural output. The Jacupiranga reserves are estimated to be 150 million tons containing 6.5 percent P_2O_5 (Agri Research Incorporated, 1964). Other estimates give lesser reserves of a somewhat higher grade material. One estimate gives 15 million tons at 10 percent P_2O_5 .

The Jacupiranga apatite deposit is part of an igneous complex 10 km long and 7 km wide with a central zone of carbonatite. The igneous complex is composed of peridotite, titaniferous magnetite, apatite, olivine, serpentine, and pyrochlore. The weathered top area is an insoluble easily mined concentration of apatite material now almost mined out. Mine heads contain 23 percent P_2O_5 .

The unweathered low-grade rock containing 6.5 percent P_2O_5 has been subjected to extensive laboratory and pilot-plant flotation tests which have yielded high-grade concentrate containing 40.2 percent P_2O_5 , 54 percent CaO, 0.11 percent insolubles, and 1.69 percent F. The ratio of concentration is 1 ton of concentrate to 8 tons of rock.

A full-scale plant is planned to have a production capacity of 100,000 tons per year in the first stage with later expansion to 300,000 tons per year. Reserves are ample for at least 50 years at this rate of production.

SERROTE APATITE DEPOSIT

The Serrote apatite deposit is near the town of Registro, São Paulo. The rock from the mine is taken 1 km to the beneficiation plant where a concentrate is produced, then transported 22 km by road to the railroad at Juquia.

Reserves are estimated to be 1 million tons containing more than 20 percent P_2O_5 , calculated to a depth of 50 m. The depth to which the apatite extends is unknown.

The deposit is about 1,800 m in length and 10–15 m in width and consists of apatite, magnetite, and barite. It is related to an intrusive mass of nepheline syenite which forms an erosion-resistant hill about 100 m in height and 1 km in diameter. Altered pyroxenite is associated with the intrusive rock, and the zone is bordered by Precambrian gneiss. There are two types of phosphate rock, a hard crystalline apatite, and a secondary rock that is an amorphous precipitate.

The secondary rock has a much greater citric solubility than the apatite, so it can be finely ground and sold for premium prices for direct application. Plant capacity is rated at 14,000 tons per year. Mining started in 1949. Production for 1963 is estimated to be 11,500 tons of rock containing 3,250 tons of P_2O_5 .

GUARIRUVA APATITE DEPOSIT

This carbonatite apatite deposit is near Registro, São Paulo, and about 22 km from Juquia station on the Sorocaba Railroad. Reserves are estimated to be 5 million tons containing 20 percent P_2O_5 .

The deposit is similar to the nearby Serrote deposit. The apatite occurs in a layer 10 m thick, said to average 22 percent P_2O_5 ; it is associated with an alkaline intrusive mass of nepheline syenite, dolo-

mite, and pyroxenite. Mining was suspended a few years ago when the pumps could not handle water in the mine.

IPANEMA APATITE DEPOSIT

The Ipanema deposit is 20 km southwest of Sorocaba, São Paulo, and about 160 km from the coast. The Sorocaba-Ponta Grossa Railroad passes close to the mine near Ipanema. The deposit is estimated to have 1 million tons of material assaying 20 percent P_2O_5 and as much as 24 percent Fe. The deposit is in a nepheline syenite and alkaline-carbonatite ring intrusive. Titaniferous magnetite, orthoclase feldspar, and biotite are associated with the apatite. The mined rock was upgraded by washing and magnetic separation to produce a 33 percent P_2O_5 product containing 12 percent Fe_2O_3 .

The mine was operated by the Brazilian Government for 5 years after it opened in 1929. Mining was first done by underground methods, then was changed to open-pit operation. This deposit is now being considered as a source of apatite for magnesium thermophosphate by Jesuino Felicissimo, Jr., of the Instituto de Geografia e Geologia, State of São Paulo.

MONTEIRO APATITE DEPOSITS

The Monteiro deposits are in the District of Monteiro, Paraíba State, about 65 km from the railroad at Sertana, which is on the Northeastern Railway about 330 km from Recife. Three deposits are said to have reserves of 200,000 tons containing 40 percent P_2O_5 . This is a hand-sorted product.

The apatite deposits are in the Serido schist and calcareous shale and are associated with pegmatite intrusions. Blue apatite is found as irregular masses in the pegmatites. Some of the pegmatite contains iron-manganese phosphate minerals and amblygonite, which are not usable. The deposits were mined some years ago by small-scale hand-sorting methods at a rate of less than a thousand tons a year. After grading and screening, a high-grade product was sent to Recife.

ANNITAPOLIS, TAPIRA, AND IPIRA APATITE DEPOSITS

At Annitapolis, Santa Catarina State, on the banks of the Pinheiro River, apatite occurs in crystalline limestone. It is associated with magnetite, biotite, and tremolite and seems to be related to nearby intrusive alkaline rocks. The apatite is said to average 11 percent P_2O_5 . In Minas Gerais State, apatite occurs in an alkaline intrusive mass near Tapira, which is about 120 km east of Sacramento. Pyrochlore was detected by radioactive anomalies in the course of an aerial survey. Samples show 5–13 percent pyrochlore which assays 27 percent Nb_2O_5 , 4.8 percent ThO_2 , and 4.0 percent ZrO_2 . In Bahia State

about 25 km from the city of Ipira in the Serra de Gurgelha and on Serrote das Panelas, apatite occurs in alaskite in a mineralized zone which extends over an area of 2-3 km. The layer sampled shows low-grade material, but further investigations in the district may reveal other intrusives.

PIROCAUA PHOSPHATE

The Pirocaua deposit is near the coast in the northeastern part of Maranhão State between the small fishing port of Aurizona and the Bairro São Jose de Pirocaua. Local roads are inadequate, and transportation is mainly by boat.

The Pirocaua deposit is an aluminous laterite type, basically an aluminum phosphate that poses a difficult processing problem. It was studied and drilled by I. G. Farben Industry, but there is no production. Reserves are reported to be 10 million tons of 27 percent P_2O_5 material.

The deposit is near the surface on a low hill which rises 100 m above the surrounding plain. The hill consists of Precambrian phyllite which has been weathered to a laterite to a depth of about 25 m. The deposit is a phosphatic bauxite containing about 27 percent P_2O_5 and 40 percent Al_2O_3 . A limonite capping about 2 m thick covers the surface. Possibly the laterite was saturated with solutions from leached guano to form the phosphatic bauxite. The P_2O_5 content increases with depth.

TRAUIRA ISLAND PHOSPHATE

Trauíra Island Maranhão State, is in the delta of the Maracassume River (lat $1^{\circ}5' S.$, long $45^{\circ}35' W.$). It is about 2 km south of Apeu Island and close to Pirocaua Hill. Estimates of reserves range from 6 million to 11 million tons. Owing to inaccessibility and difficulty of treatment, exploration work has been limited.

The geology of Trauíra Island is very similar to that of Pirocaua. A surface limonite cap covers a weathered residual deposit of aluminous phosphate and laterite. The unweathered rock is phonolite and coral limestone. Genesis of the phosphatic bauxite is considered to be chemical interaction between bauxite laterite and downward-percolating solutions derived from guano.

Four samples of phosphate bauxite show the following analyses, in percent:

P_2O_5	Al_2O_3	Fe_2O_3	CaO
30.5.....	23.4.....	6.5.....	5.1
33.2.....	36.2.....	4.7.....	4.5
33.0.....	25.8.....	8.7.....	2.3
33.2.....	33.9.....	7.4.....	

GUANO DEPOSITS

Many islands off the coast of Brazil contain small amounts of guano or phosphatized rock formed from the leaching of guano. Guana Brazil investigated many of these but has not yet found large concentrations comparable to those on the west coast of Chile and Peru.

Rata Island (lat $3^{\circ}49'$ S., long $32^{\circ}33'$ W.) is one of a volcanic group that makes up the Fernando Noronha Archipelago. Guano has been mined here on a small scale for many years. In addition, calcium and aluminum phosphates have been formed by leaching of limestones and phonolite. Part of the calcium phosphate assays 24 percent P_2O_5 , and the aluminum phosphate contains 29 percent P_2O_5 . The overall average is lower, but it has a high citric acid solubility, which makes it a desirable phosphate fertilizer.

Offshore guano-type fertilizers are reported to total 600,000 tons, a liberal figure according to some experts.

POTASH

At present (1965), no potash is produced in Brazil. The total consumption of 110,504 tons of potash, mostly as potassium chloride, was imported during 1964. Costs are estimated to have been about \$8,500,000. Three possibilities have been considered for producing the potash from local sources. One plan would extract potassium sulfate from a large body of orthoclase feldspar. Another would recover potassium chloride as a byproduct from a large-scale sea-water salt project by solar evaporation. The third possibility is exploration of a buried salt basin found during oil-well drilling operations in Sergipe State in northeast Brazil. All these possibilities require extensive feasibility studies to determine their economic practicability.

SERGIPE ROCK SALTS

The best possibility of satisfying Brazil's potash requirements, with perhaps an excess for export, may be the newly discovered potash-bearing salt beds found during petroleum exploration drilling near the cities of Aracaju, Sergipe State, and Maceio, Alagoas State. A harbor at Maceio can dock boats of 15,000 tons displacement, and these port facilities already are served by a railway. The Government highway traverses the sedimentary basin area. Additional geological work and test drilling are necessary to determine whether potash reserves can be developed in the basin areas where preliminary drilling results indicate both carnallite and sylvite in the salt beds. More than a hundred wells have been drilled in the Sergipe-Alagoas basin. Twenty-nine of these penetrated salt beds. One hole drilled, Aracaju

1 (AU-1-SE), shows two potash-rich zones, one 2 m thick and the other 6 m thick at a depth of 1,178 m below the surface. Early drilling did not recover cores within the salt zones, because the primary objective was petroleum exploration; however it has been recently reported that both sylvite and carnallite have been recovered in cores.

The coastal sedimentary-basin belt extends through the States of Sergipe and Alagoas and into Pernambuco and beyond. In relation to its length, the belt is narrow, from 11 to 20 km in width, and it probably is a graben structure. The basement rock below this narrow deep trough is the Precambrian crystalline shield, which outcrops as low hills to the west and parallel to the coast. The east side of the trough is bounded by an underwater escarpment which is 10-25 km from the shore and may represent the east side of a graben.

Depths of the sedimentary rocks in the basin reach as much as 6,000 m in some places. Faults are common, and in the Sergipe-Alagoas area they cut the basin in a complicated undetermined pattern. Most of the basin fill is Tertiary and Cretaceous in age, but locally there are Paleozoic and Jurassic formations overlain by younger Tertiary unconsolidated terrestrial material. Marine beds outcrop in some places.

The salt beds are found in the Middle and Upper Cretaceous, locally called the Muribeca Cretaceous in the Aracaju area, and the slightly older Maceio Cretaceous at Maceio.

The following is extracted from a report for the United Nations by S. R. Harding, consulting geologist, J. C. Sproule and Associates Ltd., 1963. A stratigraphic summary from drill hole Aracaju 1 (AU-1-SE) shows the following:

Formation or age	Lithology	Depth interval (meters)
Cenozoic.....	Gravel, sand, and clay.....	0- 63
Calumbi.....	Mudstone, calcareous shale, siltstone, and sandstone.....	63- 855
Riachuelo.....	Calcareous shale, argillaceous limestone, and some dense micro-crystalline to sublithographic limestone; sparsely dolomitic, slightly sandy beds in lower parts.....	855-1137
Muribeca.....	Evaporites, anhydrite, and salt; interbeds of shale and sand in basal part.....	1137-1422

In general, the beds are flat lying or dipping at relatively shallow angles, but drill hole AU-1-SE is believed to be very close to a fault zone. Faults are common in both the Aracaju and Maceio areas.

In the general Maceio area, the first formations to be penetrated in a well or drill hole will depend to some extent on whether the well is spudded on the plateau or at a lower altitude. The following section would apply to a well on the plateau.

Formation or age	Lithology	Depth interval (meters)
Barreiras.....	Unconsolidated sands and clays.....	0- 50
Older Tertiary.....	Clay and calcareous sandstone.....	50- 120
Alagoas-Maceio (down to first salt) ..	Interbedded sandstone, conglomerate, and shale. This formation comprises largely nonmarine beds but near-marine beds occur in upper part of Alagoas Formation.	120- 935
Maceio Salt.....	Salt with interbedded shale and sandstone.....	935-1250±

Additional drilling and geological work is necessary to evaluate this deposit. Cansult Ltd. (a Canadian consulting firm) recommends the drilling of another well close to Aracaju No. 1 to obtain a section of core in the salt zone. More detailed geological work in the areas covered with recent sediments is necessary. Seismic methods will indicate faults, but not the salt beds unless they are at least 70 m thick. Some stratigraphic holes will be needed to correlate formations in different parts of the basins.

POTASH FROM SEA WATER, FELDSPARS, AND OTHER SOURCES

A large salt company is studying the possibility of producing by-product potassium chloride from sea water in a solar salt operation. To date in other parts of the world, the only successful operations of this type start with a concentrated brine.

Companhia Nacional de Fertilizantes Potassicos is conducting a feasibility study for the production of K_2SO_4 from a large feldspar deposit near Natal, Rio Grande do Norte.

Although there are no other active prospects for potash in Brazil, the potential in an area of this size should not be discounted. All types of deposits described in the earlier part of the report could be present in Brazil. The fact that the promising Sergipe deposits were discovered only recently shows something of the stage of exploration and suggests that wider and more intensive search may reveal many more prospects.

SULFUR

No sulfur is produced in Brazil. Sulfur imports for 1964 are given as 140,801 tons, valued at \$2,973,216.

Probably the best possibility for local manufacture of sulfuric acid is pyrite from high-sulfur coals. Samples of coal from Santa Catarina are 5 percent S; some others contain as much as 7 percent. Pyrite is accumulated at the coal-washing plant at Tubarão, Santa Catarina, and the amount will increase when a new thermoelectric plant is completed. Oil shales high in sulfur may also be possible material for acid manufacture.

Gypsum and anhydrite deposits in the northeast are also potential sources of sulfur. In India, gypsum is used in the manufacture of

$(\text{NH}_4)_2\text{SO}_4$. However, gypsum as a source material for acid manufacture involves a high-cost extraction process.

CHILE

PHOSPHATES

In Chile, phosphate is found in marine sedimentary beds, igneous apatite, and guano. Production of phosphatic guano in 1964 was 15,051 metric tons averaging 23.1 percent P_2O_5 . However, this source of phosphate is rapidly being depleted. Apatite deposits in Coquimbo and Atacama Provinces are mined on a small scale; production is estimated to have been 13,000 tons for 1964. It is planned to increase production from this source. Marine phosphorite beds of Cretaceous age at Tongoy in Coquimbo Province have not been mined but are being investigated (September 1965) to determine their potential.

The Chilean Government recognizes the importance of phosphate fertilizers and sent \$5 million for importation of triple phosphate in 1964, mostly from the United States. Farmers buy this at a subsidized price of 25–50 percent of the cost.

IGNEOUS APATITE DEPOSITS

A belt of grandodiorite along the coast range and longitudinal valley in Coquimbo and Atacama Provinces contains about 20 known deposits of apatite which are associated with local intrusives or dikes. The deposits are in the area bounded by lat $28^\circ 40'$ S. and lat $30^\circ 00'$ S.

Los Choros, on the railroad about 80 km north of La Serena, is the shipping center for the area. About 20 lens-shaped apatite deposits are associated with amphibole and magnetite. Composite samples assayed as follows: 26.3 percent P_2O_5 , 36.5 percent CaO, 31.1 percent Fe_2O_3 , 1.7 percent Al_2O_3 , and 4.8 percent Cl. Reserves are estimated to be 420,000 tons. Similar deposits are found to the north near Vallenar.

In Atacama Province, intrusives containing apatite have been worked at Los Barros and Domeyko. Reserves at Domeyko are estimated by the British Sulfur Corporation to be 540,000 tons of material. The ore contains from 22.5 to 32 percent P_2O_5 .

GUANO

Chilean guano can be classified into two types: white fresh bird droppings and red fossil guano. Red guano is formed by solution of the surface guano by percolating water, followed by redeposition in and partial replacement of the underlying bedrock. Sociedad Chilena de Fertilizantes give the 1964 production for both types as follows:

	Tons	Percent		
		P ₂ O ₅	K	N
Red.....	11,464	34.0	0.3	0.7
White.....	3,587	15.0	2.0	12.0

The local product is mixed with imported guano from Peru (2,024 tons, 1964), imported triple phosphate (17,348 metric tons, 1964), and some potash salts to make a combined product for the local market. There are no fertilizer exports.

The white guano is an annual crop dependent on sea-bird droppings on the islands off the coast of Antofagasta and Arica, between Mejillones and Arica, of Tarapaca Province.

MARINE PHOSPHATE ROCK

To date there is no production from marine rock deposits, but some geologically favorable environments are worthy of investigation. The Tertiary formations along the coast and the Jurassic and Cretaceous rocks near Copiapo and Concepción are possible favorable areas.

Near Tongoy in Coquimbo Province, 40 miles south of La Serena on the Coastal Highway (lat 30°21' S., long 71°35' W.), the U.N. Special Fund has been conducting geochemical and radioactivity surveys on a marine phosphorite deposit. Inferred reserves are 5-6 million tons of material assaying 5-18 percent tricalcium phosphate.

The phosphorite occurs in a marine basin 10 km long and 3 km wide. Pleistocene fluviomarine sedimentary rocks fill the trough to a depth of 700 m. The principal phosphate bed is about 60 cm thick and lies above a shell formation. A 10-cm bed occurs at a shallower depth than the main bed, which is covered by 85 m of overburden.

There may be other places along the coast of Chile where marine sedimentary rocks occupy troughs or depressions. In particular, such rocks of the La Negra Formation may be worth prospecting.

Phosphate is also known to occur on the sea bottom off the coast of northern Chile, but its potential has not been explored.

SULFUR

Chile produced 59,552 metric tons of refined sulfur in 1964 and imported 5,887 tons. Of the 59,552 tons, 41,146 tons were produced from volcanic-type deposits, and most of the remainder came from smelter gases. Braden Copper accounted for 9,241 tons, and Chile Exploration, 6,432 tons. The remainder, about 2,700 tons, was mined from volcanic sulfur deposits or pyrite.

SMELTER GASES AND SULFIDE

The potential is large for side-product sulfuric acid from copper smelters. Much of it is now wasted in the air, but additional sulfuric

acid plant capacity is planned where a market can be developed. Much of the anticipated demand for sulfuric acid is for the manufacture of fertilizers such as superphosphate.

Corporacion de Fomento de la Produccion (CORFO) estimates there are about 90,000 tons of sulfur in the various smelter flue gases each year. The breakdown is as follows:

	<i>Annual capacity of sulfur (short tons)</i>
Chuquicamata.....	27, 000
Potrerrillos.....	24, 000
Paipote.....	5, 600
Chagrez.....	3, 600
Ventanas.....	6, 700
Calcetons.....	23, 000
Total.....	89, 900

Because these are side-product gases the cost of recovery would mostly be the capital costs for sulfuric acid plant equipment at the smelters. Braden (Kennecott Copper) can easily double capacity when a market for the acid is developed.

Pyrite (FeS_2) is another large source of sulfur for acid. It is now separated in the flotation machines and then thrown away with the waste tailings. Pyrite and smelter gases offer the most rapid and economical material to satisfy any immediate large demands for sulfuric acid.

VOLCANIC-TYPE SULFUR DEPOSITS

Sulfur deposits occur in the volcanic rocks along the border of Argentina and Bolivia in a sulfur-bearing zone which extends about 600 miles from Ollague, north to the Peruvian border. Some are found at altitudes of 18,000 feet or more and most lie above 10,000 feet. The richest areas are at Tacora and Ollague.

The sulfur occurs in Recent volcanic rocks, mainly impregnating beds of ash or tuff. Many of these are on the slopes of volcanoes where the layers containing 50 percent S or more may be 1 to several feet thick. Material containing less than 50 percent S is not considered ore.

Of the 104 known sulfur deposits of volcanic type, 41 are said to contain reserves of 41 million tons of ore that is 51 percent S. However, all these are at very high altitudes—therefore difficult of access—so the cost of mining, refining, and transportation make many of them of questionable value.

The largest producer is Sociedad Azufrera Aucanquilcha, which had an output of 33,354 metric tons of sulfur in 1964 from ore assaying 58 percent S. Mining is by open pit. The ore (sulfur caliche) is

heated in nine stationary autoclaves at a rate of 2,000–2,500 kilos a batch. The company hopes to increase production to 45,000 tons in 1965. Most of the product is sold for manufacture of acid.

The second largest sulfur producer is Sociedad Azufrera Borlondo y Cia. In 1964 it treated 19,978 metric tons of ore by autoclaves to produce 5,760 tons of refined sulfur. Some high-grade ore (3,600 tons) was sold directly for fertilizer.

Other smaller mines are operated, but only three approached an output of 1,000 tons per year. The Government attempts to assist sulfur miners by protected high prices and grants.

POTASH

Potash salts are produced in northern Chile from the Salar de Pintados and the Taltal region. G. E. Ericksen (written commun., 1963) reported that these deposits of caliche were worked for potassium-bearing salt during 1962. The salt crust is processed by Shanks and Guggenheim plants to make potassic salitre. Salar de Bellavista has been worked for potassium salts, and a number of other solar evaporation processes at Maria Elena allow recovery of potassium. Output of potassium nitrate salts in Chile in 1963 was 1,135,881 tons, of which 143,973 tons was potassium nitrate. About 75 percent was in granular form obtained by the Guggenheim method. Production continued at the same rate during the first half of 1964.

Exploration for additional potash reserves could include drilling for brines such as those found in the Sechura Desert in Peru. The salar areas in Tarapaca and Antofagasta Provinces and the closed basins of the Andean region are possibilities for the occurrence of potash brines.

Another potassium-bearing material mined in Chile is fresh white guano. Sociedad Chilena de Fertilizantes, Ltd., reports that their mined product contains 2.29 percent K_2O . There is little opportunity for finding increased reserves of this material.

COLOMBIA

Colombia's production of fertilizer minerals is very small when measured against imports and needs. Imports in 1963 were 54,000 tons of phosphate and 35,284 tons of potash. Phosphate slag containing 18 percent P_2O_5 is produced at the rate of about 28,000 tons a year. Annual production of 40,000 tons of nitrogen compounds, in the form of acid, ammonium nitrate, and urea, comes from the Paz del Rio Steel Plant at Belencito, Department of Boyaca. Nitrogenous compounds are also obtained as side products of petroleum and gas. Industria Colombiana de Fertilizantes at Barrancabermeja,

Department of Santander, produces 15,000 tons of nitrogenous and mixed fertilizers annually. Abonos Colombianos, near Cartagena, has a capacity of 650 tons of nitrogenous fertilizers per day from the nearby Intercol Petroleum Co. works. A large potential source of nitrogenous material exists in a newly discovered oil field at Putumayo in southwest Colombia.

Transportation in Colombia is difficult and costly owing to the three high north-south ranges that traverse the length of the country. Low-cost bulk material, such as fertilizer, that originates on the coast, becomes very costly in the interior.

SULFUR

In 1964, sulfur production was 12,124 tons, all from Compañía Industrias Purace, operating on the slope of the Purace volcano. This is an active volcanic cone in southwest Colombia, not far from the city of Popayan, Department of Cauca. Access is by steep mountain road from Popayan.

The ore consists of impregnated andesite tuff beds and fracture fillings in Recent porous volcanic rocks. The average grade is 30 percent S; reserves, estimated in 1963 after diamond drilling in four mineralized zones, are said to be 6 million tons.

Ten autoclaves had been installed by 1963, and an increase in production to 18,000 tons annually is planned.

Sulfur is protected by a very high import duty, and only a small amount is imported.

PHOSPHATES

HIGH-PHOSPHORUS SLAG

At present (1965) the most important phosphatic material produced in Colombia is the high-phosphate slag at the Paz del Rio steel plant. Its favorable location at Belencito, north of Bogota and near the altiplano farming district, makes it a very economical source of phosphate for this area.

SEDIMENTARY PHOSPHORITES

Phosphate deposits or prospects are mentioned in the literature, but none have been worked. Enrique R. Hubach (1958) mentioned a few showings in Boyaca Department. Two deposits are on the Pisba Plateau between the Chicamocha and Pauto Rivers in Municipio of Socota. One is at Motuba, 1 km southeast of El Cardon on the Socha-San Salvador highway. The other is at El Tablon, 1½ km south of kilometer 23 on the same highway.

At Motuba the upper parts of beds of dark-gray limestone 2-3 m thick contain phosphatic material. A sample from the upper part

of a bed analyzed 9.0 percent P_2O_5 , and the underlying limestone was 0.40 percent.

At El Tablon four phosphate layers are as follows:

	Thickness (meters)	P_2O_5 (percent)
Shell bed.....	0. 8	1. 08
Sand and phosphatic nodules.....	0. 8	11. 35
Fossiliferous limestone (contains wavellite).....	0. 5	12. 69
Fossiliferous limestone.....	1. 2	0. 78

Near Santa Elena, at the junction of the Chicamocha and Susacon Rivers, a phosphatic chalk 20 cm thick lies between layers of shales and limestones. Analysis of the chalk shows 16.25 percent P_2O_5 . The limestones and shales contain 0.28–2.39 percent P_2O_5 .

In the Barco concession at the junction of the Catatumbo and Oru Rivers, Santander Department, the Colombian Petroleum Co. explored Cretaceous shales that contain abundant fossil fish; the samples contain 0.55–1.35 percent P_2O_5 . This occurrence is a possible indication of more phosphatic facies elsewhere in rocks of the same age.

In the Guajira peninsula, in northeast Colombia, arenaceous shales near Puerto Lopez contain 0.11–0.55 percent P_2O_5 . Again, this occurrence is of interest only in drawing attention to rocks that might have more phosphatic counterparts elsewhere.

PHOSPHATIZED ROCK

On Malpelo Island, a small volcanic island 250 miles west of Buenaventura (lat $3^{\circ}59'$ N., long $81^{\circ}35'$ W.), vesicular basalts at the top of lava flows have been phosphatized by leaching of a guano cover. The phosphatic layer on the average is 0.90 m thick and in places is 1.48 m thick. Reserves of 452,000 tons are indicated. Composition is as follows: 30 percent P_2O_5 , 22.9 percent Fe_2O_3 , and 7.9 percent Al_2O_3 . This deposit has never been exploited, and steep cliffs, lack of water, and heavy ground swells would make mining difficult.

CURRENT PHOSPHATE RECONNAISSANCE

Earl M. Irving (written commun., Sept. 24, 1965) reports that reconnaissance underway by the Ministerio de Minas y Petr leos and the U.S. Geological Survey has shown the presence of phosphatic black shales underlying thin-bedded cherts, west of the small town of Villeta (80 km northwest of Bogota). The beds are of Cretaceous age. Some possibly minable layers contain 25–30 percent P_2O_5 .

Irving also notes that reconnaissance south of the Fusagasug -Melgar road revealed two beds 1–2 m thick containing 15 and 25 percent P_2O_5 ; west of Pache, Cundinamarca, are two beds 1–2 m thick containing 10 and 15 percent P_2O_5 . Cretaceous phosphatic sedimentary rocks also exist in the Barrancabermeja area 400 km to the north,

in the Sogamoso area 20 km farther to the northeast, and in the Luna formation near Cucuta along the Venezuela border.

POTASH

The Zipaquira-Nemocon-Sesquile salt deposits of the Bogotá region, also Cretaceous in age, might have potash associated with them and should be investigated for this possibility.

ECUADOR

Ecuador imports all fertilizer materials, including manufactured fertilizers and raw-material ingredients for a local mixing plant at Guayaquil. Officials of this plant say that the mixing-plant enterprise is not very profitable owing to costs of phosphate rock imported from Florida, potash from New Mexico, and sulfur from Mexico. Volcanic sulfur deposits in the high Andes have been worked during periods of world shortages when sulfur prices were very high, but no other fertilizer minerals have been produced in Ecuador.

The geology of Ecuador is poorly known, except in a very few local areas where mining and petroleum companies have had concessions, but its broad aspects are outlined here as a basis for indicating terrains that may be favorable for the occurrence of fertilizer minerals.

GEOLOGY AND FUTURE PROSPECTS

The coastal belt of Ecuador is somewhat similar to that of Peru and should be the first target in the search for possible phosphate and potash deposits. Much of the Andean Cordillera is covered with late Tertiary and Recent volcanics which are a possible source of sulfur. The Oriente is remote jungle-covered country and is practically unknown except for a small area where Shell Oil Co. did some exploration work.

The Coastal Province in Ecuador is bounded by two major faults: one is along the base of the Cordillera Occidental to the east, and the other is an offshore fault on the shelf which has been traced from Peru as far north as Cabo San Mateo. The age and thickness of the rocks in the province are summarized in table 2.

The oldest rocks, Paleozoic, crop out in only two places along the coast, one in Punta Piedra 25 km south of Guayaquil and the other at Cerros de Masvale just east of Punta Piedra.

A wide band of Jurassic and Lower Cretaceous rocks extends 80 km northwest from a position 15 km north of Guayaquil. They include igneous rocks such as pillow lavas, andesite, pyroclastics, and conglomerates and small amounts of shale and sandstone. Granodiorite near Pascuales is said to be intrusive.

The sequence of sedimentary rocks of Late Cretaceous to Quaternary age can be traced on a generalized geological map by reference to the work of J. G. Marks (in Lewis and others, 1956) and the work

of geologists for International Ecuadorean Petroleum Co. and Standard Oil Co. of New Jersey. Chert, limestone, and sandstone occur in complicated faulted relationship, but the paleogeography cannot be determined without more detailed studies on both surface and sub-surface geology.

TABLE 2.—*Stratigraphic column for the Coastal Province of Ecuador*

[From Lewis, Tschopp, and Marks (1956, p. 278)]

Age and stratigraphic position		Rock units	Thickness (meters)
Quaternary	Recent	Andean piedmont, fluvial, and mangrove deposits.....	?
	Pleistocene	Tablazos, alluvial fans.....	?
Tertiary	Pliocene	Pluná formation, Jama formation, Canoa formation.....	80
	Upper Miocene	Borbón formation (part), Punta Gorda formation, strata on Puná Island.....	?
	Middle Miocene	Borbón formation (part), Bahía formation, Daule formation, Progreso formation....	3,000
	Lower Miocene	Angostura formation (part), Onzole shale, Charapotó shale, Subibaja formation....	600
	Upper Oligocene	Angostura formation (part), San Agustín sandstone, Viche shale, Tosagua shale, Laceruz formation, Rodeo formation (part).....	650
	Middle Oligocene	Chumundé ash beds, Zapotal sandstone, Rodeo formation (part).....	?
	Lower Oligocene	Playa Rica formation, San Mateo formation (part), Ancon Point formation.....	170
	Upper Eocene	Zapallo Shale, San Mateo formation (part), Jusa shale, Salanguillo sandstone, Seca shale, "Zapotal" formation (sub-surface), red-beds of El Morro.....	275
	Middle Eocene	San Eduardo limestone, Middle grits, Clay Pebble bed, Javita limestone, Socorro formation.....	500
Upper Cretaceous and Lower Eocene	Paleocene	Estancia sandstone, San José sandstone, San José shale, Atlanta formation.....	1,300
	Upper Cretaceous	Callo formation, Guayaquil chert.....	3,000
Cretaceous igneous		Pascuales granodiorite.....	
Cretaceous or Jurassic?		Piñón Volcanics.....	1,000
Paleozoic		Punta Piedra rocks.....	

The Andean Cordillera, which forms the backbone of the country, is marked by two spectacular rows of volcanic peaks separated by a long trough or central valley 20–40 km in width. Mapping by G. E. Lewis (in Lewis and others, 1956) shows that the valley is a large graben, the volcanoes aligned along the two large fault zones indicating zones of compression and uplift. Gravity work indicates that the Cordillera is very active; this is confirmed by a history of many destructive earthquakes.

Some basins of the trough area are filled with volcanic rocks, but other basins contain sedimentary material contributed from the highlands. The Cuenca and Loja Basins contain sedimentary rocks believed to be Miocene in age and some beds of lignite. This belt is not considered to be of interest for phosphate or potash. Sulfur deposits of volcanic origin have been known and worked for many years by hand-mining methods. In Chimborazo Province near Tixan there was an attempt by an American company to work ore of this type, using flotation to recover the sulfur. Dr. Putzer, geologist (written commun., 1958), reported the ore, which contains 25 percent S, is workable by open-pit methods of mining, but by that time the mines had been abandoned owing to the low cost of imported sulfur. Reserves are unknown.

Other sulfur deposits were reported at Cerra Chiles, El Angel, Virginia, and Rosario by W. C. Stoll (written commun., 1960).

High-sulfur coals at Biblian are found in the Azoques-Biblian basin in Canar Province. The sulfur is not recoverable by ore-dressing methods because it is in a fine-grained amorphous form.

PERU

Peru is perhaps the most favorably situated country in South America in its known and potential resources of fertilizer minerals. A substantial tonnage of guano is harvested annually from islands along the coast, and within the last decade large phosphate deposits and potash brines have been discovered in the Sechura Desert, and phosphate has also been found in the Andes. Sulfur from smelter gas, volcanic-type deposits, and perhaps salt domes east of the Andes also has a high potential.

PHOSPHATES

SECHURA DESERT PHOSPHORITE

The Sechura Desert phosphate deposits are the largest known in South America. They are about 800 km (496 miles) north of Lima (lat 5°50'15" S., long 81°02'15" W.) and are favorably situated for ocean transportation near the port of Paita. Air service is available

at Piura, a city of 80,000 people, on the Pan American Highway. Unimproved roads in the Sechura Desert can be traversed by 4-wheel-drive vehicles. The Minerales Industriales del Peru has concessions which cover 1,850,000 acres in the western part of the desert and has a base camp at Bayovar 90 miles from Piura.

The Sechura Desert is a large coastal basin, 160 miles long and about 50 miles wide, filled with unconsolidated marine sediments. The Tertiary sedimentary rocks filling the basin range in age from Eocene through Pliocene and are covered with Recent alluvium. The phosphorites are in the upper 600–700 feet of Miocene sedimentary rocks which are covered in some places by 120 feet of Pliocene deposits. Most of the beds are laterally continuous, and unconformities or faults are few. Oil exploration indicated that the maximum sedimentary section was 8,000 feet thick. This whole section is younger than the western shelf basin of northwestern Peru. The Sechura basin is bounded on the east by the main Andean uplift and on the west by the Paita, Illescas, and Lobo Island uplifts which are made up of complex Paleozoic formations.

The phosphate occurs as pellets, interbedded and intermixed with diatomite. The phosphorite beds are 3–5 feet thick and contain about 20 percent P_2O_5 . Diatomite beds are 10–20 feet thick and contain 3.5–7.0 percent P_2O_5 . Three ore zones in ascending order are as follows: Zone 1 is 126 feet thick and 7.6 percent P_2O_5 , zone 2 is 21 feet thick and 7.6 percent P_2O_5 , and zone 3 is 86 feet thick and 5.2 percent P_2O_5 . These formations are uniform over large areas, there being only minor folding and faulting.

The phosphates are marine-deposited pellets of carbonate-fluorapatite with impurities of diatoms, volcanic glass, soluble sodium and potassium salts, quartz, feldspar, gypsum, and mica. (See tables 3, 4.) The pellets are mostly subelliptical, but some are rod shaped; they have a hard smooth shiny surface, have an average specific gravity of 2.9, and average less than 1 millimeter in diameter.

The Sechura phosphate deposits are now (1965) being developed by Minera Bayovar S. A. through an operating contract with Midespa Industries, Ltd., of Montreal, Canada. Under the terms of a recent contract with the Peruvian Government, an annual production of 1 million tons of phosphate concentrate (31 percent P_2O_5) is to be developed within 5 years. This concentrate will be obtained from 6–7 million tons of mined ore.

A wheel excavator is being assembled and will have a capacity of 1,000 cubic yards per hour where layers of hard rock are not too numerous. Initial mining will be in the western part of the Sechura depression where overburden does not exceed 20 m. Three of the

richest beds and an interlayered phosphorite and diatomite will be mined to produce an average ore head of 10 percent P_2O_5 . Moving sand dunes, high overburden in some places, and shortage of fresh water present problems to be overcome. A bulk direct-loading unit is planned for construction at Bayovar near the deposits.

TABLE 3.—*Comparison of analyses (in percent) of typical washed pellets from Sechura, Peru*

[From Midespa Industries Ltd.]

	Bed 1	Minerva ore zone	Diana ore zone (area 1)	Diana ore zone (area 2)	Lower part of Diana ore zone
P_2O_5	31.82	27.07	26.47	28.30	25.50
K_2O.....	.10				
CaO	47.80	41.64	41.57	43.51	40.53
SiO_2	2.55	14.00	14.20	8.88	16.80
SO_2	4.02	2.78	3.06	3.20	2.36
Al_2O_3.....	.85	1.10	.93	.93	1.01
Fe_2O_3.....	.63	.51	.51	.77	.61
F.....	2.11	1.87	1.78	1.78	1.78
CO_2	3.25	3.38	4.39	4.48	4.39
Na_2O	1.74	1.00	1.17	1.39	1.09
MgO.....	.76	.96	1.06	1.21	1.06
Cl.....	.02	.02	.02	.02	.02
Insoluble siliceous matter.....	1.83			8.72	
Loss on ignition.....	4.15			3.04	
CaO/P_2O_5	1.50	1.538	1.570	1.537	1.59
SO_3/P_2O_5.....	.126	.103	.0839	.1131	.0925
CO_2/P_2O_5.....	.102	.125	.166	.158	.172
F/P_2O_5.....	.0663	.0691	.0672	.0628	.0698
Na_2O/P_2O_5.....	.0547	.0369	.0442	.0491	.0427
CO_2/F	1.54	1.81	2.47	2.52	2.47

Core drilling started in 1959 on a 1,000-m grid in the Sechura depression, and by late 1961 about 15,000 feet of core and surface trenching had developed a large reserve in five areas (table 5).

The drill cores contain from 1.5 to 23 percent P_2O_5 . The lower ore zone, partly penetrated in Bayovar and in the depression, lies at a depth of 124 feet and is reported to average 7.6 percent P_2O_5 . A generalized section of a drill hole (the highest grade section drilled as of May 1961) is given in table 6.

LA OROYA PHOSPHORITE

Reconnaissance work along a belt of Lower Cretaceous and Jurassic marine sedimentary rocks suggests that they extend for about 150 km from Huancayo to La Oroya. La Oroya is about 130 km east of Lima. Only 45 km of this belt has been mapped.

Phosphorites are found in beds several feet thick and assaying about 10 percent P_2O_5 , associated with black shale, cherty limestone, and chert. Formations of these ages flank the Andes on both the west and east sides.

SUBMARINE PHOSPHATES

Phosphate nodules have been dredged from the sea bottom at many places off the coast of Peru, but as with most other submarine deposits, their extent and potential value have not been explored.

TABLE 4.—Comparison of the composition (percent) of Sechura phosphate with that of north Africa and the United States

[From Midespa Industries Ltd.]

	Sechura Bed 1	Southwest Tunisia	Metleoui Gafsa	Rebiba	Morocco	Algeria	Kourigha Boujmibe	Phosphoria (Western United States)	Florida
P ₂ O ₅	31.82	29.81	30.20	30.57	34.26	30.90	35.11	29.5	33.39
K ₂ O.....	.10		.08	.13	.09	.37	.16	.6	.09
CaO.....	47.80	49.40	49.52	50.80	52.60	48.00	53.00	43.9	48.79
SiO ₂	2.55	1.70	3.06	.20	2.47	4.50	.86	10.0	5.83
SO ₃	4.02	2.91	2.70		1.67	1.49	1.40	2.9	.93
Al ₂ O ₃.....	.85	.32	.97	.40	.40	.70	.45	1.5	1.04
Fe ₂ O ₃.....	.63	1.28	.35	.80	.37	1.24	.12	1.0	1.27
F.....	2.11	2.96	2.73	3.42	3.70	2.56	4.24	3.1	3.50
CO ₂	3.25	5.40	5.72	7.92	3.15	4.02	4.12	3.0	2.78
Na ₂ O.....	1.74		1.35	1.48	.70	1.00	1.19	1.0	.30
MgO.....	.76	.50	.53	.72	.28	1.44	.16	.5	.40
Cl.....	.02		.03		.02				.05
Loss on ignition.....	4.15	5.70		3.40		3.50		8.3	
Carbonaceous material.....			3.71		2.79			4.4	3.02
CaO/P ₂ O ₅	1.50	1.66	1.64	1.66	1.54	1.55	1.51	1.49	1.46
SO ₃ /P ₂ O ₅.....	.126	.098	.089		.049	.036	.0399	.098	.0278
CO ₂ /P ₂ O ₅.....	.102	.181	.189	.259	.0919	.130	.117	.102	.0832
F/P ₂ O ₅.....	.0663	.0993	.0904	.112	.108	.063	.121	.105	.105
Na ₂ O/P ₂ O ₅.....	.0547		.0447	.0484	.0204	.0324	.0339	.0339	.0339
CO ₂ /F.....	1.54	1.82	2.10	2.32	.851	1.57	.972	.968	.794
Citrate solubility (Technique, Wagner).....	14.06		10.5		6.6			3.0	7.3

TABLE 5.—*Summary of reserve estimates of phosphate rock, Sechura deposit, Peru (31 percent P₂O₅)*

[From U.S. Bureau of Mines Mineral Trade Notes for 1962]

Area	Drilled ore (million metric tons)
Bayovar:	
Area 1.....	56. 83
Depression:	
Area 2.....	269. 22
Area 3.....	108. 25
Total.....	377. 47
Tablazo:	
Area 4.....	63. 30
Estuary:	
Area 5.....	63. 32
Grand total.....	590. 92

TABLE 6.—*Generalized section of the middle Miocene Zapayal Formation (marine) in depression area 2, Sechura deposit, Peru*

Composition	Thickness		P ₂ O ₅ (percent)	Bed
	Feet	Inches		
Diatomite with phosphorite.....	6		8. 0	
Phosphorite strata.....	4	8	17. 8	0
Sandstone.....	2			Clambore 65
Diatomite with phosphorite.....	15		6. 1	
Phosphorite strata.....	4	1	23. 4	1
Diatomite with phosphorite.....	11	2	6. 3	
Phosphorite strata.....	3	4	14. 8	2
Diatomite with phosphorite.....	10	3	5. 7	
Phosphorite strata.....	3	2	22. 4	3
Diatomite, small amount of phosphorite.....	10	3	3. 8	
Phosphorite strata.....	2	11	18. 1	4
Diatomite.....	15	6	3. 5	
Phosphorite strata.....	2	7	17. 9	
Diatomite.....	15	9	4. 1	
Phosphorite strata.....	14	4	11. 9	

GUANO

W. C. Stoll (written commun., 1960) stated that guano is an important renewable source of fertilizer from 20 groups of islands and peninsulas, most being harvested from the Chincha group, La Vieja, Santa Rosa in the south near Pisco, and Guanape and Macabi in the north. The Peruvian Government now operates the guano deposits to protect the bird life and the anchovies on which they feed; the islands were almost depopulated of bird life during the latter part of the 19th century. Fishermen are now not allowed to operate in the vicinity of the islands.

The bird population is currently estimated at 12 million, and each bird eats 2½ times its own weight in fish each day. It is said to require 12 tons of fish to produce 1 ton of guano. In 1963 the harvest of guano was estimated to be 191,700 tons, valued at \$5,727,000. It is

an excellent fertilizer because the contained nitrogen, potassium, and phosphorus are in a form readily available to plant life. Production is consumed in Peru and is not sufficient to meet the demand.

POTASH

SECHURA DESERT POTASH BRINES

In the Sechura Desert, just northeast of the Sechura Desert phosphate deposit, is an extensive flat shallow basin that has a maximum relief of 5 m above sea level. This so-called brine reservoir is filled with permeable and porous Quaternary sediments saturated with brines.

Underlying the porous sediments are impermeable Miocene sediments of diatomite, clays, silts, and some sand. These Miocene sediments form the impervious container for the porous younger fill material and underlie the entire reservoir at shallow depths to form a leak-proof bottom with a maximum depth of 100 feet below the surface.

The brines are very close to the surface in the topographic lows where they are indicated by evaporite-crusts, pressure ridges, and hummocks caused by crystal growth. Crusts and layers near the surface are composed of gypsum and halite. The net thickness of the brine-saturated porous sedimentary layer that underlies the crust is said to average 7 m, measured from the surface of the brine to the impervious floor. The deep parts of the reservoir show 25 m of brines and contain the bulk of the brine reserves.

In some places the Government is mining salt from thick layers of halite. South of Lago Ramon a large massive salt bed is being worked. Salt minerals are halite, gypsum, and polyhalite (potassium sulfate and some calcium and magnesium sulfates).

The source of the brines is considered to be lateral seepage and flood waters from the Piura and Cascajal Rivers into the reservoir area where capillary action and solar evaporation enrich the brines as they percolate through the porous medium toward the estuary. Tests along the estuary show that brines are continuously discharged into the upper end of the estuary from the reservoir. In 1962 the estuary was dammed by a causeway which will enable 400 square kilometers of flood waters to be retained and reduced by solar evaporation in the estuary. The brines in the lower part of the reservoir basin will be pumped from wells to a recovery area where 20 km of evaporation basins are under construction.

Within the brine reservoir basin there are three areas under consideration for brine production. These are given by the Midespa Co. as:

<i>Area</i>	<i>Sq km</i>	<i>Depth (feet)</i>
I—Zapayal	306	22
II—Ramon	128	27. 2
III—Namuc	176	17. 1

Potassium chloride, magnesium chloride, and the sulfate radical are reported as percentages in the brines as follows:

<i>Area</i>	<i>Specific gravity</i>	<i>Percent</i>		
		KCl	MgCl ₂	SO ₄
I.....	1. 1480	0. 41	3. 36	0. 62
II.....	1. 2047	1. 00	8. 62	1. 46
III.....	1. 1438	. 42	3. 76	. 79

Brine reserves are calculated in million short tons as :

<i>Area</i>	<i>Brine</i>	<i>Potassium chloride</i>	<i>Magnesium chloride</i>
I.....	1, 700	6. 96	57
II.....	898	8. 98	77
III.....	754	3. 16	28
Total.....	3, 352	19. 1	162

Experimental work is in progress on recovery of the salts by solar evaporation. As evaporation progresses, sodium chloride and calcium sulfate are first precipitated. Potassium, magnesium, and some sodium chloride and bromine are retained in the enriched liquor until a gravity of 1.242 is reached. At this point the sodium and potassium contents are equal. The high ratio of magnesium chloride to potassium chloride then causes carnallite (a double salt of potassium and magnesium chloride) to precipitate. The balance of the magnesium chloride with some sodium chloride and most of the sulfates remains in the liquor with the bromine.

The carnallite, which has a 1:1 ratio of potassium chloride to magnesium chloride, can be redissolved, and the sodium chloride and potassium chloride will precipitate as the mineral sylvite; the sylvite can then be purified by flotation or can be vacuum cooled and precipitated for a high-grade potassium chloride.

Analysis of brines from many drill holes shows 8.47 parts of magnesium chloride to 1 part of potassium chloride. If potassium chloride were produced, there would be a substantial side product of magnesium salts. Bromine may also be a profitable side product because each ton of liquid contains 4 pounds of bromine.

A refinery could be built near the estuary where there is a nearby bay said to be adequate for building dock facilities for ocean-going vessels.

OTHER SALT DEPOSITS

According to Dr. Victor Benevides, chief geologist of International Petroleum Co., salt deposits occur in several areas of Peru that have not been tested for their possible potash salt contents. Approximate locations are:

<i>Latitude (S.)</i>	<i>Longitude (W.)</i>
12°30' -----	74°0'
13°30' -----	75°0'
10°30' -----	74°0'
11°30' -----	74°30'
6°0' -----	75°0'
7°0' -----	76°0'

There are also extensive caliche deposits on the coast of southern Peru which have not been adequately tested for potash.

SULFUR

Smelter gas currently is vented off and lost from the two principal base-metal smelters in Peru. It is estimated that 150 tons of sulfur per day is lost in stack gas at Cerro de Pasco's refinery at La Oroya and 300 tons per day at Ilo refinery at Tutupaco. Banco Minero, a Government corporation, plans to build a new zinc smelter at Lima to refine concentrates that are now exported. Byproduct sulfur gas from this operation will be used to produce 55,000–70,000 tons of sulfuric acid per year at an estimated cost of \$4.50 per ton. There are plans to use smelter-gas sulfuric acid for manufacturing superphosphate when Sechura phosphate rock becomes available.

Sulfur in volcanic rocks has been reported, but not developed, in several places in southern Peru, as follows:

	<i>Latitude (S.)</i>	<i>Longitude (W.)</i>
Paucarani-----	17°30'	69°45'
Cano-----	17°15'	70°05'
Yacamane-----	17°10'	70°10'
Tutupaca-----	17°05'	70°20'

According to the director of the Instituto Nacional de Investigaciones Fomento y Mineros, concentrations of sulfur have been found near porphyry copper deposits at Topuepala (lat 17°15' S., long 70°37' W.), and others have been found near Cajamarca (lat 7°0' S., long 78°25' W., and lat 6°40' S., long 78°45' W.).

About 60 years ago a French mining company made an unsuccessful attempt to produce sulfur from sulfur-impregnated sandstones in northern Peru; these are on the coast near the Sechura Desert phosphate. Estimated reserves are 650,000 tons of sulfur.

In the jungle lowlands along the east side of the Andes are several salt domes (G. E. Ericksen, U.S. Geological Survey, oral commun. 1965) which may have associated deposits of sulfur or potash salts.

VENEZUELA

Dr. Louis J. Medina, executive secretary of the Direccion de Investigaciones, Ministerio de Agricultura y Cria, stated (written commun., October 1965) that fertilizer use in Venezuela has increased from about 18,000 tons in 1958 to about 45,000 tons estimated for 1965. Demand for fertilizers has increased steadily and will doubtless accelerate in the future as the Government has announced a plan to distribute 1.6 million hectares (3.952 million acres) to 60,000 families. The Government through its agricultural extension agencies, the Shell Foundation, and private agencies have all devoted much effort to demonstrate to the farmers the value of chemical fertilizers. Shell Formation spent more than \$900,000 (U.S.) on farm assistance during the 1963-64 fiscal year. Chemical-fertilizer use is still far below that in countries using modern farming methods. However, Venezuela does have fairly large phosphate resources, and some sulfur is obtainable from petroleum. Workable potash deposits are as yet unknown.

The Government-owned Venezuela Petrochemical Institute (IVP) has a large petrochemical complex at Moron and plans to fill domestic needs by 1966. To date there have been no restrictions on imports of fertilizers, but there will be no more import licenses issued after this year (1965). IVP officials say that estimated 1965 production will be as follows:

<i>Fertilizer</i>	<i>Metric tons</i>
Superphosphate -----	4, 800
Triple superphosphate-----	19, 200
Urea -----	12, 000
Ammonium sulfate-----	50, 000
Ammonium Nitrate-----	21, 000
	<hr/> 107, 000

The total for 1964 was 96,350 metric tons. Nitric acid, sulfuric acid, phosphoric acid, and ammonia are the basic chemicals produced. In 1964 during the first four months 13,199 metric tons of ordinary superphosphate were exported compared with a total of 23,878 tons for the year 1963. No mixed fertilizers are exported.

Other fertilizer mixing plants produced at a combined rate of 375 metric tons a year for a small specialty market.

PHOSPHATES

Several phosphate deposits in Venezuela are mined for both the manufacture of superphosphates and direct application to the soil. Guano deposits on the islands near the coast have been worked for

many years; some of these are depleted. Most production comes from bedded phosphate-rock deposits.

RIECITO PHOSPHORITE

Phosphate rock is mined from Miocene beds southwest of Riecito in Estado Falcon (lat. $10^{\circ}53'$ N., long. $68^{\circ}45'$ W.). This material is used by IVP in the plant at Moron to produce phosphate fertilizers. The deposit is only 4 km from the Tocuyo River, which is navigable. A road paved most of the way to Moron connects the mine and the fertilizer plant.

The phosphorite occurs in the middle Miocene beds of the Riecito Formation which dip gently to the southeast. The phosphorite is yellow red to gray; it contains angular quartz fragments, composing 15–25 percent of the whole rock, cemented by a collophane matrix. The whole rock is hard and compact.

In 1962, reserves were given as follows: Proved, 11,711,752 tons; probable, 2,658,480 tons.

Analysis of the rock given by the company is 29.98 percent P_2O_5 , 15 percent SiO_2 , 2.59 percent Al_2O_3 and Fe_2O_3 , 1.13 percent $CaCO_3$, and 1.57 percent CaF_2 .

Mining is by open-pit methods at a rate governed by the demand at the acid plant at Moron, which will require increased mine output above the past production level of about 30,000 tons per year. Screening gives a 32.8 percent P_2O_5 product which is suitable for making superphosphates.

LOBATERA PHOSPHORITE, TACHIRA STATE

The Venezuelan Ministry of Mines discovered phosphates in 1960 in the La Luna Formation of Cretaceous age near Lobatera (lat. $79^{\circ}55'$ N., long $72^{\circ}15'$ W.), near the Pan American Highway at La Molina. Experimental grinding in a cement mill has been undertaken to produce sufficient ground phosphate to determine its value for direct soil application. Production is now 20 tons a day, and a plant with a capacity of 100 tons a day is under construction. Total tonnage produced to date is 2,800 tons.

Nine beds of phosphatic breccia occur in the black Tachira Chert Member of the La Luna Formation. The chert member is about 60 m thick and contains interbedded siliceous limestone in addition to the phosphate beds. The phosphate beds range from 5 cm to 1.8 m in thickness; most are 5–25 cm thick. The beds are part of an overturned anticline and dip at very steep angles or are vertical. The Tachira Chert Member is found in fairly restricted areas in the central and southern parts of Estado Tachira.

The principal bed, where mined, averages 1.8 m in thickness over an area of 3.5 hectares. Proved reserves are 264,000 tons, and probable reserves are 500,000–1 million tons. The grade of the rock is reported as 21.85 percent P_2O_5 obtained from 23 samples taken along a tunnel. Other components are 1.96 percent F, 47.55 percent CaO, 9.10 percent CO_2 , 0.86 percent Al_2O_3 , 1.23 percent Fe_2O_3 , and 10 percent SiO_2 . By hand sorting the grade of the concentrate is raised to 29 percent P_2O_5 . The concentrate is then ground to 200 mesh.

Mining is by shrinkage stopes from a 374-m drift driven along the strike in the lower part of the thickest phosphate bed.

OTHER CRETACEOUS PHOSPHORITES

In Quebrado Orevado and about 3 km northwest of the village of Santa Barbara in Estado Barinas (lat. $7^{\circ}54'$ N., long. $71^{\circ}03'$ W.), layers in the Quevedo Formation contain phosphorite pellets and fragments of fish bones.

In Quebrada Agua Fria, 36 km northeast of La Morita, Estado Tachira (lat. $7^{\circ}40'$ N., long. $71^{\circ}40'$ W.), thin calcareous layers with phosphorite pellets and fish bones are intercalated in the La Morita Shale.

Phosphorite is also reported in some places in a glauconitic sandstone, the Tres Esquinas Member at the base of the Colon Formation that overlies the La Luna Formation in Maracaibo and Barinas Basins and the southeastern flank of the Andes. This member becomes more sandy and more phosphoritic toward the southeast, whereas the glauconite gradually decreases. In the Chajende area of Estado Trujillo (lat $9^{\circ}35'$ N., long $70^{\circ}20'$ W.), there is abundant phosphorite and little glauconite. The member is several meters thick, and its thickness is variable. It has no phosphorite in the section between La Grita and Pregonero in Estado Tachira (approx lat $8^{\circ}05'$ N., long $71^{\circ}50'$ W.). In Estado Merida (lat $8^{\circ}37'$ N., long $71^{\circ}20'$ W.), on the road from Ejido to La Azulita, a few kilometers north of the intersection with the road to Jaji, the glauconitic member is black, strongly phosphatic, and several meters thick. A section 50–80 cm thick contains 16–18 percent P_2O_5 .

SULFUR

At present, Venezuela is not producing sulfur from any source. Some has been obtained in the past from copper sulfide ores mined at Aroa (lat $10^{\circ}25'$ N., long $68^{\circ}55'$ W.) in Estado Yaracuy by Instituto Venezolano de Petroquímica. Deposits of pyrite and chalcopyrite occur south of La Victoria in Estado Aragua (approx lat $10^{\circ}05'$ N., long $67^{\circ}15'$ W.), but are not now being mined.

At El Pilar (lat $10^{\circ}35'$ N., long $63^{\circ}10'$ W.) in Estado Sucre, sulfur is precipitated from thermal springs in an area of strong Tertiary

faulting. During 1966 the Direccion de Geologia will attempt to determine if sulfur deposits of any value are present in the area.

A sulfur deposit at El Azufre in Departamento Ayacucho of Estado Tachira is reported to be of small potential and without economic importance.

In eastern Venezuela, high-sulfur crude oils occur in the Quiriquire (lat 10°00' N., long 63°10' W.) and Pedernales (lat 10°00' N., long 62°15' W.) oil fields at Estado Monagas and Territorio Delta Amacuro respectively. Oil produced from these fields is shipped to Trinidad where refineries are equipped to process the high-sulfur-content oils of that island. Elsewhere in Venezuela, oil and natural gas have low sulfur contents, and sulfur is not removed.

POTASH

No deposits of potash have been reported in Venezuela, and no deposits of bedded evaporites have been reported from petroleum exploration. Common salt is obtained from evaporation of sea water in various places along the coast.

SUMMARY AND OUTLOOK

In spite of the present limited production of fertilizer minerals in South America, the continent as a whole has potential resources adequate not only to meet most of its current consumption—which is far below its need—but to support a much expanded use of mineral fertilizers.

PRESENT CONSUMPTION

Something of the need for fertilizers in South America may be seen from data on the current consumption. The data are probably incomplete, but from 1963 statistics compiled by the United Nations, it appears that the total annual consumption is about 180,000 metric tons of P_2O_5 , 155,000 tons of N, and 88,000 tons of K_2O . Much of South America has a tropical and subtropical climate, in which nutrient salts are naturally leached from the soil, and some of its soils have been further mined of their nutrients through centuries of agriculture; therefore the present use of fertilizers represents only a fraction of the need. For example, on a per capita basis, the South American annual consumption is 1.2 kg P_2O_5 , 1.0 kg N, and 0.58 kg K_2O compared to 14.3 kg P_2O_5 , 18.1 kg N, and 11.4 kg K_2O for the United States—a younger country, from the standpoint of soil use, with a far less corrosive climate.

PHOSPHATE RESOURCES

The prospects are bright for discovery and increased production of phosphate in South America. The newly discovered Sechura phosphate deposit in Peru may come to rank among the great deposits of the world; recently discovered deposits in the Andes are not as promising for export but could be important local sources in Peru. Deposits on the present sea bottom off the coast of Peru, although little explored, probably are extensive and might be dredged economically by techniques presently being developed if there were a need. Guano deposits, the only present source of production, do not have much potential for increased yield. Venezuela and Brazil are mining sedimentary phosphate deposits that could yield increased production, and both have prospects for further discoveries, including sea-bottom deposits. Brazil also has numerous igneous apatite deposits, some of which may have a good potential. Colombia presently produces a small amount of high-phosphate slag as a byproduct of the Paz del Rio steel plant and has good prospects for discovery of workable sedimentary phosphates. Chile has small production of guano and also of apatite from deposits associated with iron-ore deposits. There are good chances for discovery of additional apatite deposits and some chance for sedimentary phosphorites; sea-bottom phosphate deposits, although unexplored, are extensive and may be one of the most promising sources of low-cost production for the future. Argentina has some production now of basic slags that can be expanded, and a sedimentary phosphate deposit has been discovered recently by geologists of Yacimientos Petroliferos Fiscales, in the Comodoro Rivadavia region of the southern part of the country. Argentina also has prospects for igneous apatite, and Bolivia has ground favorable for both sedimentary and igneous types. Although there are no known occurrences of phosphate in Ecuador, its geologic character permits, if not favors, the occurrence of phosphates of sedimentary origin.

Because phosphate is a comparatively low-value commodity that is used in substantial bulk, transportation costs may quickly increase the price to the consumer. There are both favorable and unfavorable implications in this for South American countries. It is certain that exploration in most South American countries would lead to the discovery of phosphate deposits which—even though some might not be competitive for export to the world market—could make phosphate available within the country at a lower cost than it could be obtained elsewhere and at a considerable saving in foreign exchange. On the other hand, the inadequate or high-cost transportation systems within some countries could deny to some of their agricultural regions the

benefit of cheap fertilizer—even where the cost of production at the mine is low by world standards.

One locally satisfactory solution to this problem may come from the use of moderately phosphatic materials, too low grade to process, directly applied to the soil. In temperate climates rock phosphate needs to be put into soluble form to yield beneficial results, and this requires a high-grade source or a beneficiated product. On acid soils, however, direct application of raw rock may be worthwhile, and its relative insolubility may, in fact, have some advantages; for this purpose low-grade deposits, which are more widely distributed than high-grade deposits, may be suitable.

POTASH RESOURCES

Potash resources in South America also have considerable potential, although the prospects for wide occurrence are not as bright as those for phosphate.

Chile is presently the only potash producer in South America. Production, in the form of potassium-sodium nitrate (about 10 percent K_2O), comes as a byproduct of the nitrate industry; production will probably increase in the near future. Other saline deposits and brines of northern Chile contain potash that may be commercially exploitable. The newly discovered potash-rich brines in the Sechura Desert of Peru have a large potential, and the unexplored salt domes east of the Andes suggest a series of salines there that could contain potash salts. The bedded potash deposits recently found in the course of petroleum exploration in the Sergipe-Alagoas basin of northeastern Brazil are other promising prospects but are as yet inadequately appraised. The Andean salars and closed basins of Argentina offer good prospects for brines, and the alunite deposits in Chubut Province are also a possible source. Salt deposits in Colombia and Ecuador need to be investigated further for possible occurrences of associated potash salts.

Although potash is a higher value commodity than phosphate, transportation costs also add significantly to its price. For this reason it may be highly desirable not only to evaluate prospects of the type just mentioned, but also to consider other sources that are not much exploited elsewhere. Among these are sea water, potassic feldspar (both of which are already being considered in Brazil), leucite, muscovite, potash-rich volcanic tuffs (which are widespread in the Andes of northern Chile and southern Peru) and some potash-rich igneous rocks, glauconite, and certain potash-rich black shales. As with phosphate, some of these potash-bearing materials may be suitable for direct application in raw and unbeneficiated form in areas of high

rainfall. Experiments already completed by AID in Brazil show good results, for example, from direct application of potash-bearing mica schist to certain tropical soils.

SULFUR RESOURCES

Potential resources of sulfur in South American countries are both large and widely distributed. Peru, again, ranks high in its sulfur potential, partly because of its volcanic deposits in the Andes and the unexplored salt domes east of the Andes—neither of which are producers now—but mainly because of its extensive sulfide deposits. Sulfur in gases from Peru's principal smelters, now vented off, could be recovered. Chile, Bolivia, Ecuador, Argentina, Venezuela, and Colombia all have substantial potential for production from volcanic deposits and from smelter gases, and in addition Venezuela has high-sulfur crude oils, from which sulfur is now being recovered. Some of the Andean volcanic deposits are being worked, and although most of them are high-cost sources by world standards, they are important for local use. Sulfur in smelter gases in these countries by and large is not now recovered and is an immediate source for expanded production. High-sulfur coals in Brazil and Ecuador are possible sources, as are gypsum and anhydrite deposits in Venezuela, Brazil, Chile, and Colombia.

Although sulfur is a moderately valuable mineral as nonmetallics go, transportation is again an important element of its cost to the consumer, and hence there is the same need to develop local sources as there is for phosphate and potash.

It cannot be emphasized too strongly that in viewing the future development of these fertilizer minerals in South American countries, the prime interest is not in producing materials for export (which has been the chief interest in nearly all of the mineral industry of these countries in the past) but in producing them for local consumption at a lower cost than they can be imported and hence at a savings in foreign exchange.

NITRATES

Nitrates have not been considered in the body of this report, but a word or two about them is appropriate here. Chile possesses the world's largest and only significant natural nitrate deposits, and while synthetic production is now generally cheaper, Chilean nitrate has remained competitive in many markets. Recent development of processes for byproduct recovery and for the manufacture of potassium nitrate should increase its competitiveness, particularly in those South American areas where synthetic nitrogen may be costly to produce.

Guano is another large source of nitrogen, as well as phosphate, in

South America, but its potential is now very nearly limited to the annual crop from sea fowl. Organic nitrogen from such sources as sewage, fish scrap, manure, and cover crops is another indigenous source with only a moderate undeveloped potential.

Although there are several processes for synthetic manufacture or byproduct recovery of nitrogen compounds, all depend on the availability of inexpensive electric power or of oil, gas, or coal. These are not readily available in all parts of South America and consequently synthetic nitrogenous fertilizers will be subject to the same kinds of transportation costs and distribution problems that affect the natural fertilizers, though perhaps to a lesser degree.

STEPS TOWARD EXPANDED PRODUCTION AND USE

From this survey of the present and potential availability of mineral fertilizers in South America, it is evident that prospecting and exploration can be expected to lead to discovery of many additional indigenous sources. It would be misleading to imply, however, that this step alone would lead to expanded production and use of fertilizers in South American countries. Successful domestic competition with world sources in any country requires development and use of highly efficient mining, processing, transportation, and marketing practices. It is plain that production from known deposits in South American countries is presently limited if not severely hampered by the weak state of the art in one or another of these areas, and this weakness will be magnified in any attempt to develop for local use sources that are marginal or submarginal by world standards. Inadequate knowledge of efficient use of fertilizers is possibly an even greater retarding factor. Substantial expenditures and efforts will be required for improvements in all of these fields, to say nothing of those required for prospecting, exploration, and mine and plant development.

Assuming that these problems will be attacked and resolved, there is no question that discovery and development of additional sources of fertilizer minerals in South American countries would aid significantly in expanding the use of fertilizers. A variety of steps can be taken to find and develop additional sources, and some of them can be expected to be successful in the short term. It should be emphasized, however, that full development of South America's resources will come only with much expanded knowledge of its geology, achievable only through geological mapping and related activities. This task, which has barely been attacked, is one of enormous magnitude in most South American countries. There is no hope of completing it as a part of any specific or finite program, but at the same time the effort, most of which is undertaken by national geological surveys and related organiza-

tions, should be encouraged as a continuing function and expanded as staff and funds permit.

Traditionally, the fertilizer industry in the United States and elsewhere has not been aggressive in prospecting for new deposits. It has explored and developed prospects found by others, but it has done little to search out new leads on its own; until recently, therefore, the industry has developed little prospecting expertise. Most companies still find it expedient to begin with a known prospect, and it is likely that their greatest contribution to the development of fertilizer-mineral resources in South America will come from exploration of such prospects. The prime aim of a mining company of course is to produce ore that can be sold at a profit, and it is natural for it to attempt to reach the production stage as quickly as possible and with a minimum expenditure for prospecting and exploration.

There is now rapidly developing, however, an interest on the part of industry in development of new sources of fertilizer minerals over the world, and many companies hitherto not active in the field are joining the search for minable deposits. Several of the large oil companies, in which there is well-developed tradition and ability in prospecting and exploration, are entering the field, some in cooperation with fertilizer companies, and the effort in prospecting and exploration is about to increase markedly. Given the proper encouragement and opportunity, there is no question but that many of these companies would participate in the search for fertilizer minerals in South America.

All the countries discussed in this report, with the exception of Ecuador, now have geological-survey capability, developed in varying degrees but nevertheless able to undertake studies of the kind that may be expected to lead to the discovery of new sources. Few of the personnel of these organizations are now trained or experienced in fertilizer-mineral geology, and all are engaged in other urgent studies related to the development of their country's mineral industry. Nevertheless, if some personnel could be assigned to this problem and field studies authorized and financed, they could be trained in a month or two to begin the work and should make good progress in identifying and appraising new sources in many countries.

Comparatively modest efforts and expenditures, then, in (a) fielding and guiding reconnaissance and prospecting activities in established geological-survey institutions in South American countries and in (b) encouraging private companies to search for and develop minable deposits, can be expected to meet with considerable success over a period of a few years in enlarging the production and use of fertilizers over the continent at large.

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