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# Bauxite Reserves and Potential Aluminum Resources of the World

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# Bauxite Reserves and Potential Aluminum Resources of the World

By SAM H. PATTERSON

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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 2 8

*A compilation of the geologic and geographic occurrence of world reserves and potential resources of bauxite, and of potential sources of aluminum in rocks and minerals other than bauxite*



UNITED STATES DEPARTMENT OF THE INTERIOR

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# BAUXITE RESERVES AND POTENTIAL ALUMINUM RESOURCES OF THE WORLD

By SAM H. PATTERSON

## ABSTRACT

Bauxite, a rock consisting chiefly of aluminum hydrate or hydroxide minerals, is the principal raw material used by the world's immense aluminum industry. The aluminum industry consumes about 90 percent of the bauxite mined; the remaining 10 percent is used in making refractories, catalysts for petroleum refining, cements, abrasives, chemicals, and for other purposes. The types of bauxite are (1) trihydrate, consisting chiefly of gibbsite,  $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ ; (2) monohydrate, consisting chiefly of boehmite,  $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$ ; and (3) mixed bauxite, consisting of both gibbsite and boehmite.

Bauxite deposits have formed chiefly by weathering of aluminous rock; some have been transported to their present locations, but most are residual accumulations from which most constituents of the parent rock other than alumina have been leached. Bauxite occurs in rocks ranging in age from Precambrian to Recent, and many deposits in the tropics are probably still forming. Most deposits of gibbsitic bauxite are in the tropics. A few occur in the temperate belts, but the climate was probably tropical or subtropical at the time these formed. Nearly all deposits of this type are of Cenozoic age. Deposits of boehmitic bauxite occur chiefly in southern Europe, the U.S.S.R., Turkey, and mainland China. Most deposits of this type are associated with carbonate rocks of Jurassic and Cretaceous age, but a few are of Paleozoic age. Though most of these deposits are north of the tropics, they could have formed under tropical conditions. Mixed bauxites are associated with both the gibbsite and boehmite types; however, they tend to be more abundant in deposits of Mesozoic and Paleozoic age than in younger rocks.

The largest bauxite deposits are in Australia, which has 2 billion tons of reserves and about 1 billion tons of potential resources, and in Guinea, which has 1.2 billion tons of reserves and about 2.4 billion tons of potential resources. Cameroon and mainland China each have at least 1 billion tons of potential bauxite resources that are unfavorably situated or otherwise unsuitable for mining. Jamaica, now the leading bauxite producer, has about 600 million tons of reserves and has potential resources that are nearly as large. Countries having 200-300 million tons of reserves include Ghana, Yugoslavia, Surinam, and the U.S.S.R.; both India and Brazil may rank with these countries when their widely distributed deposits are fully explored. Bauxite reserves in Hungary are probably about 150 million tons. Countries having 50-100 million tons of bauxite reserves include Nyasaland (now Malawi), Greece, France, British Guiana, French Guiana, and the Dominican Republic and Haiti combined. The United States, the largest consumer, has about 45 million tons of

reserves. The United States also has approximately 300 million tons of potential resources that are so low grade that they would not be classified as bauxite if they were in a country possessing large high-grade reserves. Most of the bauxite used in the United States is imported from the Caribbean Islands and from countries in the northern part of South America.

Potential sources of aluminum other than bauxite include aluminum phosphate rock, aluminous shale, alunite, dawsonite, high-alumina clay, igneous rocks, metamorphic rocks, saprolite, and sillimanite group minerals. Alumina is now produced from igneous rock and alunite in the U.S.S.R., and high-alumina clay is reported to be the raw material used in an alumina plant in Poland. When normal supplies of bauxite were cut off during World War II, small quantities of alumina were produced from alunite, aluminous shale, and aluminum phosphate rock in Japan, and from igneous rock and sillimanite group minerals in Norway. Attempts were made to use materials other than bauxite in the United States and other countries. Since World War II, both government and private interests in several bauxite-deficient countries have investigated the possibilities for using rock or minerals other than bauxite as a source of aluminum. The extraction of aluminum sulfate was attempted by one company in the United States, and a large producer of aluminum has announced plans to design a plant for processing high-alumina clay.

The United States has very large potential alumina resources other than bauxite, none of which have been used profitably. Resources of anorthosite, an igneous rock containing 25–30 percent  $Al_2O_3$ , are virtually inexhaustible. Very large masses occur in California, Oklahoma, Wyoming, Minnesota, New York, and Virginia. Deposits of aluminous shale are also extremely large; however, the alumina content is ordinarily only 20–22 percent. Very large masses of aluminous shale occur in rocks of Pennsylvanian age in the Appalachian region and the Mississippi River valley, in rocks of Cretaceous age in the Plains States, and in rocks of various ages elsewhere.

High-alumina clay contains more alumina than most other nonbauxite materials, and some deposits can be mined cheaply. The best grade high-alumina clay, containing 35 percent or more  $Al_2O_3$ , is in rocks of Pennsylvanian age in Pennsylvania, Ohio, Kentucky, and Missouri, and of Cretaceous or Tertiary ages in Vermont, South Carolina, Georgia, Alabama, Mississippi, Tennessee, Kentucky, Arkansas, California, Oregon, and Washington. Moderate- and low-grade deposits are scattered throughout the country.

Very large resources of saprolite occur in the Piedmont province of the Southeastern States. Saprolite is associated with bauxite in Arkansas and with ferruginous bauxite in Oregon, Washington, and Hawaii. Some saprolite contains 35–40 percent  $Al_2O_3$ , but most is lower in alumina. Nearly all saprolite contains appreciable iron oxide, and alumina occurs as a constituent of a number of fine-grained minerals. Because of these characteristics, saprolite would be difficult to beneficiate, and processing the entire rock would be costly.

Alunite resources in the United States occur in scattered deposits that are probably not large enough to support a major aluminum industry. Resources of aluminum phosphate in Florida are large, but the rock is low in alumina unless beneficiated, and resources are being lost as stripping of calcium phosphate deposits progresses. Large resources of sillimanite group minerals occur in several States. Though the alumina content of these minerals is high, the prospects for using them as a substitute for bauxite are not good because the minerals are costly to mine and beneficiate, and alumina is difficult to extract from them.

The aluminous mineral dawsonite has recently been discovered in large quantities in oil shale in Colorado. Possibilities for recovering alumina from these deposits have not been evaluated, but large tonnages of acid-soluble  $Al_2O_3$  may remain in the residue after oil extraction if this shale is processed on a large scale.

Some metamorphic rock is uncommonly rich in alumina. However, the alumina in such rock is tightly bonded in silicate minerals, and recovery of the alumina would probably be costly.

### INTRODUCTION

This report is a compilation of information on the geology, distribution, and amount of world reserves and potential resources of bauxite and of other minerals and rocks that are possible sources of alumina. It is chiefly a revision and enlargement of a chapter (III, Sources and Reserves, 60 p.) prepared by Elizabeth C. Fischer, U.S. Geological Survey, for the "Materials Survey—Bauxite," a report in looseleaf form released by the U.S. Bureau of Mines (1953). It is a part of a continuing program of the U.S. Geological Survey and the U.S. Bureau of Mines to provide information on mineral commodities and to assist in economic and technical planning by industry and the Federal Government.

In preparing this report, an attempt was made to review most of the significant articles on world bauxite deposits published since the chapter by Fischer (in U.S. Bur. Mines, 1953). Most of these reports are listed in the "References Cited" section. Several publications on foreign bauxite resources not referred to in this report are listed in the bibliography of a report by Bracewell (1962). Considerable information on bauxite was also included in 35 papers published for the First International Symposium on Bauxite, Oxides, and Hydroxides of Aluminum held at Zagreb, Yugoslavia, October 1-3, 1963 (Karšuln, 1964). Most older reports on world bauxite deposits are listed in an annotated bibliography by E. C. Fischer (1955). Many articles have been published on potential sources of aluminum other than bauxite. Only a few of the major ones are listed in the bibliography of this report.

### DEFINITIONS

The term "bauxite" is commonly employed (as by Gordon and others, 1958, p. 73) for "an aggregate of aluminous minerals, more or less impure, in which aluminum is present as hydrated oxides." Harder and Greig (1960, p. 65) used the term for "the ore from which aluminum is smelted but it has large use also in the manufacture of artificial abrasives as well as of aluminous cement—'ciment fondu'. An important and growing use is the manufacture of refractory products." As used in this report, bauxite is a rock that is rich in aluminum hydrate or hydroxide minerals but may contain

amorphous aluminous matter. Bauxite has real or potential value for any use requiring a material with a high-alumina content.

Bauxites composed chiefly of gibbsite are commonly termed "trihydrate bauxite," or the Surinam type; those composed of boehmite as "monohydrate bauxite," or the European type; and those composed of a mixture of gibbsite and boehmite as "mixed bauxites." The term "Jamaica type" is also applied to very fine grained high-iron gibbsitic bauxite containing minor quantities of boehmite. Many bauxites can be upgraded by washing out the clays and other fine-grained impurities; however, Jamaica-type bauxite cannot be beneficiated profitably in this manner because the bauxite minerals and the impurities are so fine grained.

The term "bauxite" as used herein does not include certain aluminum-bearing minerals and materials such as aluminous shales, aluminum phosphate rock, alunite, dawsonite, high-alumina clay, igneous and metamorphic rocks, saprolite, and sillimanite group minerals that are being used or have been considered for use as a source of aluminum. These rocks and minerals are discussed in the last section of this report.

#### PHYSICAL PROPERTIES OF BAUXITE

Bauxite occurs in a number of different forms, and its physical properties vary appreciably. Bauxites may be massive or earthy, pisolitic, oolitic, brecciated, nodular, botryoidal, cellular, platy, or vermicular. Many pisolites consist of concentric layers, and banding is common in other structures. Some high-grade bauxite is light gray or nearly white, but shades of brown, yellow, red, pink, and purple are common; a few deposits are green, and those rich in organic matter are nearly black. The hardness and specific gravity of the bauxite minerals are summarized in table 1. The bulk density of most bauxite ranges from 80 to 120 pounds per cubic foot, considerably less than the specific gravity of the mineral chiefly because of the high porosity.

TABLE 1.—*Properties of bauxite minerals*

Mineral	Common chemical formula and name	Alternate chemical formula and name <sup>1</sup>	Crystal system	Alumina content (per cent)	Combined water content (per cent)	Specific gravity	Hardness (Mohs scale)
Gibbsite...	$Al_2O_3 \cdot 3H_2O$ , alumina trihydrate.	$Al(OH)_3$ , aluminum trihydroxide.	Monoclinic..	65.35	34.65	2.3-2.4	2.2-3.5
Boehmite..	$Al_2O_3 \cdot H_2O$ , alumina monohydrate.	$AlO(OH)$ , aluminum oxide hydroxide.	Orthorhombic.	84.97	15.03	3.01-3.06	4-5
Diaspore....	do <sup>2</sup>	do <sup>2</sup>	do	84.98	15.02	3.3-3.5	6.5-7

<sup>1</sup> Newsome and others, 1960, p. 9-10.

<sup>2</sup> Diaspore differs from boehmite in having a more closely packed and tightly bonded atomic structure.

## USES AND SPECIFICATIONS

About 90 percent of the world production of bauxite is used for making alumina, most of which is consumed in the manufacture of aluminum. The remaining 10 percent is used in the production of abrasives, refractories, chemicals used chiefly in water purification and in the manufacture of paper, petroleum catalysts, aluminous cements, materials for the purification of kerosene and other petroleum products, and for other purposes. High-alumina content is desirable in all bauxites, and the value of the bauxite is directly related to the quantity and purity of the alumina present. However, depletion of very high grade deposits and modification of processes for treating lower grade bauxites have resulted in a lowering of the compositional requirements for bauxites. In 1941, the specifications for metal-grade bauxites were a minimum of 55 percent  $\text{Al}_2\text{O}_3$  and a maximum of 7 percent  $\text{SiO}_2$ , 8 percent  $\text{Fe}_2\text{O}_3$ , and 4 percent  $\text{TiO}_2$  (Thoenen and Burchard, 1941, p. 35). By 1960, metal-grade bauxite treated in certain plants in the United States could contain a minimum of 48–50 percent  $\text{Al}_2\text{O}_3$  and as much as 15 percent  $\text{SiO}_2$ ; iron oxide was regarded only as a diluent having virtually no cut-off (Harder and Greig, 1960, p. 80).

National Stockpile Purchase Specification P-5a-R2, issued July 23, 1958, covers two grades of bauxite suitable for the production of metallic aluminum. According to these specifications, all bauxite purchased should be amenable to efficient treatment by conventional or modified Bayer process as practiced in the United States. The chemical and physical requirements are outlined as follows:

*Chemical requirements.*—Bauxite delivered under any given contract shall conform, on a weighted-average basis, to the following applicable chemical requirements:

	Percent by weight (dry basis <sup>1</sup> )	
	Trihydrate ore (Surinam type)	Mixed monohydrate-trihydrate ore (Jamaica type)
Alumina ( $\text{Al}_2\text{O}_3$ )..... min.....	55.0	47.0
Silica ( $\text{SiO}_2$ ) <sup>2</sup> ..... max.....	5.0	4.0
Total alkalies (as oxides)..... max.....	1.0	1.0
Ferrous iron (as $\text{FeO}$ ) <sup>3</sup> ..... max.....	3.0	3.0
Phosphorus (as $\text{P}_2\text{O}_5$ )..... max.....	1.0	1.0
Manganese, chromium, and vanadium (as $\text{MnO}_2 + \text{Cr}_2\text{O}_3 + \text{V}_2\text{O}_5$ )..... max.....	2.0	2.0
Loss on ignition ( $\text{H}_2\text{O}$ ) <sup>4</sup> ..... min.....	50 percent of actual $\text{Al}_2\text{O}_3$ .	40 percent of actual $\text{Al}_2\text{O}_3$ .

<sup>1</sup> Sample dried at 105°C. Free water removed; combined water not removed.

<sup>2</sup> Alumina shall be considered to be the difference between 100 percent and the sum of the percentages of the silica, iron oxide, titania, and the loss on ignition.

<sup>3</sup> Alumina shall be considered to be the difference between the percentage of combined oxides ( $\text{R}_2\text{O}_3$ ) and the sum of the percentages of total iron oxide, titanium oxide, and phosphorus pentoxide. The combined oxides ( $\text{R}_2\text{O}_3$ ), total iron oxide, titanium oxide, and phosphorus pentoxide shall be determined on the silica filtrate after routine triacid digestion, as outlined in Furman (1939, paragraphs 4, 5, 8, 9, and 14, "Aluminum," p. 19–23, and paragraphs 4A, 5A, 8A, and 9A, "Analysis of Bauxite," p. 23–25). The phosphorus pentoxide may also be determined by the spectrophotometric method.

<sup>4</sup> Silica shall be determined by the standard triacid method of analysis.

<sup>5</sup> Includes only iron compounds in the ferrous form, calculated to and expressed as  $\text{FeO}$ .

<sup>6</sup> Combined water, obtained by calcination of dried sample.

*Physical requirements.*—Dried bauxite is preferred, but crude bauxite may be purchased. Each purchase contract shall stipulate whether crude or dried bauxite is to be delivered and, if the latter, the minimum and maximum permissible content of free moisture.

Most refractory-grade bauxite purchased for the stockpile has a minimum bulk density of 3.10 (calcined basis) and conforms to the following chemical specifications set forth in National Stockpile Specification P-5c, issued December 5, 1951:

	<i>Percent by weight (calcined basis)<sup>1</sup></i>
Alumina (Al <sub>2</sub> O <sub>3</sub> ).....	min. 85.00
Silica (SiO <sub>2</sub> ).....	max. 7.00
Iron oxide (Fe <sub>2</sub> O <sub>3</sub> ).....	max. 3.75
Titanium (TiO <sub>2</sub> ).....	max. 3.75
Loss on ignition.....	max. .50

Much of the metal-grade Surinam-type bauxite purchased for the national stockpile is also suitable for use in abrasives, chemicals, and cements, and no specifications for bauxite purchases for these uses were in effect in 1964. However, the following specifications listed by the U.S. Bureau of Mines (1953, p. II-11—II-12) for abrasive-grade bauxite give an indication of the quality desired in abrasive-grade bauxite:

	<i>Percent by weight (calcined basis)<sup>1</sup></i>
Alumina (Al <sub>2</sub> O <sub>3</sub> ) <sup>2</sup> .....	min. 80.0
Silica (SiO <sub>2</sub> ).....	max. 7.0
Lime (CaO).....	max. .4
Magnesia (MgO).....	max. .4
Total alkalis (as oxides).....	max. .7
Total iron (as Fe <sub>2</sub> O <sub>3</sub> ).....	max. 8.0
Phosphorus (as P <sub>2</sub> O <sub>5</sub> ).....	max. .5
Manganese, chromium, vanadium, combined (as MnO <sub>2</sub> +Cr <sub>2</sub> O <sub>3</sub> +V <sub>2</sub> O <sub>5</sub> ).....	max. 1.0
Titanium (as TiO <sub>2</sub> ).....	min. 3.5

<sup>1</sup> Sample to be dried at 105°C, and analyzed in the dried condition, including a determination of combined moisture content. Dry basis assay to be converted to calcined basis by computation, using the actual combined moisture determination. Thus:

$$\text{Percent by wt., calcined basis} = \frac{\text{Percent by wt., dry basis} \times 100}{100 - \text{Percent combined H}_2\text{O in dried sample}}$$

<sup>2</sup> Alumina shall be determined by difference, using the "triacid" method of analysis.

Bauxite low in both iron oxide and silica is desired for use in making aluminous chemicals. According to old specifications (U.S. Bur. Mines, 1953, p. II-20—II-21), dry bauxite should not contain more than 2.25 percent Fe<sub>2</sub>O<sub>3</sub>, nor more than 10 percent SiO<sub>2</sub>. Titanium is generally insoluble in chemical processing of bauxite for aluminous chemicals, and 2–3 percent TiO<sub>2</sub> can be tolerated.

Activated and catalytic-grade bauxite must be high in alumina trihydrate (gibbsite) and must pass certain tests. Silica in the form of kaolin minerals reduces the efficiency of bauxite used in cracking petroleum, but small quantities of quartz can be tolerated. Catalytic-grade bauxite also must be more cohesive than for other purposes, and a pisolitic bauxite that will not disintegrate is generally preferred. The suitability of a bauxite for catalyst is usually best evaluated by trial use in plants, and specifications regarding composition or physical properties are of little value.

Bauxite for use in aluminous cements should not contain more than 6 percent  $\text{SiO}_2$  nor less than 10 percent  $\text{Fe}_2\text{O}_3$ ; otherwise the temperature of fusion may be too high (U.S. Bur. Mines, 1953, p. II-22—II-23). These specifications for cement-grade bauxite are probably out of date, but no revisions had been made at the time of the writing.

#### BYPRODUCTS

Iron and other metallic oxides are concentrated by the weathering processes that form bauxites; accordingly, several possibilities exist for the recovery of metals as byproducts of alumina extraction as well as the use of the red or brown muds remaining after alumina has been removed. Pig iron is a byproduct of the bauxite treated by the Pederson process in Norway (Bracewell, 1962, p. 54, 60), and iron oxide is a byproduct of bauxite in Hungary (Wilmot and others, 1959). Vanadium and chromium were recovered as byproducts of bauxite processing in Germany during World War II, and vanadium is still recovered occasionally from bauxite in France (Bracewell, 1962, p. 59-60). One United States company recovers gallium during the processing of Arkansas bauxite (Wilmot, 1960, p. 20), and gallium is recovered from bauxite in Hungary (Wilmot and others, 1959). Red mud is used in making cement (Clausen, 1960, p. 210) and as a red pigment (Bracewell, 1962, p. 30), and it is reported to be suitable for use in surfacing roads when mixed with asphalt (Am. Metal Market, 1957). In the U.S.S.R., potash, soda ash, and materials for making cement are produced as byproducts from alumina extraction from nepheline syenite (Baer, 1959) and potassium sulphate and sulfuric acid are produced in extracting alumina from alunite (Sokoloff, 1964, p. 769); however, neither raw material is bauxite.

The high titanium content of bauxites has long attracted attention to that metal as a potential byproduct (Calhoun, 1950). Titanium is unaffected by the alkaline digestion processes used in alumina extraction, and the concentration of this oxide in the red mud tailings is appreciably higher than in beach sands that are mined for titanium in the United States (Hartman, 1959, p. 1402). Some of the red muds in India contain 25-30 percent  $\text{TiO}_2$  (Bracewell, 1962, p. 58). Most of the titanium in bauxites is in the minus 325-mesh fraction and is difficult to concentrate efficiently, and no cheap method has been devised for the chemical treatment of the red mud tailings to recover the titanium.

Other possible byproducts from bauxite that have not yet been recovered commercially include: (1) Platinum and silver from bauxite in India (Chhibber, 1947); (2) gold that occurred in quartz

veins in the parent rocks of bauxite in Ghana and was concentrated as the rock weathered (Cooper, 1936, p. 20); (3) diamonds that occur in laterite in British Guiana (Fox, 1932, p. 70); (4) niobium (columbium) that makes up an average of 0.05 percent of bauxite in Arkansas (Gordon and others, 1958, p. 99; M. Fleischer and others, 1952) but is difficult to recover (Nieberlein and others, 1954); and (5) thorium that occurs in concentrations of half a pound in a ton of red mud at one United States alumina plant (Adams and Richardson, 1960, p. 1672). Trace amounts of beryllium, uranium, manganese, and other metallic oxides and rare earths also occur in bauxites, but probably none are in sufficient abundance for profitable recovery.

#### UNITED STATES AND WORLD PRODUCTION

The following brief history of bauxite is summarized from a discussion by Gordon, Tracey, and Ellis (1958, p. 71-73), who listed appropriate references to published sources. P. Berthier in 1821 first recognized the high-alumina content of rocks now known as bauxite after he made chemical analyses of samples from southern France. The term "beauxite" was first published by A. Dufrenoy in 1847, and the name was later changed to bauxite to comply with a change in spelling of the town and hill names at the type locality at Les Baux, France. Though rocks in the United States later found to be bauxite were described under the names "amygdaloid" and "pudding stone" as early as 1842, bauxite was first identified in occurrences along the road from Little Rock to Sweet Home, Ark., by J. C. Branner, State Geologist of Arkansas, in 1887. His report, however, was not published for 4 years. In the meantime a note was published by E. Nichols (1888, p. 905) describing bauxite in Floyd County, Ga. This is usually considered to be the first documented discovery in the United States. The actual identification of bauxite in Georgia may have taken place as early as 1881. Production of bauxite in Georgia began in 1888, and the first few tons were mined in Arkansas in late 1894 or early 1895.

Aluminum was extracted from bauxite in both France and England in the middle of the 19th century, but less than 50 tons of metal had been produced by 1885 (Fox, 1932, p. 230). Production increased at a rapid rate in the late 1800's, but the yearly demand for bauxite did not reach 1 million tons until 1917, under the influence of World War I. World production of bauxite dropped sharply after the war and reached a low of 334,000 tons in 1921. A little more than 1 million tons was produced in 1923, and a yearly production of 2 million tons was first reached in 1929. World production again dropped in the depression years of the early 1930's (fig. 1) but

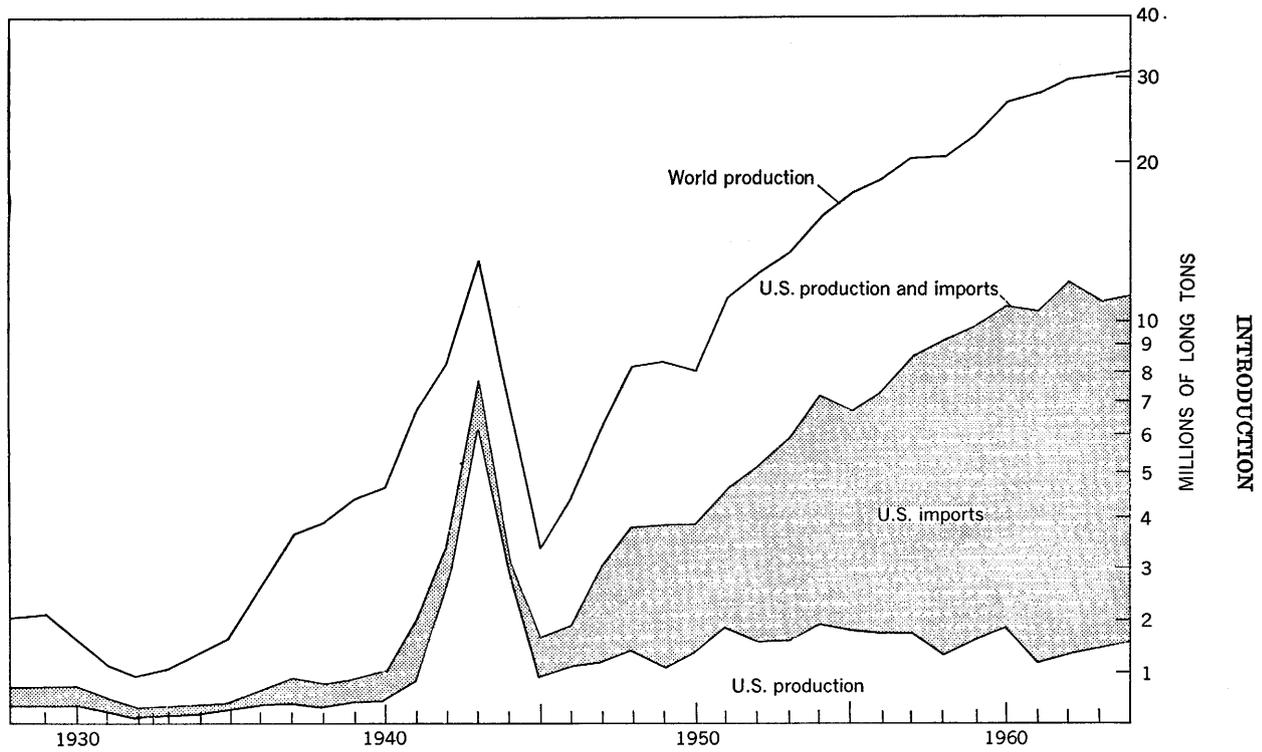


FIGURE 1.—United States production and imports and world production of bauxite, 1928-64.

recovered in the last half of the decade and reached a sharp peak of more than 13 million tons in 1943. Production again slumped sharply after World War II as the economy changed to peacetime conditions and accumulated stocks were consumed. After recovering from this slump, world production reached 11 million tons in 1951 and has since remained on a sharply increasing trend, reaching 20 million tons in 1947, and about 31 million tons in 1963. Consumption of aluminum has surpassed that of copper, and aluminum now ranks second to iron as the most widely used metal; the industry is of major worldwide economic importance. However, the tonnage of bauxite consumed is surpassed by that of copper ore, because 1 ton of aluminum is recovered from 4-5 tons of bauxite whereas the average copper ore mined in the United States contains less than 1 percent metal.

Domestic production, including the World War I peak, remained below 1 million tons annually until very intensive mining was started in 1942 to meet World War II requirements; a record production of 6.2 million tons was reached in 1943 (fig. 1). This provided such large stocks that only 2.8 million tons was mined in the following year and only 981,000 tons in 1945, the final year of the war. Since 1945, production has remained between 1 and 2 million tons per year, and imports have risen sharply.

The Arkansas district has produced more bauxite than all other districts in the United States combined. About 51 million tons was produced in Arkansas from 1896 through 1963. Production in all Southeastern States from 1889 through 1963 amounted to only 2.8 million tons, dry basis. Georgia and Alabama each produced about 48 percent of this total, Tennessee about 3 percent, and Virginia and Mississippi less than 1 percent.

#### UNITED STATES SOURCES OF BAUXITE

Foreign sources have supplied significant proportions of the bauxite consumed in the United States for many years. In 1900 more than 8,000 tons of bauxite was imported, and this tonnage fulfilled about 25 percent of the requirement. Imports exceeded domestically mined bauxite for the first time in 1925. Though domestic production exceeded imports in a few years between 1925 and 1941, the first major reversal of the trend to rely on foreign bauxite came during World War II, when the unavailability of shipping and the losses at sea from enemy submarine activity forced record domestic production (fig. 1). Imports again exceeded domestic production in 1947, and in recent years foreign sources have supplied nearly 90 percent of the bauxite consumed in the United States. In 1964, 10.2 millions tons was imported, and 1.6 million tons was mined

domestically (L. R. Williams, 1965, p. 1). About 57 percent of the imported bauxite came from Jamaica, 30 percent from Surinam, and most of the remainder from the Dominican Republic, British Guiana, and Haiti. Nearly all the bauxite imported in recent years (table 2) has come from these countries.

TABLE 2.—United States imports of bauxite for consumption (crude and dried), by countries, 1950-64 (in thousands of long tons)

[Compiled from U.S. Bur. Mines Minerals Yearbooks]

Year	Dominican Republic	Haiti	Jamaica	British Guiana	Surinam	Total <sup>1</sup>
1964	640	396	5,792	253	3,070	10,180
1963	729	328	5,239	335	2,518	9,170
1962	719	436	6,010	560	2,853	10,585
1961	722	289	4,936	316	2,885	9,206
1960	632	341	4,175	330	3,256	8,739
1959	382	307	4,220	160	3,078	8,149
1958		317	4,950	223	2,425	7,919
1957		318	3,622	391	2,767	7,098
1956			2,573	269	2,798	5,670
1955			2,178	242	2,462	4,882
1954			1,717	175	3,096	4,988
1953			1,016	102	3,099	4,230
1952			229	178	3,023	3,462
1951				127	2,309	2,819
1950				91	1,968	2,516

<sup>1</sup> For some years includes small tonnages from other South American countries, Europe, Africa, and Asia.

At the present rate of consumption of more than 10 million tons annually, the reserves of high-grade bauxite in Arkansas, Georgia, and Alabama are adequate to last less than 5 years, if all foreign sources were cut off. Though small undiscovered bauxite deposits similar to those in Arkansas may be associated with igneous rocks at depth in the Mississippi embayment area (Jespersion, 1964), may be buried by Coastal Plain rocks in Georgia and Alabama, or may occur in sinkhole fills of the type that are widely scattered in the Appalachian region (Knechtel, 1963, p. C155), virtually no possibility remains for the discovery of high-grade bauxite deposits of sufficient size to furnish more than small supplies during an emergency. Potential resources, chiefly in low-grade and deeply buried deposits associated with the reserves in Arkansas, Georgia, and Alabama and low-grade ferruginous bauxite in Oregon, Washington, and Hawaii, which cannot be used commercially now, contain about 300 million tons of bauxite. Reserves of bauxite in the Caribbean Islands, British Guiana, and Surinam are adequate to fulfill the demands of the United States aluminum industry for the foreseeable future. Significant tonnages of bauxite may also be imported from Africa, particularly to supply a plant now under construction in the Virgin Islands (Higbie and others, 1963, p. 300).

Long-range forecasts for the sources of bauxite involve very complex political and economic factors. Organizations concerned with future needs for bauxite forecast that the United States yearly requirement will be 25 million tons by 1975 (K. L. Wang, 1963, p. 15) and more than 75 million tons by the year 2000 (Landsberg and others, 1962, p. 208). At this rate of consumption, known reserves in countries now supplying United States demands may be nearing exhaustion in 35 years. If the projected long-range demands are of the right order of magnitude, new bauxite discoveries will supply part of the requirements, but many of the potential bauxite resources in countries now supplying bauxite and in other South and Central American countries may become major sources. Part of the drain on present sources will probably be reduced by increases in the current trend of American aluminum industry to establish integrated operations abroad, and by the year 2000, much of the country's alumina and aluminum needs may be fulfilled by imported metal made by American companies in Australia and countries in Asia and Africa. The drain on present sources of bauxite may also be reduced by the use of materials other than bauxite. High-alumina clays, saprolite, and other potential sources of alumina will become more competitive with bauxite as costs of mining, transporting, and processing foreign bauxite increase. Possibly an economical method of extracting alumina from some of these materials will be developed, and some of the materials may become major sources of aluminum by the year 2000.

#### PROSPECTING AND APPRAISAL OF BAUXITE DEPOSITS

Most early discoveries of bauxite were made by prospecting outcrops or by tracing float or bauxitic stream gravels to their source. In discoveries of this type, the distinctive colors and textures characteristic of some bauxites first attracted attention and later served as useful guides in exploring deposits. Aluminous laterites in several countries and the large earthy bauxite deposits in Jamaica lack distinctive colors and textures and were discovered during investigations of soil infertility or other scientific studies. The lack of fertility in soils associated with many bauxites results in stunted vegetation or barren areas that contrast with the more heavily vegetated nonbauxite areas. Areas favorable for bauxite may be outlined by distinctive vegetation, a characteristic that has been used to locate bauxite in Guinea, French Guiana, Surinam, Palau Islands, and elsewhere. Where vegetation serves as a guide to the distribution of bauxite deposits, aerial photographs are valuable in prospecting because areas of dwarfed vegetation stand out clearly. Buried bauxite deposits are difficult to locate. Probably most such deposits have

been found by exploratory drilling after thorough geological investigations have been completed. However, geophysical methods are useful in finding buried deposits where the bauxite occurs between rocks having distinctly different physical properties. Areas favorable for bauxite in Arkansas were outlined by geophysical techniques (Thoenen and others, 1945). Resistivity methods have been used successfully in the search for bauxite in Yugoslavia and Italy, and magnetic, gravimetric, and seismic methods have been applied in bauxite prospecting in Hungary (Bárdossy, 1964, p. 45). Airborne-magnetometer surveys have been used in locating bauxite in British Guiana (Bracewell, 1962, p. 20), and magnetometer, seismic, and gravity techniques would be useful in Surinam (Doeve and Groeneveld Meijer, 1963), where the occurrence of bauxite is related to igneous and metamorphic rocks.

Once located, bauxite deposits must be thoroughly sampled and tested for an appraisal. Samples are commonly collected by drilling and test pitting. Sampling is ordinarily done in two or more stages. In the first stage, sample locations are widely spaced to determine the extent of deposits; in the later stages, sample locations are closely spaced to determine grade and to guide mining. Some test pitting is essential in appraising most deposits because other methods do not yield representative samples, and larger samples than can be obtained by drilling are required for metallurgical tests.

Analyses for aluminum, iron, titanium, and silicon oxides and determination of loss on ignition are adequate in most bauxite appraisals; however, complete chemical analyses of selected samples is desirable. Most chemical analyses are made by standard wet chemical methods. Some bauxites are difficult to analyze, and high standards of accuracy in quantitative determination of alumina in the presence of iron, titanium, silicon, and calcium oxides are not easy to maintain even by experienced chemists (Watts, 1958, p. 968). Some laboratories are now using the X-ray fluorescence spectrography technique for the quantitative determination of metallic oxides in bauxite samples. This technique, which is similar to the one described by Rose, Adler, and Flanagan (1963) and Tertian, Fagot, and Jamey (1964), is both rapid and accurate when used by experienced personnel.

Alumina contents of bauxite can also be calculated from estimates of the quantities of aluminous minerals present. Very little information can be obtained by study of bauxite hand specimens because most bauxites are extremely fine grained, commonly more than one aluminous mineral is present, and in nearly all deposits the aluminous minerals are intimately associated with mineral impurities. Investigations by petrographic microscope—the only tool available

to most early students of bauxite—may provide much mineralogical information; however, most deposits contain some minerals that are too fine grained to be identified by optical methods. The electron microscope is useful in the study of bauxites, particularly those containing halloysite or amorphous materials, because its very high magnification enables determination of the size and shape of particles, which is not possible by other methods.

Probably the best method of identification of minerals in bauxite is by X-ray diffraction, as the minerals in most bauxites can be identified accurately by their diagnostic X-ray reflections (Rooksby, 1961). Estimates of the quantities of aluminous minerals present can also be made from the intensities obtained with an X-ray diffractometer (Rohner, 1958; Black, 1953). Another way is to measure the peaks in curves obtained by differential thermal analysis. This technique is more accurate when sensitive laboratory apparatus is used (Mackenzie, 1957), but portable apparatus is useful in obtaining preliminary results in the field (Hendricks and others, 1946; C. J. Parker and others, 1956). A third means of identification is based on weight loss between 110° and 440°C (Pollard and Barron, 1954, p. 109–112), a temperature range in which the hydroxyls are driven from gibbsite but not from kaolinite.

All the mineral-estimation methods of appraising bauxite yield accurate results only when carefully controlled and used in conjunction with chemically analyzed samples. Intolerable errors may be introduced when the X-ray diffractometer method is used with bauxite containing aluminous gels or other amorphous forms. Both the differential thermal analysis and weight-loss methods are most accurate when used with bauxite containing gibbsite and kaolin. These methods may be very inaccurate if applied to bauxite that contains goethite or other minerals that lose weight in the same temperature range as gibbsite or if bauxite minerals other than gibbsite are present.

M. E. Lewis (1962) described a method for distinguishing bauxite suitable for mining from that too low in grade by measuring pH and the oxidation-reduction potentials of deposits in the field. This method was used in investigation of bauxites in Jamaica, where bauxite suitable for mining was found to have higher oxidation-reduction potentials than that too low in grade to be of value. Whether or not this method can be applied to other deposits has not been determined.

#### ACKNOWLEDGMENTS

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## GEOLOGY OF BAUXITE

### TYPES OF DEPOSITS

Bauxite deposits of several types occur under many different geologic conditions (fig. 2) and are associated with rocks of widely differing geologic ages. A completely satisfactory classification of bauxite is not possible because of the variations in occurrences; however, most deposits can be assigned to one or more of the following three groups.

*Blanket deposits.*—This type occurs at or near the surface and consists of a flat-lying layer of variable thickness and extent. Most blanket deposits are residual, having formed from underlying alumina-silicate-bearing rocks of varying types, and only a few contain transported material. Many blanket deposits occur on old plateaus and plains formed during late stages of geomorphic cycles,

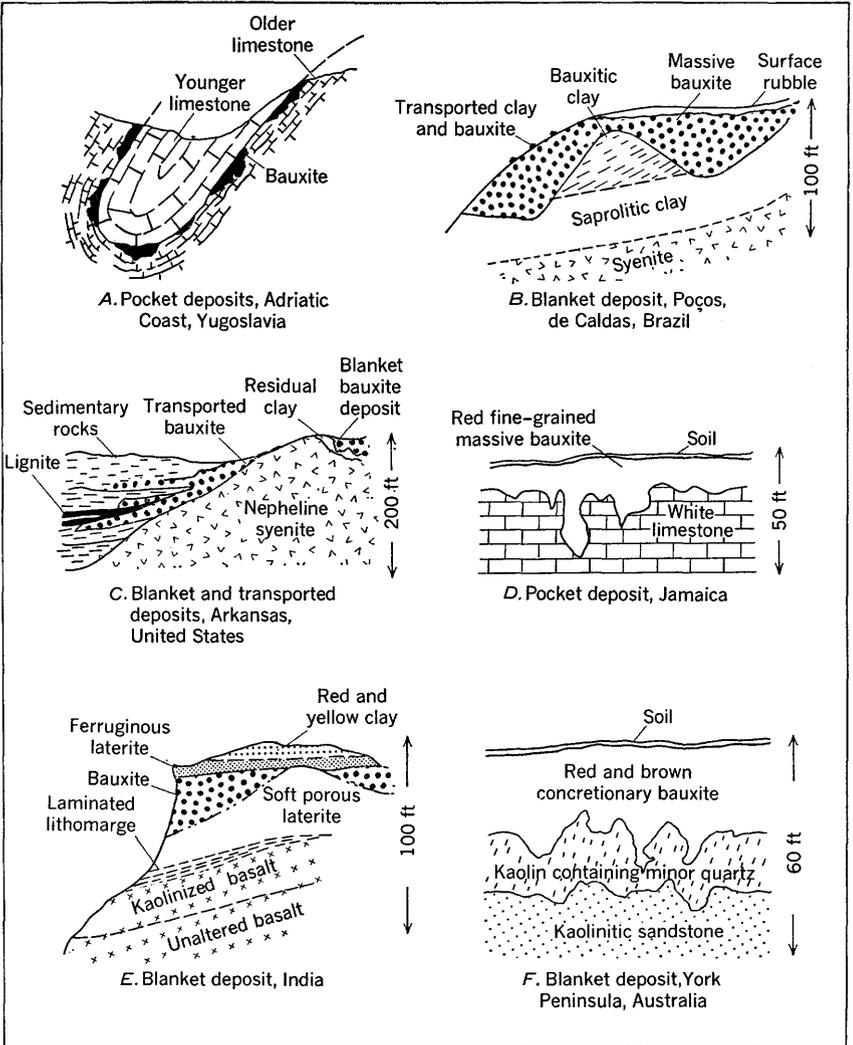


FIGURE 2.—Typical occurrences of bauxite.

representing long periods of stable geologic conditions. Typical bauxite in blanket deposits is high in iron and is of the type referred to as aluminous laterite (Fox, 1932). Several of the very large bauxite deposits in the world are of the aluminous-laterite blanket type; extensive deposits occur in Australia (fig. 2F), Africa, South America, and India (fig. 2E). Low-iron blanket-type deposits form locally and contain very high grade bauxite. High-grade blanket-type deposits overlie nepheline syenite in Arkansas and elsewhere (fig. 2B, C).

*Interlayered deposits.*—This type of deposit occurs as discontinuous beds and lenses interstratified in sedimentary or volcanic rocks or along the contact between igneous or metamorphic and younger rocks. Interlayered bauxites are chiefly remnants of old residual blanket deposits that were covered by younger rocks, but they also include transported bauxites that are enclosed by sedimentary rocks. Interlayered bauxites occur (1) enclosed by sedimentary rocks in Arkansas (fig. 2C), northern South America, Urals region of the U.S.S.R., mainland China, and elsewhere; (2) along the contact of igneous or metamorphic rocks with overlying sedimentary rocks in Arkansas and in the northern part of South America; and (3) interbedded in sequences of basaltic lava flows at several places in Australia.

*Pocket deposits.*—Pocket deposits occur chiefly as fillings of depressions formed in limestone or dolomite, but some are associated with other types of rock. Extensive pocket deposits occur at or near the surface in Jamaica (fig. 2D) and in Hungary. Some pocket deposits are so extensive that they virtually form blankets; others, such as those in France, Yugoslavia (fig. 2A), Greece, and Hungary, are interbedded with sedimentary rocks and are therefore interlayered pocket deposits. Nearly all pocket deposits formed on carbonate rocks are partly red or are separated from the underlying strata by zones of red clay or other fine-grained rock. Because of their association with red earthy materials, common occurrence in solution depressions in limestone, and widespread distribution in southern Europe, these deposits are commonly referred to as terra-rossa-, limestone-, karst-, French-, or Mediterranean-type bauxites (Zans, 1961, p. 208).

A second classification used by many geologists, particularly those working in Europe, is the assignment of all bauxite deposits to either laterite or karst types (Weisse, 1964). This system is not entirely satisfactory because the laterite classification is based on origin and the karst classification is based on the occurrence of deposits on the uneven surface of carbonate rocks. The laterite-karst classification is convenient for most bauxites, but for some deposits, such as those in Jamaica, which occur on a karst surface and may have formed by lateritic weathering, its application may lead to confusion.

Bauxite has formed intermittently throughout much of geologic time (table 3) and more intensively during certain periods than others. The oldest known bauxite deposits—in the East Sayan Mountains of Asiatic U.S.S.R.—are of late Proterozoic age (Goretzky, 1958); several bauxite deposits have formed in Pleistocene and Recent time, and others are believed to be still forming in many

tropical areas. Major bauxite formation took place during the following geologic time intervals: (1) Devonian in the Urals region, U.S.S.R.; (2) Carboniferous in the Tikhvin district, U.S.S.R., and on mainland China; (3) Cretaceous in several deposits in southern Europe; (4) Triassic in Yugoslavia; (5) Tertiary in the United States, Jamaica, British Guiana, Surinam, Hungary, Yugoslavia, and parts of Australia; and (6) Quaternary (Pleistocene and Recent Epochs) in many of the very large blanket aluminous-laterite deposits in tropical regions.

TABLE 3.—*General age relations of principal world bauxite deposits*

[Modified from Harder and Greig (1960, p. 67)]

Cenozoic:

Quaternary:

Recent and Pleistocene. Tropical lateritic bauxite of Panama, Costa Rica, Hawaii, Fiji, Mandated Solomon Islands, and parts of Queensland, Australia. Gibbsite bauxite deposits in Brazil, Venezuela, Guinea, Ivory Coast, Ghana, and Western Australia are at the surface but overlie older rocks and may have formed earlier than the Pleistocene. Bauxitic materials have formed in Hawaii, Surinam, and at many other places in the tropics in Recent time.

Tertiary:

Pliocene----- United States (Oregon)—lateritic bauxite.  
Germany (Vogelsburg Mountains)—ferruginous bauxite.  
British Guiana, Surinam, and French Guiana—gibbsite, pre-Pliocene but underlain by Precambrian rocks.

Miocene----- Australia (Victoria)—bauxite.  
Jamaica, Haiti, and Dominican Republic—gibbsite, underlain by Eocene and Oligocene rocks and probably formed intermittently in Miocene and post-Miocene time.

Oligocene----- India—bauxite and laterite developed on Deccan trap.  
Northern Ireland (County Antrim)—ferruginous gibbsite bauxite enclosed by basalt flows.

Eocene----- United States (Arkansas, Alabama, and Georgia)—gibbsite, underlain by Paleocene (Midway Group) Cretaceous rocks, overlain mainly by lower Eocene (Wilcox Group) rocks.  
Yugoslavia—boehmite and gibbsite, underlain by lower Eocene and Upper Cretaceous rocks.  
India (Kashmir-Jammu)—diaspore, underlain by Jurassic and overlain by Eocene rocks.  
Hungary—boehmite, underlain by Rhaetic (Upper Triassic) rocks and overlain by Eocene rocks.  
Australia (Queensland, Northern Territory, and Tasmania)—bauxite, underlain by Cretaceous, Jurassic, and Precambrian rocks.

TABLE 3.—*General age relations of principal world bauxite deposits*—Continued

## Mesozoic:

## Cretaceous:

## Upper:

Senonian..... Greece—boehmite and diaspore, underlain by Jurassic rocks and overlain by Upper Cretaceous rocks.

Turonian..... Italy (central Apennines)—boehmite, associated with rocks of Cenomanian and Turonian age.

## Lower:

Albian..... France (Var)—boehmite, underlain by Lower Cretaceous rocks and locally Jurassic rocks and overlain by rocks of Cenomanian age.

France (Hérault)—boehmite, underlain by Jurassic rocks.

Yugoslavia (Montenegro)—chiefly boehmite, in Upper and Lower Cretaceous rocks.

Urgonian..... France (Ariège)—boehmite, underlain by Jurassic rocks and overlain by rocks of Urgonian or Aptian age.

Neocomian... Rumania (Bihar)—boehmite and diaspore, underlain by Malm (Upper Jurassic) rocks and overlain by Lower Cretaceous rocks.

## Jurassic.

## Triassic:

Upper..... Yugoslavia (Croatia)—boehmite, underlain by Middle Triassic rocks.

Lower..... Mainland China (Poshan)—diaspore, underlain by Permian and Carboniferous rocks.

## Paleozoic:

## Permian:

Pennsylvanian(?)..... United States—diaspore in Missouri and Pennsylvania enclosed by rocks of Pottsville age, but diaspore may not have formed in Pennsylvanian Period.

Mississippian..... Mainland China (Yunnan)—boehmite, underlain by Devonian rocks.

U.S.S.R. (Tikhvin)—bauxite, underlain by Devonian rocks.

Mainland China (Kweichow)—diaspore, underlain by Ordovician rocks.

Devonian..... U.S.S.R. (Ural)—bauxite, in Middle and Lower Devonian rocks.

## Precambrian:

Late Proterozoic..... U.S.S.R. (Bokson, Siberia)—boehmite and diaspore(?).

## GEOGRAPHIC DISTRIBUTION

In a very general way, bauxite deposits are distributed according to geographic and geologic-age patterns. Gibbsite is more abundant in younger deposits than in older ones. The largest gibbsitic deposits are in the Caribbean region and in tropical or subtropical parts of South America, Africa, Asia, and Australia. Some gibbsitic deposits, such as those in Arkansas and Northern Ireland, occur north of the subtropical belt; however, these deposits may have formed at times when tropical climates extended much farther north and south than at present. Large deposits that are mainly boehmitic occur north of the subtropical belt in southern Europe, U.S.S.R., Turkey, and mainland China, and most diasporic deposits occur in areas now having temperate climates. Most boehmite deposits are of Mesozoic age, and most diasporic deposits are of Paleozoic age. The ages of these two types of deposits may be a more important factor in their origin than their apparent geographical relationships with cooler climates. Both types may have formed originally in warm wet climates and may have been initially gibbsite deposits.

Most of the world's large bauxite deposits are in countries that lack industrial capacity to consume large tonnages. For this reason much bauxite is transported considerable distances to plants in the United States, European countries, Canada, and Japan. A trend for the establishment of integrated aluminum industries near major bauxite deposits is developing, however, and Australia, Brazil, Guinea, Ghana, and India may become major producers of aluminum.

## MINERALOGY

*Gibbsite*.—The mineral gibbsite, termed "hydrargillite" in European literature, is commonly referred to as an alumina trihydrate,  $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ , because chemical analyses of the mineral indicate a ratio of one molecule of alumina ( $\text{Al}_2\text{O}_3$ ) to three molecules of water. The atomic structure of gibbsite, however, contains no water molecules, and all water detected by analyses is in hydroxyl (OH) form. Gibbsite is, therefore, more correctly an aluminum trihydroxide,  $\text{Al}(\text{OH})_3$  (Newsome and others, 1960, p. 62). Bayerite, a polymorphic form of gibbsite, has been made synthetically in the laboratory. Bayerite has been reported to occur in Hungarian bauxites (Gedeon, 1956), but thorough investigation has not verified this occurrence (Bárdossy, 1959, p. 6). Nordstrandite, a second polymorph of gibbsite, has been prepared synthetically in the laboratory (Van Nordstrand and others, 1956). Nordstrandite occurs in soils in west Sarawak (Wall and others, 1962, p. 264) and Guam (Hathaway and Slinger, 1965), but there are no published accounts of its presence in bauxite deposits.

*Boehmite*.—This mineral is commonly classed as an alumina monohydrate,  $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$ , but it is more accurately an aluminum oxide hydroxide,  $\text{AlO}(\text{OH})$ , because all water that appears in analyses is in hydroxyl form. Boehmite is present in minor amounts in many bauxite deposits that are dominantly gibbsite, and it is the most abundant mineral in many bauxite deposits in Europe, U.S.S.R., and mainland China.

*Diaspore*.—Diaspore has the same chemical composition as boehmite, but its atomic structure is more dense. Diaspore is present in minor amounts in many bauxite deposits in Europe (Bárdossy, 1959, p. 7) and the U.S.S.R.; it is the principal bauxite mineral in some deposits in mainland China and Turkey and occurs in clay deposits of Pennsylvanian age in Missouri, Pennsylvania, and Scotland.

*Corundum*.—Corundum ( $\text{Al}_2\text{O}_3$ ) is not common in bauxites. It occurs in the emery deposits in Turkey and on the islands of Samos and Naxos in the Aegean Sea. These deposits may be thermally metamorphosed bauxite deposits (Lapparent, 1946; Papastamatiou, 1964). Corundum has also been identified in bauxite deposits in Northern Ireland that are adjacent to dikes of igneous rock (Eyles and others, 1952, p. 34) and in pisolites in bauxite deposits in the U.S.S.R. (Kuzemkina, 1960); trace amounts of corundum have been identified by X-ray methods in samples from Arkansas bauxite (Keller, 1964, p. 130).

*Amorphous matter*.—Extremely fine grained or amorphous hydrated aluminous matter is present in many bauxite deposits. Such material has been called cliachite (Palache and others, 1944, p. 667); it presumably has a composition similar to gibbsite, but some of it may be more hydrated. In addition to cliachite, the names "sporogelite," "gibbsitogelite," "diasporogelite," and "alumogel" have been used for noncrystalline aluminous matter in bauxite (Bárdossy, 1959, p. 7). Allophane, an amorphous form of silica and alumina of variable composition (Ross and Kerr, 1934), is probably also present in many bauxites.

The terms for amorphous materials listed in the preceding paragraph presumably are applicable only to solid matter, and the presence of true alumina gels in bauxites is difficult to establish. Several authorities believe that many of the banded colloform structures in bauxites are the result of precipitation from hydrogels (Hose, 1960, p. 237; Jurkovič and Sakač, 1964, p. 260; Beneslavsky, 1962), and Vletter (1963, p. 1005) has observed jellylike masses in the overburden above bauxite at Onverdacht, Surinam. A gel material associated with gibbsite-bearing weathered rocks in Hawaii consists approximately of 4.9 percent  $\text{Al}_2\text{O}_3$ , 2.2 percent  $\text{SiO}_2$ , 0.3 percent  $\text{Fe}_2\text{O}_3$ , and about 90

percent water (S. H. Patterson, 1964). Its existence supports theories that very hydrous gels occur naturally and may be important in the formation of bauxite deposits.

#### MINERAL IMPURITIES

*Iron minerals.*—Hematite,  $\text{Fe}_2\text{O}_3$ , and goethite,  $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$  or  $\text{FeO}(\text{OH})$ , are the most abundant impurities in many bauxite deposits. They occur as nodules, concretions, and as finely disseminated forms intergrown with aluminous minerals. They are the chief cause of the red and brown colors that are characteristic of many bauxites. Magnetite,  $\text{FeFe}_2\text{O}_4$ , and ilmenite,  $\text{FeTiO}_3$ , are common in some bauxites, particularly those that have altered from basic igneous rocks. Maghemite,  $\gamma\text{Fe}_2\text{O}_3$ , has been identified in several bauxite deposits, and pyrite,  $\text{FeS}_2$ , and siderite,  $\text{FeCO}_3$ , occur in a few deposits.

Ferruginous boehmite in which iron is substituted for aluminum in a 1:1 ratio without any appreciable distortion of the crystal lattice occurs in bauxite deposits in Hérault, France (Caillère and Pobeguín, 1961). Ferruginous boehmite, boehmite, goethite, and hematite have also been made in the laboratory (Caillère and Hémin, 1961).

*Titanium minerals.*—The titanium minerals in bauxite include the primary minerals ilmenite,  $\text{FeTiO}_3$  or  $\text{FeO} \cdot \text{TiO}_2$ , rutile,  $\text{TiO}_2$ , and titaniferous magnetite; and the secondary minerals, anatase,  $\text{TiO}_2$ , and leucoxene,  $\text{TiO}_2$ , formed during weathering. Titaniferous hematite and sphene,  $\text{CaTiSiO}_5$  or  $\text{CaO} \cdot \text{TiO}_2 \cdot \text{SiO}_2$ , are also present in some bauxites. Anatase, ordinarily very fine grained or cryptocrystalline, has been reported in many bauxites and is probably even more common than recognized. In many bauxites it can be identified most satisfactorily by X-ray examination if the samples are first treated with acid to destroy gibbsite and heated to destroy kaolinite. The treatment is necessary because the X-ray reflections from these two minerals mask those of anatase (Brindley and Sutton, 1957, p. 395). Leucoxene commonly occurs as a coating on weathered ilmenite and as pseudomorphic replacements of ilmenite or other titanium-bearing minerals. All the X-ray reflections on photographs of nearly 200 samples investigated by Hartman (1959, p. 1401) matched either anatase or rutile, which suggests that leucoxene can be either one or a mixture of these two minerals.

*Clay minerals.*—The kaolin minerals—kaolinite,  $(\text{OH})_2\text{Si}_4\text{Al}_4\text{O}_{10}$ , halloysite,  $(\text{OH})_2\text{Si}_4\text{Al}_4\text{O}_{10}$ , and endellite,  $(\text{OH})_2\text{Si}_4\text{Al}_4\text{O}_{10} \cdot 4\text{H}_2\text{O}$ , the hydrated form of halloysite—are the most common clay minerals associated with bauxite deposits. They occur virtually pure in pockets, veins, and concretions and are intergrown with aluminum- and iron-bearing minerals. Kaolinite, the most common mineral in this group, is particularly abundant in deposits of Eocene age or older. Most of the kaolinite associated with bauxite is perfectly

crystallized. In some deposits, however, the atomic structure of kaolinite is disordered, and the mineral has been incorrectly referred to in many reports as the "fire-clay mineral" (Brindley, 1961, p. 65). Halloysite is most common in deposits younger than Eocene, but it also occurs in a few older deposits. Endellite is probably much more common in bauxite than is generally recognized because it converts to halloysite when dried in air at room temperature, and many investigators may have failed to preserve the natural moisture in samples until mineral identifications were made.

Minor amounts of chlorite occur in some bauxite deposits (Caillère and others, 1962; Gordon and others, 1958, p. 91), and this mineral is reported to be a major constituent of the weathered rock from which bauxite has formed in Surinam (Kersen, 1956, p. 317) and in Guinea (Lajoinie and Bonifas, 1961, p. 29-30). Probably much of the chlorite associated with bauxite deposits is an aluminous variety similar to that which occurs in high-alumina clays (Keller, 1964, p. 144).

*Silica minerals.*—Nearly all the silica in many high-grade bauxite deposits is in the form of kaolin minerals, but some deposits contain minor quantities of quartz, and in a few deposits quartz is a major impurity. Chalcedony is reported to occur in the transition zone between the parent material and the bauxite in some deposits (Kersen, 1956, p. 366; Jeremić, 1957, p. 152).

*Accessory minerals and other minor mineral impurities.*—Any resistant accessory mineral that occurs in the parent rock may remain in the bauxite, and a few minor secondary minerals may have formed with or after the bauxite. Accessory minerals in Arkansas bauxite include zircon, tourmaline, kyanite, and garnet; the secondary minerals barite and chamosite are scarce (Gordon and others, 1958, p. 91-92). Accessory minerals in British Guiana bauxites include zircon, tourmaline, rutile, and andalusite (Bleackley, 1961, p. 219).

#### ORIGIN

Geologists have been interested in the origin of bauxite for more than a hundred years; many theories have been proposed, and many problems remain unsolved. Older theories include those that bauxite formed by (1) precipitation from hot waters rich in aluminum salts, (2) the alteration of aluminous parent materials in sea water, (3) the deposition of aluminous materials in lakes, and (4) the leaching of aluminous rocks by naturally evolved acid. Most authorities (V. T. Allen, 1960; Bárdossy, 1958b, p. 283-284; Fox, 1932, p. 80-89; Gordon and others, 1958, p. 71-153; Harder, 1952, p. 35; Hose, 1960; and Zans and others, 1961; and many others) now agree that bauxite forms by weathering under conditions favorable for the retention of alumina and the leaching of other constituents of the

parent rock. Conditions favorable for the formation of bauxite, as listed by Harder (1952, p. 35), include, "(1) presence of rocks with easily soluble minerals yielding residues rich in alumina; (2) effective rock porosity, enabling easy access and free circulation of water; (3) normal to abundant rainfall alternating with dry periods; (4) vegetation, including bacteria, advantageously distributed; (5) available sources of appropriate solutions and precipitation agencies; (6) a tropical or at least a warm climate; (7) low to moderate topographic relief, allowing free movement of the water table but a minimum of erosion; and (8) long quiet periods in earth history."

Opinions differ among geologists regarding the origin of karst-, Mediterranean-, or pocket-type deposits. This type of bauxite typically occurs above carbonate rocks containing very little alumina. One group of geologists believes that the bauxite formed from residual material remaining after the carbonate rocks were leached, and another group believes that aluminous parent materials of the bauxite were transported to positions above the carbonate rocks. Problems regarding the origin of these types of deposits in the Caribbean Islands are summarized on page 42, and European deposits have been discussed by Bushinsky (1964b), Lisitzina and Patukhova (1964), and Weisse (1964).

Bauxite deposits have formed from almost every type of rock that contains alumina (Fox, 1932; Harder, 1952). Although bauxite forms more readily from rocks that are high in alumina and lack resistance to weathering than it does from resistant rocks that are low in alumina, parent materials are not as important as the intensity and duration of weathering. Very large deposits of bauxite have formed from quartzose rocks containing as little as 4 percent  $\text{Al}_2\text{O}_3$  in Australia (Loughnan and Bayliss, 1961, p. 209) and possibly from carbonate rocks containing only 0.03 percent  $\text{Al}_2\text{O}_3$  in Jamaica (Hose, 1961, p. 196). The more common rock types from which bauxite has formed are rich in feldspar, feldspathoids, micas, amphibole, pyroxene, or clay minerals. The rock types include syenite, granite, basalt, dolerite, schist, phyllite, slate, arkosic or argillaceous sandstone, shale, and clay.

The major chemical changes that take place during weathering and the formation of bauxite deposits are loss of silica, alkalis, and alkaline earths, and hydration and residual accumulation of alumina oxides. Titanium oxide and hydrated oxides and hydroxides of iron are commonly concentrated by the weathering processes that produce bauxite; therefore, iron- and titanium-bearing minerals and unleached silica-bearing minerals are the major impurities in bauxite. Chemical analyses of typical bauxites and their parent rocks illustrating these chemical changes are given in table 4.

TABLE 4.—Chemical analyses (in percent) of typical bauxites and their parent rocks

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Al <sub>2</sub> O <sub>3</sub> .....	21.11	59.8	17.29	59.00	12.18	29.15	62.44	14.01	32.92	62.96	18.20	60.53	12.36	37.03	60.19
SiO <sub>2</sub> .....	56.51	5.3	52.00	9.80	49.75	23.39	2.79	48.75	36.20	.40	60.97	1.42	51.27	5.83	1.30
Fe <sub>2</sub> O <sub>3</sub> .....	1.80	1.9	2.90	1.10	.03	23.68	2.05	3.44	13.55	.63	4.69	9.75	3.29	31.73	3.91
FeO.....	1.20		8.26	.97	9.88		1.32	10.80	.00	Trace			6.16		
MgO.....	.48		6.95	Nil	9.54	.05	.14	6.99	.25	.19	2.75		13.26	.06	
CaO.....	.91		8.80	Nil	11.79	.01		7.90	Trace	Trace	.63	.73	10.66	.19	.17
Na <sub>2</sub> O.....	9.13		2.81	.05	1.19	.08		2.52	.34	.55	.61		1.60		
K <sub>2</sub> O.....	6.34		.18	.07	.11	.07		.45	.00	Trace	3.01		.41		
TiO <sub>2</sub> .....	.50	2.0	.53	.70	4.60	4.07	.45	1.10	3.41	3.89	.98	2.21	.70	1.29	1.03
ZrO <sub>2</sub> .....	.04														
P <sub>2</sub> O <sub>5</sub> .....	.06		.01	.38	.06	Trace		.14	.13	.34			.11		
SO <sub>3</sub> .....	.15														
Cl.....	.39														
MnO.....	.24		.05	Nil	.48			.20	.00	Trace	.42				
H <sub>2</sub> O.....	.09							.10	.56	.74					
H <sub>2</sub> O+.....	1.50		.35	28.06	.35	18.25	31.96	3.53	12.97	30.12		25.59	.40	23.02	32.00
Loss on ignition.....		30.6									7.47				
Insolubles.....														.96	1.40
Total.....	100.45	99.6	100.13	100.13	99.96	100.07	99.83	99.93	100.33	99.82			100.22	100.11	100.00

- Nephelinesyenite ("gray granite"), Saline County, Ark. (Gordon and others, 1958, table 6, sample 5).
- "Granitic-textured" bauxite derived from nepheline syenite, Saline County, Ark.; average of 3 samples (Gordon and others, 1958, table 10, samples 8-10).
- Dolerite, Eagle Mountain, British Guiana (Harrison, 1934, p. 17).
- Leached bauxite from 3 (Harrison, 1934, p. 17).
- Hornblende schist, Yarrikita Hill, British Guiana (Harrison, 1934, p. 31).
- Primary laterite above 5 (Harrison, 1934, p. 31).
- Surficial bauxite above 6 (Harrison, 1934, p. 31).
- Solid hornblende basalt, chloritized and saussuritized, Nassau Mountains, Surinam (Kersen, 1956, p. 322, sample I).
- Residual kaolinitic clay above 8 (Kersen, 1956, p. 322, sample IV).
- Yellowish-white pisolitic bauxite above 9 (Kersen, 1956, p. 322, sample V).
- Green shale from the Voltaian System, Ghana (Cooper, 1936, p. 11, table I, sample 2047).
- Average of 17 samples of lateritic bauxite formed on shale of the Voltaian System, Mount Ejuanema, Ghana (Cooper, 1936, p. 18, table IV).
- Diabase, Mount Bougourou, Guinea (Lacroix, 1913, p. 290).
- Porous gibbsitic laterite in contact with 13 (Lacroix, 1913, p. 290).
- Compact superficial gibbsitic laterite above 14 (Lacroix, 1913, p. 290).

Very high grade deposits result when iron oxide is removed during or after the formation of some bauxites; the processes that remove the iron are not completely understood. Removal of iron and the formation of bauxite in peat swamps were suggested by Behre (1932) as an explanation for low-iron bauxite in Arkansas. This idea drew criticism from Harder (1933), who pointed out that many bauxite deposits could not have formed this way. Nevertheless, in Ghana and the Nassau Mountains of Surinam, low-iron bauxite occurs only in swampy areas rich in decaying organic matter (Cooper, 1936, p. 24; Vletter, 1963, p. 1005; Bracewell, 1962, p. 193). The role of humic acids and swamps in the formation of bauxite was discussed in a report on deposits in British Guiana (Harden and Bateson, 1963, p. 1307-1308); their role in the formation of laterite in the former Belgian Congo was discussed by Danse (1959). Organic matter in the upper part of bauxite deposits or overlying them has also been noted in France (Lapparent, 1930, p. 71-72), Yugoslavia (Wiesse, 1948, p. 16, 35, 41), and Greece (Aronis and Roch, 1953, p. 941). In Surinam and Hawaii, minor amounts of low-iron gibbsite formed under layers containing decaying organic matter in swamps during Recent geologic time (Kersen, 1956, p. 298-299, 367; S. H. Patterson, 1964). The role of decaying organic matter in the removal of iron is particularly apparent in Hawaii; there, gibbsite that formed in nonswampy areas is very ferruginous.

How bauxite minerals form after the removal of nonaluminous materials from parent rocks is not well understood. Gibbsite is abundant in young deposits and is the most common bauxite mineral formed during weathering. Gibbsite has directly replaced feldspar at many places; elsewhere, gibbsite appears to have passed through a colloidal or gel stage. Weisse (1948, p. 116) noted that in Europe gibbsite generally tends to occur in deposits of Tertiary age, boehmite in deposits of Mesozoic age, and diaspore in deposits of Paleozoic age. A marked increase in boehmite in older rock has been noted in Surinam (Kersen, 1956, p. 366); boehmite is concentrated in the older upper parts of deposits in Australia and similar relationships exist elsewhere. This age relationship suggests that with geologic time gibbsite is dehydrated and altered to boehmite and boehmite is further altered to diaspore. As both boehmite and diaspore occur in rocks that could not have been deeply buried and are not associated with igneous rocks, temperatures and pressures considerably above those that exist at the surface do not appear necessary for the formation of these minerals. Most occurrences of corundum are in metamorphosed rocks or in deposits that have been altered by igneous activity, such as those in Northern Ireland; thus,

high temperatures and pressures may be required for the formation of this mineral.

Kaolin is associated with nearly all bauxite deposits and is probably an intermediate stage between the parent rock and many bauxites, as has been suggested by V. T. Allen (1952, p. 685), Hose (1960, p. 240-241), Harden and Bateson (1963, p. 1307), Bushinsky (1964a), and many others. Some kaolin associated with bauxite, however, probably formed by resilication of bauxite minerals as suggested by Goldman (1955, p. 608-609); Gordon, Tracey, and Ellis (1958, p. 139-142); and V. T. Allen (1952, p. 677-680). The type of kaolin present varies considerably. Extensive deposits of transported kaolin underlie or are associated with some of the bauxites in Arkansas, the Coastal Plain area of Georgia and Alabama, British Guiana, Surinam, and elsewhere. Kaolinite is commonly the most abundant mineral in transported deposits of kaolin, but halloysite may also be present. Residual kaolin is associated with many of the world's extensive blanket-type deposits, such as those in Oregon, Australia, Guinea, many places in South America, and elsewhere. This kaolin occurs as replacement of feldspar and other aluminous minerals of the parent rocks and as fillings of veins and vugs. Though this kaolin is commonly a major constituent of the rock intermediate between the parent rock and the bauxite, it is ordinarily not as pure as most of the transported kaolins. Halloysite and endellite are commonly much more abundant in residual than in transported kaolin, particularly in tropical areas where bauxite is probably still forming.

## WORLD RESERVES AND POTENTIAL RESOURCES

In this report the term "reserves" is used as outlined by the Geological Survey and the U.S. Bureau of Mines (U.S. Geol. Survey, 1958, p. 59-60) as follows:

\* \* \* the term "mineral reserves" refers only to the material that in some degree has been inventoried in terms of commercial enterprise \* \* \* [and] can be mined, processed, and marketed without financial loss under the economic and technologic conditions prevailing at the time of the inquiry. \* \* \* It does not contain material of submarginal grade which, with improved economic conditions, may become a reserve, nor does it include off-quality material which cannot be treated satisfactorily under current technologic practices. \* \* \*

The use of materials classed as "marginal" and "submarginal" primarily awaits more favorable prices, whereas utilization of most of the material classed as "potential future sources" must await new—in some cases revolutionary—technologies as well. \* \* \* It is recognized, however, that in certain instances these materials contain some of the greatest potentialities for future sources of supply even though they cannot be tapped economically by existing mining and metallurgical methods.

For many countries, reserve estimates include measured, indicated, and inferred bauxite. The inclusion of inferred bauxite is necessary because in several countries—Guinea and Australia for example—the favorably located deposits are so large that the exploration of less favorably situated ones that is required to calculate proved and indicated bauxite has not been necessary. Also, the type of exploration required for many bauxite deposits does not provide adequate information for the assignment of deposits to indicated and inferred categories. The exclusion of crude estimates of inferred bauxite in areas of this type would result in misleading data. Inferred bauxite is included in reserves of other countries, such as France, where geological conditions suggest that large unexplored deposits exist at depth.

Potential bauxite resources include deposits that are too low in grade for present use, are in remote areas, or are at depths greater than the present limits of profitable mining. Potential resources include large deposits in remote areas, such as those in the Cameroon, that, in grade, are as good as, or better than, many currently used, but are of no value now because there is no feasible method of transporting them to the consumer. Many bauxites that are now considered to be potential resources will become reserves within a few years as supplies in currently mined areas are depleted, as markets develop in new areas, as transportation facilities in some countries are improved, and as cheaper methods of extracting alumina from low-grade bauxite are developed.

The accuracy of an estimate of world bauxite reserves and potential resources is limited because of the many problems involved. The problems include wide differences in thoroughness of geologic investigation, in methods of appraising deposits, and in reporting data; errors and incompleteness of chemical analyses and mineralogical determinations; lack of information on the type of tons used in compiling figures and whether the estimates are on a dry or in-the-ground basis; the existence of large tropical areas favorable for bauxite that have not been explored; and so forth. These problems are so great that two authorities concerned with world bauxite reserves have stated (Harder and Greig, 1960, p. 81) :

The estimation of world reserves of aluminum ores presents a variety of problems that are not encountered in most other ore calculations, and therefore most estimates reflect individual opinions. One of the problems in any such estimate is the variety of raw materials which contain appreciable amounts of alumina ranging from 20 percent or less to about 35 percent in clay, shale, anorthosite, nepheline, and leucite rocks; from 30 to 50 percent in aluminous laterite and low-grade bauxite; from 50 to 62 percent in medium- and high-grade bauxite and from 55 to about 75 percent in diaspore rocks.

Possibilities for errors are so great that most tonnage figures used in this report indicate, at best, only orders of magnitude. Furthermore, the exploration for bauxite is being carried on vigorously by companies in several countries, and estimates of bauxite reserves in many countries can be expected to increase considerably.

World bauxite reserves (table 5, pl. 1), including inferred bauxite, are estimated to be 5.8 billion tons, and potential bauxite resources are estimated to be 9.6 billion tons. The figure for reserves is similar to the world total of 5.2 billion tons estimated by Vidal (1963, p. 189) in 1960. Estimates of 1.1 billion tons of proved and 8.2 billion tons of indicated bauxite by Bardossy (1964, table 2) do not include inferred deposits and, therefore, are not as different from the figures in table 5 as the totals indicate. Estimates of approximately 10 billion tons for the world's bauxite by Daniels and Derbyshire (1959) include both reserves and potential resources estimated in this report at 15.4 billion tons. Much of the difference in these two estimates results from an increase in the published knowledge of some of the world's very large deposits during the last few years. The differences between the 1.6 billion tons estimated by Fischer (in U.S. Bur. Mines, 1953, p. III-60) for the world reserves and the present estimates is due chiefly to the discovery of the very large deposits in Australia and in Guinea, but relatively small discoveries have been made in several countries.

TABLE 5.—*Estimated total reserves and potential resources of bauxite, in millions of tons,<sup>1</sup> 1965*

[L, large; S, small; VS, very small]

	Reserves <sup>2</sup>	Potential resources
North America:		
United States:		
Arkansas.....	44	65
Southeastern States.....	1	25
Oregon and Washington.....		85
Hawaii.....		125
Total (rounded).....	45	300
Central America:		
Coasta Rica.....		150
Honduras and El Salvador.....		10
Panama.....		25
Total (rounded).....		200
Caribbean Islands:		
Dominican Republic and Haiti.....	85	40
Jamaica.....	600	400
Total (rounded).....	690	450
South America:		
Argentina.....		S(?)
Brazil.....	40	200
British Guiana.....	80	250
French Guiana.....	70	100
Surinam.....	200	350
Venezuela.....		103
Total (rounded).....	390	1,000

See footnotes at end of table.

TABLE 5.—*Estimated total reserves and potential resources of bauxite, in millions of tons,<sup>1</sup> 1965—Continued*

	Reserves <sup>2</sup>	Potential resources
<b>Europe:</b>		
Austria.....	1	-----
France.....	70	190
Greece.....	84	100
Hungary.....	150	(L)
Italy.....	24	S
Northern Ireland.....	-----	3
Poland.....	-----	S(?)
Rumania.....	20	-----
Spain.....	7	-----
U.S.S.R. (including Soviet Asia).....	<sup>3</sup> 300	(?)
Yugoslavia.....	200	100
Total (rounded).....	850	400
<b>Africa:</b>		
Angola.....	S(?)	S(?)
Cameroon.....	-----	1,500
Chad.....	-----	30
Congo (Léopoldville).....	-----	100
Ghana.....	290	110
Guinea.....	1,200	2,400
Malagasy Republic.....	-----	120
Mali.....	-----	550
Mozambique.....	2	-----
Nyasaland (Malawi).....	60	S(?)
Portuguese Guinea.....	-----	10
Southern Rhodesia.....	-----	2
Sierra Leone.....	30	M(?)
Tanzania.....	-----	S(?)
Total (rounded).....	1,580	4,800
<b>Asia:</b>		
China (mainland).....	150	1,000
India.....	64	190
Indonesia.....	20	10+
Iran.....	-----	S
<b>Malaysia:</b>		
Peninsular Malaysia.....	10	40
Sarawak.....	5	S
North Viet Nam.....	VS	-----
Pakistan.....	-----	15
Philippines.....	-----	28
Turkey.....	30	100
Total (rounded).....	280	1,400
<b>Oceania:</b>		
Australia.....	2,000	1,000
Fiji Islands.....	-----	1
New Zealand.....	-----	20
Palau Islands.....	5	40
Total (rounded).....	2,000	1,050
Total for world (rounded).....	5,800	9,600

<sup>1</sup> Most figures are in metric or long tons, dry basis; however, many estimates used in compilation failed to designate type of tons used and whether tonnages had been converted to dry basis.

<sup>2</sup> Chiefly measured and indicated reserves that in some degree have been inventoried in terms of commercial enterprise and could be used under economic and technological conditions existing in 1965, but inferred bauxite is included for some large deposits, such as those in Australia not fully explored.

<sup>3</sup> Estimate probably includes much low-grade bauxite that would be classed as potential resources in other countries, and possibly aluminous rocks other than bauxite.

Only tentative and temporary ratings of countries according to the size of their bauxite reserves and potential resources are possible. Many deposits are so large that accurate appraisals are unnecessary, and several large tropical areas favorable for bauxite have not been explored or have been examined by only cursory reconnaissance methods. Very large deposits in some countries will shift from

marginal and submarginal categories to reserves as deposits now being mined are depleted. Australia with approximately 2 billion tons and Guinea with 1.2 billion tons have the largest reserves; however, deposits in Guinea considered to be potential resources because of their remote location amount to 2.4 billion tons, and potential resources in Australia may be about 1 billion tons. The total resources of bauxite in the two countries are, therefore, approximately equal. Jamaica, with reserves of 600 million tons and potential resources that are nearly as large, is now the world's leading bauxite producing country. Cameroon and mainland China each have at least 1 billion tons of bauxite and possibly more than twice this total that must now be considered as potential resources—the Cameroon deposits because of their remoteness, and those in China because some are unfavorably situated and most consist of mixtures of boehmite and diaspore, from which aluminum is difficult to extract.

Next in importance are Ghana, Yugoslavia, Surinam, and U.S.S.R., which have 200–300 million tons reserves each. Bauxite reserves in Hungary are estimated to be 150 million tons, and potential resources in this country may be large. Brazil and India now have relatively small known reserves, but bauxite is widely distributed in both countries, and when all localities are adequately explored both may rank much higher as sources of bauxite. Countries that have 50–100 million tons of bauxite reserves include Nyasaland (Malawi), Greece, France, British Guiana, French Guiana, and Dominican Republic and Haiti. The United States, with approximately 45 million tons of reserves, ranks with the countries possessing minor bauxite reserves. The 300 million tons of submarginal resources in the United States exceeds the submarginal resources of many countries, but included in this figure is rock so low in grade that it would not be classified as bauxite in several countries having large high-grade deposits. Also, the potential bauxite resources in the United States have been investigated more thoroughly than those in several other countries, and probably several countries that now appear to have small potential resources have much larger low-grade deposits that have not been investigated.

The chemical composition of bauxite varies with mineral content, purity, methods of preparation, and grade. Very little information has been published on the chemical composition of bauxite that is produced in several countries. Principal reasons for this are that deposits are not uniform and the grade of the bauxite varies with type of selective mining employed and the processing before use. Most analyses of typical bauxites listed in table 6 are representative of the grade used in making aluminum; several of these analyses are of washed or otherwise beneficiated bauxite.

TABLE 6.—Principal chemical constituents of typical bauxites (in percent)

Location and material analyzed	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	H <sub>2</sub> O	Loss on ignition
Australia:						
Cape York—washed (Evans-1959, p. 54).....	52.3	2-4				
Cape York—unwashed (Loughnan and Bayliss, 1961, p. 214).....	30-50	10-32	9-26	1.2-2.6	10.6-26.6	
British Guiana (Pollard and Barron, 1954, p. 39):						
Mackenzie.....	60.45	6.79	1.25	1.9		29.61
Ituni.....	59.03	5.34	2.85	2.38		30.40
Courantyne.....	51.08	13.09	8.16	3.13		24.54
France (Harder and Greig, 1960, p. 71):						
Red.....	55-58	3-6	20-25	2.5-3.5	12-16	
White or gray.....	60-70	8-16	4-12	2-3	12-14	
Ghana (Cooper, 1936, p. 18, 21):						
Mount Ejuanema.....	52-61	.6-2	9-18	1.5-2.2	25-26	
Afioh.....	48-53	.4-1.7	15-21	1.1-2	27-30	
Greece:						
Parnassus-Helikon—average of 30 analyses (Aronis, 1956).....	57.61	3.05	22.80	2.75		
Eleusis-Mandra district (Aronis, 1953, p. 197).....	45-47	.07-2	21-31	2.7		8.6-13.72
India:						
Pokhra Pat, Bihar (Roy Chowdhury, 1958, p. 84).....	60-62	.40-.48	3.9-4.7	8.9-10.8		
Jabalpur, Madhya Pradesh (Fox, 1932, p. 138).....	55-65	1.2-2.7	1.8-10.1	3.2-8.8	25.4-28.1	
Indonesia (Bemmelen, 1941, p. 631):						
Bintan.....	53	2.5	13.5	1.2		
Jamaica (Bracewell, 1962, p. 115):						
Alumina Jamaica Ltd.....	50.61	.75	18.91	2.59	27.14	
Reynolds Jamaica Mines Ltd.....	49.08	.69	20.47	2.51	27.25	
Kaiser Bauxite Co.....	50.53	1.64	19.75	2.67	24.63	
Malaysia (Harder and Greig, 1960, p. 74):						
Johore.....	56-58	4-6	6-8	.5-1.0	29-31	
Surinam (Schols, 1953, p. 21):						
Paranam.....	55.0-55.3	3.7-4.0	9.7-10.3	2.0-2.2		28.9-29.0
Onverdact:						
Metal grade.....	58.4-59.2	4.4-4.6	3.8-4.7			
Chemical grade.....	60.8-60.9	3.8-4.0	1.9-2.3			
Guinea:						
Iles de Los (Moyal, 1956, p. 1059).....	54	6.0	11		28	
Boké and Fria (Harder and Greig, 1960, p. 73).....	40-55	1-5	10-30			
United States—Arkansas district:						
Granular bauxite (Gordon and others, 1958, p. 105).....	59.7	5.4	1.1	3.7		29.7
Pisolitic bauxite (Gordon and others, 1958, p. 105).....	61.2	1.8	1.9	2.3		32.1
Metal-grade (U.S. Dept. Commerce, 1956, p. V-1).....	48.0-53.0	10.0-15.0	4.0-6.0	1.7-2.7		28.0-30.0
U.S.S.R.:						
Soverouralsk (Shabad, 1960, p. 15).....	49-59	3-7				
Tikhvin (Latus and others, 1938, p. 28).....	42-48	10-20	15-25	2.0-2.5		
Yugoslavia (Franotovic, 1955, p. 81-82).....	51-53	4.0	17-26	2.5-3.5	13-27	

## NORTH AMERICA

## UNITED STATES

The bauxite deposits in the United States occur along the boundary between the Gulf Coastal Plain and the Interior Highlands in central Arkansas (pl. 2); in the Coastal Plain province in Georgia, Alabama, and Mississippi; and in the Valley and Ridge province in Georgia, Alabama, Tennessee, and Virginia (pl. 2). Large deposits of low-grade ferruginous bauxite occur in Oregon and Washington,

and bauxitic saprolites and soils occur on four of the Hawaiian Islands. Diaspore occurs with kaolinitic clays in central Missouri and central Pennsylvania. Diaspore has been considered as part of the potential resources of bauxite for many years; therefore it is discussed on pages 39-40 and also in the section "High-Alumina Clay."

#### ARKANSAS DISTRICT

The largest deposits of high-grade bauxite in the United States are in an area of about 275 square miles in Saline and Pulaski Counties, Ark. (fig. 3). Arkansas bauxite is associated with a nepheline syenite intrusive (fig. 4) which during early Tertiary time stood as low hills above a plain sloping gently southeastward. Thick bauxite deposits formed on the hills by weathering processes, erosion, and slumping, and by subsequent weathering of heterogeneous material. Bauxite also accumulated as sedimentary deposits near the edge of the plain. After a change in physiographic conditions, the whole area was covered by a series of flat-lying sand and clay beds, and only the tops of the hills remained exposed. Consequently, the largest deposits, and those with the least overburden, are nearest the present nepheline syenite exposures. No commercial deposits are known more than a few miles south and east of the syenite.

The Arkansas bauxite district was thoroughly explored by the U.S. Geological Survey and the U.S. Bureau of Mines in a joint drilling program from 1941 to 1945. The reserves of bauxite in the Arkansas deposits were estimated in January 1950 by the U.S. Geological Survey (Gordon and others, 1958, p. 168) as follows:

Grade of ore <sup>1</sup>	Average content (percent)		Reserves (millions of tons)	
	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	In deposits 8 ft thick or more	In deposits 5 ft thick or more <sup>2</sup>
I-----	59	6	4. 0-5. 5	5. 0-6. 3
II-----	52	10	38. 9	48. 9
III-----	50	9	70. 7	88. 9

<sup>1</sup> Specifications: I, Prewar—not more than 7 percent SiO<sub>2</sub>, nor more than 3 percent FeO. II, War Production Board requirements—not more than 15 percent SiO<sub>2</sub>; not more than 6 percent FeO; not less than 40 percent Al<sub>2</sub>O<sub>3</sub>; and not less than 32 percent "available alumina." III, Same as II, but no restriction as to iron content. The tonnage listed under each specification is cumulative; that is, grade II includes grade I, and grade III includes grades I and II.

<sup>2</sup> Tonnage figure of reserves in deposits 5 ft thick or more also includes the figure for reserves 8 ft thick or more;

#### SOUTHEASTERN UNITED STATES

The bauxite deposits of the Southeastern United States occur in the Coastal Plain and the Valley and Ridge provinces (pl. 2). Most deposits in the Coastal Plain province lie along an arc, referred to as the "outer line" (Bridge, 1950, pl. 1), that extends from central Georgia into southern Alabama and thence to eastern and northeastern Mississippi (pl. 2). A few deposits similar to those on the

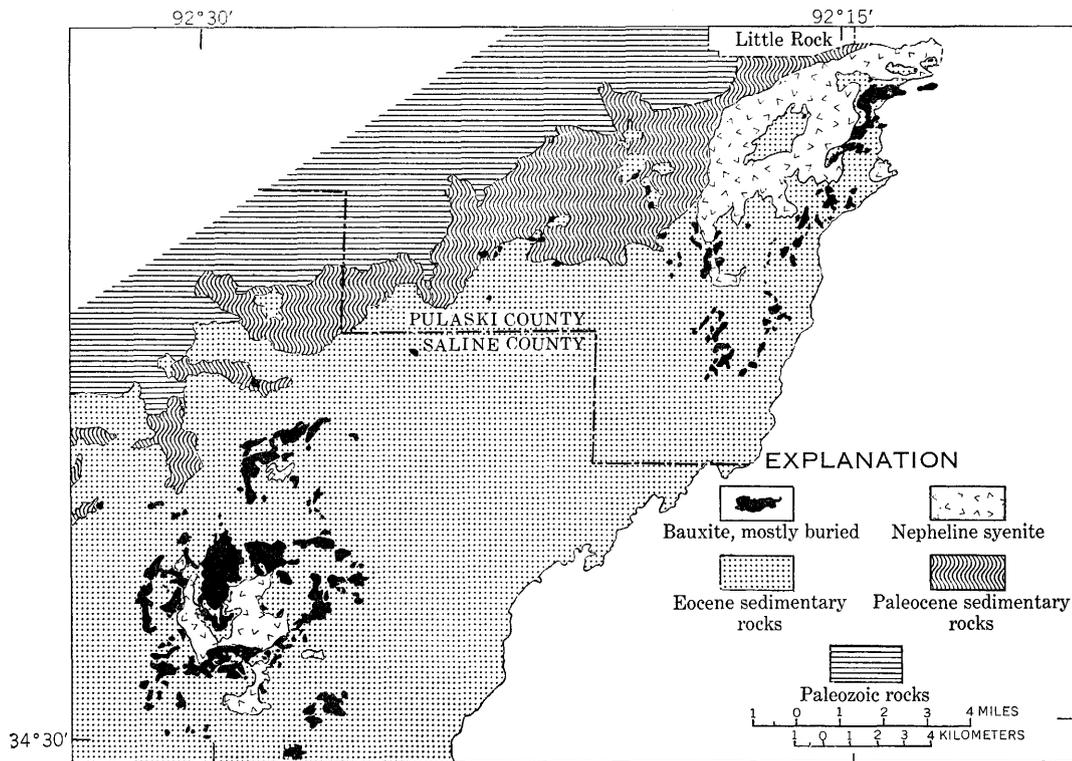


FIGURE 3.—Generalized geology of the Arkansas bauxite district. Adapted from Gordon, Tracey, and Ellis (1958).

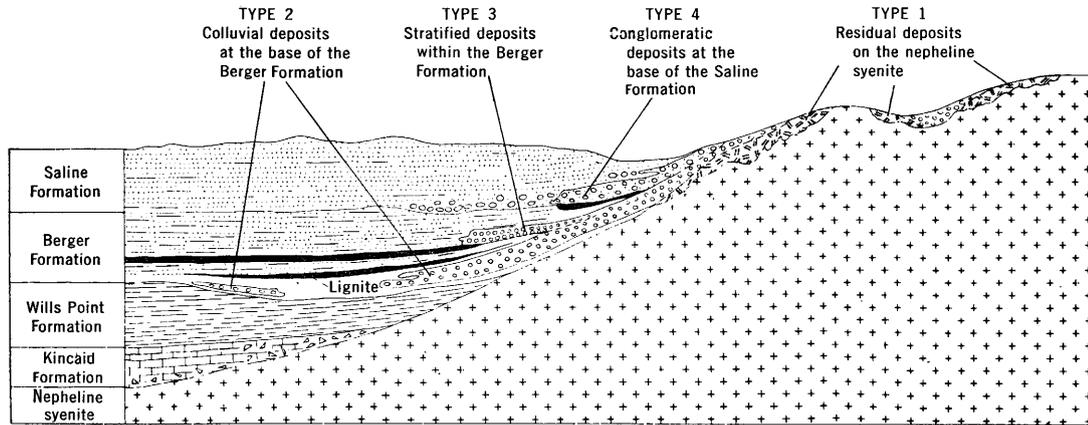


FIGURE 4.—Principal types of deposits in the Arkansas bauxite district. Adopted from Gordon, Tracey, and Ellis (1958, fig. 33).

Coastal Plain extend as far inland as the "inner line" (pl. 2) in western Tennessee, northwestern Alabama, and central Georgia. The "inner line" is the approximate inland boundary of the coastal plain that existed in Paleocene and Eocene time when the bauxite formed (Overstreet, 1964, p. A7). Deposits of the Valley and Ridge province extend discontinuously from northeastern Alabama north-northeastward through adjacent parts of Georgia and Tennessee into northeastern Tennessee and west-central Virginia (Bridge, 1950).

The only Coastal Plain areas in which bauxite has been produced in recent years, and in which the reserves are sizeable, are the Eufaula district in eastern Alabama and the Andersonville district in west-central Georgia (pl. 2). The bauxite occurs within large flat-lying kaolin bodies, into which it grades both vertically and laterally. The deposits are overlain by sand and clay of early Tertiary age. Bauxite from these districts typically contains 56 percent alumina, 13 percent silica, and less than 1 percent iron. Because of the low iron content, the bauxite is now used in the refractory and chemical industries. The bauxite bodies in the Eufaula district extend over areas ranging from about one-half acre to nearly 4 acres and are 3-50 feet thick. Most bodies contain less than 10,000 long tons; average size is about 3,000 long tons. Those in the Andersonville district, Georgia, however, are larger and thinner and may be as much as 10 acres in extent, with an average thickness of 8 feet.

The bauxite deposits in the Valley and Ridge province are sinkhole fillings related to an old land surface that is now largely eroded. These deposits are small, scattered, and difficult to discover. Most of the deposits contained only a few thousand tons, but 200,000-300,000 long tons has been mined from some scattered ore bodies. Bauxite was mined in Virginia intermittently during the 1940's and in Georgia during the 1950's, but known deposits in the Valley and Ridge province are nearly depleted.

Reserves of measured, indicated, and inferred bauxite in deposits 5 feet thick or more and under less than 50 feet of overburden in the Southeastern United States were estimated in 1944 as 1,739,000 long tons (Bridge and others, 1947, p. 223). In addition, as much as 5 million tons was believed to be present under overburden more than 50 feet thick (Bridge and others, 1947, p. 221) but was not considered as reserves. All estimates of bauxite reserves in the Southeastern States were made during World War II. In recent years, several companies have been carrying on exploration programs in the Eufaula, Ala., district, and the Andersonville and northwest Georgia districts in search for refractory- and chemical-grade bauxite. Many deposits have been found, and the reserves in the Southeastern States

are now more than twice the 1.7 million tons estimated by Bridge, Dorsh, and Weitz in 1947 and may be several times this figure.

Accurate estimates of reserves of bauxite deposits in the United States in 1965 could not be made because of lack of precise information regarding the following: (1) Size of new deposits discovered by aluminum and bauxite companies that have conducted active exploration programs since 1950 (possibilities of new discoveries are limited, but new deposits containing a few million tons may have been found) and (2) amount of bauxite that must be reclassified from "potential future sources" to "reserves" owing to (a) advancements in profitable mining of deposits that are less than 8 feet thick (the cutoff used in 1950 estimates), and (b) use of low-grade Arkansas ores by blending them with high-grade ores, some of which are imported, to obtain a plant feed that has an average of 50 percent alumina and a low ferrous iron content, generally much less than 6 percent. This blending practice in effect removes the iron cutoff of the Arkansas ore and permits the use of some bauxitic clay.

#### RESERVES

The reserves of bauxite in the United States are estimated to be approximately 45 million long tons. This figure is based on the assumption that the estimates of 48.9 million long tons of grade I and II bauxite in Arkansas deposits and of 1.7 million tons in the Southeastern States deposits were accurate when they were made. A further assumption is that most of the reserves depleted by 1963 (22.3 million tons mined in Arkansas and 1.2 million tons in the Southeastern States) since estimates were made have been nearly replaced by the following: (1) Discovery of new deposits, (2) improvements in the profitable mining of thin deposits and the removal of excessive overburden, and (3) use of some high-iron, grade III bauxite and bauxitic clays by blending with both domestic and imported high-grade bauxite.

#### POTENTIAL BAUXITE RESOURCES

The potential future sources of bauxite in the United States, other than reserves, are chiefly in (1) large low-grade bauxitic clay deposits and deeply buried and thin bauxite deposits in the Arkansas, Eufaula, Ala., and Andersonville, Ga., districts; (2) ferruginous bauxite deposits in Oregon and Washington, and (3) deposits of low-grade ferruginous bauxite in soils and weathered basalts on Kauai and Maui, Hawaii. Diaspore deposits occur in Missouri and Pennsylvania, but they have little potential value for use as bauxite.

The potential future sources of bauxite in Arkansas consist of low-grade bauxite, bauxite in beds that are too thin or too deeply buried

to be mined profitably under existing economic conditions, and bauxitic clays that are associated with the bauxite deposits. Material in these categories includes the 55.5 million tons of bauxitic clay and approximately half of an estimated 24.7 million tons of submarginal bauxite (Malamphy and others, 1948, p. 9), plus certain recently discovered deposits of unknown size. The total amount of bauxite in the potential future resources category in Arkansas is estimated to be approximately 65 million tons.

Low-grade gibbsitic bauxite is associated with the bauxite now being mined in the Eufaula, Ala., and Andersonville, Ga., districts. Most of these low-grade deposits contain much kaolinite, and many of them are covered by overburden 50 feet thick or more. The amount of low-grade bauxite and bauxitic clay, containing 40–51 percent  $\text{Al}_2\text{O}_3$ , in the Andersonville district, Georgia, was estimated by Zapp (1965, p. 21) to be more than 23 million tons. The total bauxite in the Eufaula district, Alabama, is estimated at more than 5 million tons (S.A. Allen, 1949, p. 84).

The low-grade ferruginous bauxite deposits of Oregon and Washington, which have formed by the weathering of basalts of the Columbia River Group, are in a belt of hills in the western parts of the two States. Large deposits occur in the Portland and Salem areas, Oregon, and small deposits occur near Estacada and Mehama, Oreg. (Corcoran and Libbey, 1956, fig. 1; Libbey and others, 1945; J. V. Kelly, 1947), and near Kelso and Cathlamet, Wash. (Livingston, 1966, p. 59).

Ferruginous bauxite in Washington and Columbia Counties, Oreg., was estimated at 10 million tons (U.S. Dept. Interior Press Notice 122147, Dec. 10, 1945), and possibly as much as 20 million tons (L. G. Bell, written commun., 1945). This bauxite, according to the average of many samples, is 34.68 percent  $\text{Al}_2\text{O}_3$ , 23.12 percent  $\text{Fe}_2\text{O}_3$ , 9.48 percent  $\text{SiO}_2$ , 4.85 percent  $\text{TiO}_2$ , 0.176 percent  $\text{P}_2\text{O}_5$ . In the Salem Hills area, Polk and Marion Counties, according to Corcoran and Libbey (1956, p. 1), "an aggregate area of approximately 1,200 acres is underlain with gibbsitic laterite which has an average thickness of 14.4 feet and a weight-volume factor estimated to be 17 cubic feet per ton in place. Analyses of drill hole samples give a weighted average of 35.0 percent  $\text{Al}_2\text{O}_3$ , 6.7 percent  $\text{SiO}_2$ , 31.5 percent  $\text{Fe}_2\text{O}_3$ , 6.5 percent  $\text{TiO}_2$ , and 20.2 percent L.O.I." This area contains approximately 44 million long tons of ferruginous bauxite.

The resources of ferruginous bauxite in southwestern Washington have not been estimated, but Livingston (1966, p. 59) stated that the "Maximum thickness of bauxite is probably between 15 and 20 feet, and it covers well over 2,000 acres." Valentine and Huntting (1960, p. 14–15) noted that the Aluminum Co. of America is reported to

have proved substantial tonnages of ferruginous bauxite in Washington. At places the deposits in Washington are overlain by silt overburden as much as 30 feet thick. In such places, resource estimations are more difficult to make; also, the cost of mining the deposits would be greater.

The total quantity of low-grade ferruginous bauxite in Washington and Oregon is probably 75–100 million tons; in table 5 it is rounded to 85 million tons.

Deposits of low-grade ferruginous bauxite occur on the islands of Kauai and Maui, Hawaii, and very low grade bauxitic material occurs on the islands of Hawaii and Oahu. The bauxite, of Pleistocene and Recent age, is in soils and saprolite weathered from basalt and is composed mainly of the mineral gibbsite, which is in the form of aggregates, concretions, veinlets, and vesicle fillings scattered throughout the saprolite and soil. The deposits on Kauai were investigated by four companies (Abbott, 1958, p. 844), but no attempts to mine the deposits have been made. The very low grade aluminous material on the island of Hawaii consists of ferruginous allophane clays containing minor quantities of gibbsite (V. T. Allen and G. D. Sherman, 1965, p. 95). This material formed on a thin layer of volcanic-ash rock overlying hard rock. The area in which these deposits occurs is now under cultivation and has far more value as cropland than as a potential source of aluminum.

The deposits on Kauai are estimated to contain 110 million short tons and consist of 25.9 percent  $\text{Al}_2\text{O}_3$ , 4.7 percent  $\text{SiO}_2$ , 39.4 percent  $\text{Fe}_2\text{O}_3$ , and 6.7 percent  $\text{TiO}_2$  (S. H. Patterson, 1962, p. 2). The deposits in West Maui contain 9 million tons and consist of 38.0 percent  $\text{Al}_2\text{O}_3$ , 7.0 percent  $\text{SiO}_2$ , 22.0 percent  $\text{Fe}_2\text{O}_3$ , and 4 percent  $\text{TiO}_2$ ; and the deposits in East Maui contain 22 million tons and consist of 33.4 percent  $\text{Al}_2\text{O}_3$ , 6.6 percent  $\text{SiO}_2$ , 31.4 percent  $\text{Fe}_2\text{O}_3$ , and 6.7 percent  $\text{TiO}_2$ . The total potential resources of low-grade bauxite in Hawaii amount to approximately 125 million long tons. Methods of beneficiating this low-grade bauxite have been investigated, and, according to Calhoun and Hill (1962, p. 1), 70.0–78.8 percent of the alumina in this bauxite can be extracted by the Bayer process. Furthermore, recovery of alumina can be increased to 79.5–85.5 percent of the amount present by calcining and caustic desilication.

The total potential resource of bauxite in the United States is approximately 300 million long tons.

Diaspore-bearing clays of central Pennsylvania are part of a widespread kaolinitic flint-clay bed associated with the Mercer coal (Middle Pennsylvanian) in the Pottsville Formation. The diasporic irregularly replaces kaolin as small veinlets and nodulelike masses

(Foose, 1944, p. 574). Diaspore-bearing clay bodies are irregularly distributed and are commonly lenticular. The resources of diaspore mixed with kaolin clay, containing 40–70 percent  $\text{Al}_2\text{O}_3$  and 5–25 percent  $\text{Fe}_2\text{O}_3$ , probably amount to 5–6 million tons (Conley and others, 1947, p. 11).

The diaspore deposits of Missouri are small and are scattered through the north-central Ozark region in Crawford, Franklin, Gasconade, Maries, Osage, and Phelps Counties. Diaspore occurs commonly as nodules and pisolites in "burley" and "nodular" clay that fills sinkholes in limestone of late Paleozoic age. High-grade material contains approximately 69 percent  $\text{Al}_2\text{O}_3$ , 12 percent  $\text{SiO}_2$ , and 1 percent  $\text{Fe}_2\text{O}_3$ . No estimates of reserves have been published, but the diaspore deposits are not large and are being depleted rapidly.

Diaspore clays are used extensively in making firebrick, and the largest and best grade deposits are earmarked for use by the refractory industry. However, this industry uses low-iron clay, and deposits containing more than 5 percent  $\text{Fe}_2\text{O}_3$  have been bypassed in mining. The quantity of diaspore clay in the Clearfield district, Pennsylvania, containing 5 percent  $\text{Fe}_2\text{O}_3$  or more and 45–50 percent  $\text{Al}_2\text{O}_3$  was estimated during World War II to be 5 million tons (Conley and others, 1947, p. 4). Probably appreciable tonnages of high-iron clay have been discovered in Pennsylvania since these estimates were made. The quantity of high-iron diaspore clay in Missouri has not been estimated, but the total in both Pennsylvania and Missouri is probably more than 10 million tons.

The value of diaspore clay as a source of aluminum is decreased by its occurrence and mineral content. The deposits are commonly in lenses, containing only a few thousand tons, that are deeply buried; therefore mining would be costly. No alumina plants using bauxite in the United States are designed to process diaspore. A new or modified plant would be required if alumina were extracted from diaspore, and any process used, such as the lime-soda-sinter process (Conley and others, 1947), would probably not be competitive with the Bayer or modified Bayer process now used with bauxite.

#### MEXICO

Bauxitic materials reportedly occur at several places in Mexico. A bauxite deposit occurring under gypsum at a locality midway between the cities of Tampico and San Luis Potosi has been declared a national reserve by the Mexican government (Wilmot and others, 1960, p. 236). High-iron lateritic weathered rocks have been investigated in the States of Veracruz, Puebla, Oaxaca, and Tabasco. Though much gibbsitic and kaolinitic rock that contains 30–40 percent  $\text{Al}_2\text{O}_3$  is present, no commercial bauxite had been found by

1959 (Salas, 1959, p. 10), and the results of more recent exploration in parts of Tabasco believed to contain exploitable deposits (Baker and others, 1962, p. 6) have not been released.

### CENTRAL AMERICA

Bauxite deposits occur at several places in Central America. Potential deposits have been investigated in Costa Rica, Honduras, and Panama. Conditions appear to have been favorable for the formation of bauxite in much of Central America, and valuable deposits may be found when remote areas are fully explored.

#### COSTA RICA

Bauxitic rocks and soils in Costa Rica have been investigated by four American companies (Wilmot and others, 1957, p. 246). Much of the exploration has been in the region south of San Isidro del General, near the Cordillera de Talamica. Very little information is available, but deposits have been estimated to contain 50 million tons (Wilmot and others, 1959, p. 220). A subsidiary of the Aluminum Co. of America reportedly has found 150 million tons of bauxite, having an average  $Al_2O_3$  content of 35 percent, in the Valle del General area south of San José (S. M. Anderson, 1964, p. 70).

#### HONDURAS

Reconnaissance prospecting for bauxite has been done in Honduras. No geologic reports on the possibilities of bauxite deposits in Honduras have been published; however, one estimate places the combined potential bauxite resources of Honduras and El Salvador at 10 million tons (Bardossy, 1964, table 2).

#### PANAMA

Bauxite occurs in weathered rocks and lateritic soils at scattered localities in the provinces of Chiriqui and Veragus. The deposits were investigated by two United States companies. Accurate estimates of the total amount of bauxite have not been made, but potential resources probably amount to at least 25 million tons (Wilmot, 1960, p. 21). No information regarding the grade of these deposits is available.

### CARIBBEAN ISLANDS

Bauxite was discovered in the Caribbean Islands in 1942, when Jamaican soil was being analyzed to find ways to improve its fertility. Attention then focused on the possibility that bauxite might be found on the other Caribbean Islands. Bauxite was recognized in Haiti in 1943 by Reynolds Mining Corp., and in the Dominican

Republic in 1944 by both the Reynolds Mining Corp. and the Aluminum Corp. of America (Schmedeman, 1948, p. 78). The long delay in the discovery of these deposits was due chiefly to the fact that they are earthy and soillike and very different from the aluminum ore that had been used prior to World War II. Mining in Jamaica is on such a large scale that the country now leads the world in bauxite exports. Bauxite is also mined in the Dominican Republic and in Haiti.

The bauxite deposits in the Caribbean Islands occur in depressions in nearly pure limestone. Some depressions are circular and range in diameter from 50 feet to 10 miles. Others are trough shaped; one large trough deposit extends for nearly 20 miles (Schmedeman, 1948, p. 80). The purity of the limestone and the restriction of the deposits to depressions has caused much difference of opinion concerning the origin of the bauxite. According to Schmedeman (1948, p. 79), Hartman (1955, p. 746), Hill (1955, p. 687-688), and Hose (1963, p. 66-68), the bauxite formed by the alteration of residual material from a considerable thickness of limestone. Other geologists (Chubb, 1963; Goldich and Bergquist, 1948, p. 109; Zans and others, 1961; Burns, 1961; and W. C. Kelly, 1961) have suggested that aluminous parent materials were transported to positions above the limestone. The origin of a thin radioactive phosphatic band occurring locally between the bauxite and the underlying limestone is also problematical (Eyles, 1958) and further complicates an understanding of the history of the bauxite.

#### DOMINICAN REPUBLIC AND HAITI

Two types of aluminous lateritic soil occur on the slopes of the Sierra de Bahoruco in the Dominican Republic (Goldich and Bergquist, 1947, p. 53). The deposits highest in alumina content underlie pine-covered savannas in limestone valleys 4,000-5,000 feet above sea level. The soil and weathered materials that has accumulated in these valleys is reddish brown, low in silica, and concretionary. The second type of soil occurs on limestone terraces and flats at lower altitudes. This soil is dark-brown friable silica-rich laterite.

The most valuable deposits in the Dominican Republic are in the Aceitillar area, about 18 miles northeast of Pedernales, Barahona Province. These deposits overlie nearly pure limestone of middle and late Eocene age. They consist chiefly of gibbsite; boehmite contents ordinarily are low. Kaolinite, which contains nearly all the silica present, occurs in amounts of 5 percent or less in eight of the nine deposits in the area (Goldich and Bergquist, 1947, p. 69). Hematite is the principal iron mineral, and the average content of this mineral is 20 percent. Some deposits are as much as 30 feet thick, and one deposit contained as much as 2 million tons.

Low-grade deposits occur in the Bucan Polo district, 9 miles northeast of Pedernales (Goldich and Bergquist, 1947, p. 80-81). The deposits are at an altitude of 1,250 feet, average 10 feet in thickness, and cover 200 acres. The content of boehmite is much higher in the deposits in this district than in the Aceitillar deposits.

The largest bauxite deposits in Haiti are on the Rochelois Plateau on the Southern Peninsula southwest of Miragoane; other deposits occur near (1) Beaumont, in the Massif de la Hotte; (2) Savane Zombie, in the Massif de la Selle; and (3) Savane Terre Rouge, on the plateau northwest of Gonaïves (Goldich and Bergquist, 1948, p. 63, 108-109). The bauxitic material is finely divided reddish-brown, yellowish-brown, and buff lateritic soil. Gibbsite, boehmite, hematite, and goethite are the principal minerals. Clay minerals, chiefly kaolinite, and compounds of titanium, manganese, and phosphorus are minor constituents; quartz, zircon, and magnetite are accessory minerals. Gibbsite and boehmite together compose about 60 percent of the deposits, but their proportions vary considerably. Some parts of the deposits are 25 percent gibbsite and 35 percent boehmite, and others are as much as 45 percent gibbsite and only 13 percent boehmite (Goldich and Bergquist, 1948, p. 82).

Total reserves of bauxite in the Dominican Republic and Haiti are estimated to be 80-85 million tons (Metal Bull., 1958, p. 22; Goldich and Bergquist, 1948, p. 85), and additional potential resources are probably as much as 40 million tons (Wilmot, 1960, p. 21). The deposits in the Aceitillar area, Dominican Republic, contain 46 percent  $\text{Al}_2\text{O}_3$ , less than 3 percent  $\text{SiO}_2$ , and approximately 20 percent  $\text{Fe}_2\text{O}_3$  (Goldich and Bergquist, 1947, p. 83). The average composition of deposits on the Rochelois Plateau, Haiti, is 46.8 percent  $\text{Al}_2\text{O}_3$ , 3.4 percent  $\text{SiO}_2$ , 2.8 percent  $\text{TiO}_2$ , 21.9 percent  $\text{Fe}_2\text{O}_3$ , 0.6 percent  $\text{P}_2\text{O}_5$ , and 0.5 percent  $\text{MnO}_2$ , and the loss on ignition is 24.1 percent (Goldich and Bergquist, 1948, p. 85).

#### JAMAICA

The largest bauxite deposits in Jamaica are in Manchester, St. Ann, St. Elizabeth, and Trelawny Parishes (Zans, 1953, p. 322), and smaller but workable deposits occur in St. Catherine, Clarendon, St. James, and Portland Parishes (fig. 5). Small deposits of bauxite occur in Hanover and Westmoreland Parishes in the western part of the island. Large deposits of low-grade kaolinitic bauxite are associated with the bauxite in St. James and St. Catherine Parishes. Most of the deposits occur above the white limestone of middle Eocene to early Miocene age, which extends over more than half the island.

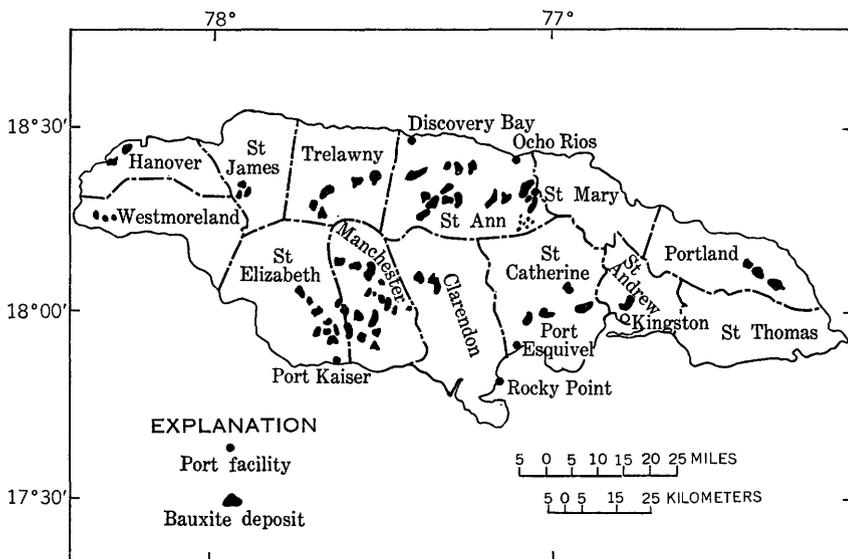


FIGURE 5.—Location of principal bauxite deposits in Jamaica.

The bauxite deposits vary in size from less than an acre to several acres and in places are so close together that they form a nearly continuous blanket that extends as much as 20 miles. The deposits range in thickness from a few inches to more than 100 feet (Schmedeman, 1948, p. 80), and the overburden at most places is only about 2 feet thick. Bodies that are less than 5 feet thick are generally considered to be too thin for profitable mining. The average mined thickness is about 25 feet. Individual ore bodies range from a few thousand to tens of millions of tons.

Gibbsite is the principal bauxite mineral present, and it is chiefly in grains of less than 1 micron size (Hill, 1955, p. 680). Minor amounts of boehmite occur in some deposits, and in a few places this mineral constitutes as much as 20 percent of the bauxite. Though the bauxite is high in iron, only small quantities of hematite are present in most deposits, and much of the iron in the bauxite is probably in amorphous form. Kaolinite and halloysite, the principal clay minerals, occur in only minor amounts in the bauxite that is mined, but they are abundant in the low-grade high-silica bauxite. Much of the titanium present is probably cryptocrystalline, but small grains of rutile, anatase, leucoxene, titanomagnetite, and ilmenite are present.

Bauxite mined in Jamaica is remarkably uniform in composition, and most of it contains approximately 50 percent  $Al_2O_3$ . It is now in silica and high in iron oxide (table 6). The economic advantage

resulting from the uniformity in composition and low silica content of the bauxite is partly offset by the fine particle size of the bauxite and the iron minerals, which makes beneficiating virtually impossible. The bauxite is not suitable for use in abrasive, refractory, or chemical products because the gibbsite cannot be profitably separated from the iron.

In 1957 the Chief Minister (Manley, 1957) announced that Jamaican bauxite reserves amount to 500–600 million tons. Much exploration has been done since 1957, and reserves now are at least 600 million tons, though considerable tonnage has been mined. The amount of noncommercial-grade bauxite is of the same order of magnitude as the reserves (Manley, 1957). Inasmuch as research is progressing on the use of noncommercial grade, this bauxite has to be considered as a potential resource. Total reserves and potential resources in Jamaica are approximately 1 billion tons.

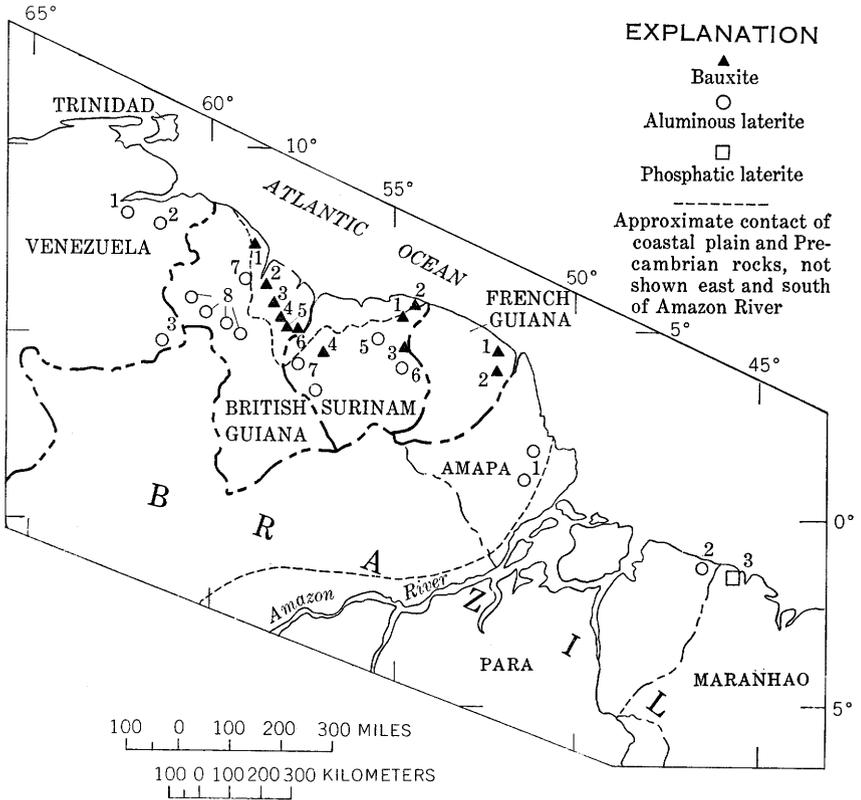
#### PUERTO RICO

Aluminous laterite, saprolite, and soil occur on remnants of a high-level peneplain in east-central Puerto Rico (Briggs, 1960), and bauxitic clay occurs in sinkholes in limestone in the north-central part of the island (Hildebrand, 1960). The clays in the sinkholes consist of mixtures of boehmite, quartz, anatase, kaolinite, and halloysite. Eight samples analyzed (Hildebrand, 1960, p. B371) contain 23.2–40.7 percent  $\text{Al}_2\text{O}_3$ , 18.7–36.9 percent  $\text{SiO}_2$ , 10.8–18.3 percent  $\text{Fe}_2\text{O}_3$ , 1.0–1.8 percent  $\text{TiO}_2$ , and 0.66–2.5 percent  $\text{P}_2\text{O}_5$ . None of this material appears to be sufficiently high in  $\text{Al}_2\text{O}_3$  to have value as bauxite.

#### SOUTH AMERICA

The principal bauxite deposits in South America occur in two large regions. Deposits have been mined most extensively in British Guiana and Surinam, where they are scattered throughout a narrow belt (fig. 6) extending approximately along the contact between Precambrian crystalline rocks and the sedimentary beds of Tertiary and Quaternary age that form the coastal plains. Deposits that have not been mined are also present in continuations of the belt in Venezuela, French Guiana, and the northern part of Brazil, and in plateau areas south of the belt in Venezuela, British Guiana, and Surinam. The second region of major deposits is in the plateaus and low mountain areas in central and southern Brazil, where deposits have been mined on a small scale for several years.

The association of bauxite and laterite deposits in northern South America with old planation levels has been recognized for a number of years (Meulen, 1948), and the major seaward-sloping levels were

**Venezuela**

1. Uputa region
2. Nuria region
3. Gran Sabana region

**British Guiana**

1. Pomeroon district
2. Essequibo district
3. Mackenzie district
4. Ituni district
5. Kwakwani district
6. Canje district
7. Blue Mountains
8. Pakaraima Mountains

**Surinam**

1. Surinam River region (Paranam, Onverdacht, Rorac, and Para River deposits)
2. Moengo and Rickanau deposits
3. Nassau Mountains district
4. Bakhuis Mountains district
5. Browns Mountains
6. Lely Mountains
7. Wana Wiero Hills

**French Guiana**

1. Roura deposits
2. Kaw Mountains deposits

**Brazil**

1. Amapa region
2. Piria River region
3. Ilha da Trauíra

FIGURE 6.—Location of principal bauxite deposits in northern South America.

identified by Kersen (1956, p. 255–317) and Bleackley (1961, p. 224–226). Deposits on the upper levels are on plateaus at altitudes of 350 to over 2,200 feet. Bauxite and laterite in the Nassau, Lely, Wana Wiero, and Bakhuis Mountains in Surinam and in the Blue and Pakaraima Mountains in British Guiana occur on plateaus. More than one sloping surface occurs at intermediate altitudes. One of these old planation levels, termed the “high-level” by Kersen (1956, p. 267–299), slopes toward the coast from an altitude of 180

feet down to about 90 feet. The deposits at Moengo and Paranam in Surinam occur along this old planation surface. Most bauxite deposits in British Guiana and some in Surinam are associated with still lower planation levels, and a few dip below sea level. The lower level deposits in British Guiana are overlain by sedimentary rock of the Corentyne Series consisting chiefly of white sand (Bleackley, 1964, p. 41). Some deposits at lower levels in Surinam have no overburden, and others are overlain by the Coropina and Demerara Formations, which consist chiefly of clay.

Bauxite deposits in northern South America formed in more than one way. Most deposits in the region are underlain by clay consisting chiefly of kaolinite, but halloysite is also present. Several authorities agree that the kaolin layers are the immediate parent material of the bauxite, and Kersen (1956, p. 326) has presented mineralogical evidence supporting this theory, including electron micrographs of leached kaolin crystals and photomicrographs of kaolinite partly altered to gibbsite. Some of the kaolin deposits have been transported and others have formed in place. Bauxite associated with transported kaolin probably formed by a two-stage process as suggested by Moses and Mitchell (1963). The first stage included deep weathering of metamorphic and igneous rocks bordering the coastal lowlands, and the transportation and deposition of the kaolinitic weathering products to the coastal lowlands. The second stage was the desilication of the kaolinitic materials and the formation of bauxite. Bauxite that formed in place from residual clay on granite occurs at the Montgomery mine in the Mackenzie, district, British Guiana (Kersen, 1956, p. 301-305), and a deposit in the southern part of the Ituni Group in British Guiana is underlain by a thin brown clay retaining relict texture of the underlying gabbro (Pollard and Barron, 1954, p. 13). Most bauxite deposits on plateaus have formed in place, inasmuch as they grade downward into hard rock through saprolite and incompletely weathered zones. Gibbsite has also formed below accumulations of decaying organic matter in swamps during Recent geologic time (Kersen, 1956, p. 367-368). The parent material of this gibbsite is an illite clay in the Coropina Formation of Pleistocene age, and halloysite occurs as an intermediate stage in the formation of gibbsite.

#### ARGENTINA

Low-grade bauxite and aluminous laterites occur in Missones Province in the northern part of Argentina. Small tonnages have been mined for use in water purification (Bracewell, 1962, p. 189). The possibilities of extracting alumina from the laterites by a sulfuric

acid process were considered in 1964 (Light Metals and Metal Industry, 1964). No estimates of the quantity of aluminous laterite in Argentina or accurate information on its grade are available.

#### BRAZIL

Bauxite deposits occur in several parts of Brazil. One group of deposits lies in a belt south of the northern coast in the Federal Territory of Amapá and the States of Pará and Maranhão (fig. 6). Other deposits are scattered throughout the States of Bahia, Espírito Santo, Rio de Janeiro, Minas Gerais, and São Paulo (fig. 7).

*Bahia*.—Bauxite deposits reported to be of the Mediterranean type (Abreu, 1962, p. 558) occur in the municipality of Correntina, near the boundary of Goiás and Barro do Mendes. These deposits contain 68–69 percent  $\text{Al}_2\text{O}_3$  and 12–14 percent combined water. Boehmite is probably the principal bauxite mineral present. No estimates of the resources of bauxite in Bahia have been published, and the total amount may be very large.

*Espírito Santo*.—Bauxite deposits occur on the Laginha property in the municipality of Mimoso do Sul. The bauxite is in spherical and ellipsoidal masses and tubular forms, and it occurs in the weathered mantle above gneiss. The washed material from these deposits is 60 percent  $\text{Al}_2\text{O}_3$ , 7 percent  $\text{SiO}_2$ , 2.8 percent  $\text{Fe}_2\text{O}_3$ , and 30 percent  $\text{H}_2\text{O}$  (Abreu, 1962, p. 557). According to one conservative estimate (Abreu, 1962, p. 557), these deposits contain 400,000 tons of bauxite; an older estimate of the bauxite in Espírito Santo is 1 million tons (Teixeira, 1942).

*Federal Territory of Amapá*.—Numerous occurrences of bauxitic laterite were located during reconnaissance work in the Territory of Amapá (Moraes, 1959). The deposits are as much as 30 feet thick and occur on two peneplain levels, at altitudes of about 150 and 600 feet. Most of the bauxitic material is in areas of metamorphosed Precambrian rocks, but rocks of Paleozoic and Tertiary ages in the lower Amazon Valley also alter to laterite (Towse and Vinson, 1959, p. 133). The laterite consists chiefly of gibbsite, goethite, hematite, and kaolin. According to the analyses published in one report (Towse and Vinson, 1959, p. 131), all the material is low grade; however, one sample listed by Abreu (1962, p. 559) contained 58.9 percent  $\text{Al}_2\text{O}_3$ , which suggests that some excellent bauxite could be washed from material present in this territory.

*Minas Gerais*.—The largest and most valuable bauxite deposits in Brazil are in the State of Minas Gerais. Deposits occur in the municipalities of Ouro Preto, Nova Lima, Mariana, Nepomuceno, Descoberto, Diamantina, Sêrro, and Poços de Caldas. Most deposits are on the undulating surface of the Poços de Caldas plateau and on

the slopes of the surrounding mountains. The plateau is at an altitude of approximately 4,000 feet, and the deposits on the mountain slopes are at altitudes of as much as 5,500 feet.



FIGURE 7.—Location of the principal bauxite districts in central and southern Brazil.

Bauxite deposits in a district near the city of Poços de Caldas have been described by Webber (1959a, b) and probably are typical of deposits at several places in Minas Gerais and São Paulo. The bauxite deposits in this district have formed by tropical weathering of a younger group of rocks consisting of phonolite, phonolite porphyry, nephelite syenite, and nephelite cancrinite syenite, and an older group consisting of eudialyte nephelite syenite and gneissoid eudialyte nephelite syenite. Bauxite occurs as (1) fragmental and nodular surface rubble commonly less than 3 feet thick formed by weathering of massive bauxite and the residual concentration of nodules as interstitial clay is removed; (2) massive material consisting of slightly iron-stained gibbsite that is friable and may be porous, cellular, or massive and that is formed by direct bauxitization of country rock; (3) nodular material in a clay matrix consisting of nodules and irregular aggregates of gibbsite disseminated through kaolin; and (4) replacement material consisting of irregular masses as much as several feet across that probably formed by complete bauxitization of clay.

Deposits at Ouro Preto and Nova Lima have weathered from schistose rocks, those at Sêrro from amphibolite, and those at Descoberto from gneiss (Abreu, 1962, p. 552-553). In the Morro do Cruzeiro deposits near Ouro Preto, the richest bauxite is in a pellet layer less than 1 meter thick. This pellet layer is underlain by an irregular zone of clay and pellets that, in turn, grades downward into schist through a layer of clay (W. T. Pecora and M. R. Klepper, written commun. 1944).

Reserves and resources of bauxite in Minas Gerais outlined by Abreu (1962, p. 552-557) are as follows: (1) Ouro Preto, 1.5 million tons plus unestimated deposits at three other localities; (2) Nova Lima, 2-4 million tons; (3) Mariana, 5 million tons; (4) DÍamantina, very large reserves suitable for use in refractory products (52 percent  $\text{Al}_2\text{O}_3$ , 25 percent  $\text{SiO}_2$ , 2 percent  $\text{Fe}_2\text{O}_3$ , and 21 percent loss on ignition); (5) Sêrro, large reserves; and (6) Poços de Caldas, estimates for a number of deposits range from 35 million to 150 million tons. Since Abreu made his estimates, the deposits at Sêrro have been investigated by da Costa (1962); they are now reported to contain a probable reserve of 20 million tons and possibly more than 100 million tons (Mining Jour., 1964b, p. 225). Abreu's estimate for Ouro Preto is probably also far too conservative, inasmuch as these deposits are now mined to supply a plant in this district, and a plant would not have been constructed if only 1.5 million tons of bauxite was present. Abreu (1962, p. 559) listed the chemical compositions, in percent, of six bauxite samples as follows. (The samples presumable were washed.)

	1	2	3	4	5	6
Al <sub>2</sub> O <sub>3</sub> -----	64.4	56.7	62.3	60.9	63.2	60.7
SiO <sub>2</sub> -----	.4	10.8	3.1	3.5	5.1	1.7
Fe <sub>2</sub> O <sub>3</sub> -----	1.6	4.9	4.8	3.0	11.5	6.1
TiO <sub>2</sub> -----					2.2	
H <sub>2</sub> O-----	33.0	26.3	30.3	32.6		30.5

1, 2. Fazenda Recreio, Poços de Caldas.

3. Fazenda Motuca, Nova Lima.

4. Moro do Cruzeiro, Ouro Preto.

5. Moro do Cruzeiro, Ouro Preto, average of 38 analyses.

6. Fazenda Gentio, Sêrro.

*Pará and Maranhão.*—Large deposits of bauxite have been discovered in lower Amazon Valley in Pará (Abreu, 1962, p. 551). The bauxite occurs as concretions in clayey materials weathered from sedimentary rocks of Tertiary and Quaternary age. Washing would be required to obtain an acceptable grade bauxite from these deposits. Much of the bauxitic material contains about 40 percent Al<sub>2</sub>O<sub>3</sub>, but some of it contains as much as 60 percent Al<sub>2</sub>O<sub>3</sub> after washing (Abreu, 1962, p. 511).

Phosphatic bauxites occur on Ilha da Trauíra and along the Maracassume River in Maranhão. Parts of these deposits are massive, and parts are porous, pisolitic, and ferruginous. They are estimated to contain 10 million tons of rock consisting of 20–30 percent P<sub>2</sub>O<sub>5</sub> and 30–40 percent Al<sub>2</sub>O<sub>3</sub> (Oliveira, 1943).

*Rio de Janeiro.*—Bauxite nodules that contain as much as 61 percent Al<sub>2</sub>O<sub>3</sub> (Abreu, 1962, p. 559) have been discovered at Barra do Piraí. No estimate of the amount of bauxite in this area is available, and reserves are probably not large.

*São Paulo.*—Bauxite occurs in the municipalities of São Paulo, São Bernardo do Campo, Águas da Prata, and Mogí-das-Cruzes. Most deposits are on part of the Poços de Caldas plateau and are similar to those in Minas Gerais (Teixeira, 1937). Total measured and inferred reserves in São Paulo amount to nearly 6 million tons (Abreu, 1962, p. 558).

*Reserves and potential resources in Brazil.*—A number of estimates of bauxite deposits in Brazil have been published; however, many deposits have been only partly explored, and others have been investigated by private interests and the results are not available. Total bauxite reserves in Brazil are assumed to be approximately 40 million tons, which is a rounded total of the estimated measured and inferred reserves in Minas Gerais and São Paulo (Abreu, 1962, p. 552–558). A realistic estimate of the potential bauxite resources of Brazil is not available; however, potential resources probably total at least 200 million tons, the figure given by Bracewell (1962, p. 189) for Brazil's total reserves of metal-grade bauxite.

## BRITISH GUIANA

Nearly 100 separate bauxite occurrences have been discovered in a belt approximately 15 miles wide that extends from the Pomeroon River south and southeast to the Corentyne River (Bleackley, 1961), and large aluminous laterite deposits occur in the Pakaraima Mountains, and others occur in the Blue Mountains and elsewhere. The Pomeroon district in the northwestern part of the bauxite belt (fig. 6) is 30 miles from the coast, and the Canje district near the Corentyne River is approximately 80 miles inland. The principal deposits in this belt occur in (1) the Essequibo district east of the Essequibo River near Bartica; (2) the Mackenzie district along the Demerara River, including those at the Montgomery, Nieu Haarden, and Maria Elizabeth mines 5–8 miles south of Mackenzie, the Christianburg district on the east side of the river, and the Topira and Warababaru districts 37 miles south of Mackenzie; (3) the Kwakwani district west of the Berbice River; and (4) the Ituni district east of the Berbice River. Other scattered occurrences of bauxite extend from the principal belt northwestward to the Venezuelan border; but none have been developed, and all are probably small.

The bauxite deposits range in size from a few tons to several million tons. Deposits 20 feet thick are common; a thickness of 40 feet is about maximum. Several types of bauxite occur in these deposits, and probably the most common form resembles breccia and consists of soft gibbsitic fragments cemented by a harder matrix of kaolinitic material. The common succession of rocks associated with the bauxite was described by Pollard and Barron (1954, p. 13). From the surface downward it is (1) "White Sand Series" consisting of white sand underlain by a unit of clay, sand, and lignite beds; (2) bauxite; (3) kaolin; (4) micaceous clay; and (5) crystalline rocks consisting of granite, granodiorite, and diorite, which are intruded locally by dolerite and epidiorite.

According to Hose (1961, p. 189–190), the following four zones can be distinguished in most British Guiana bauxite deposits:

1. A lenticular layer 6–10 feet thick consisting of pink bauxite concretions. This layer is commonly cut by veins of white, pink, and gray kaolinitic clay.
2. A zone of soft earthy yellow or red bauxite 3–5 feet thick, which is commonly cemented by ironstone into hard compact bands.
3. A zone 2–3 feet thick consisting of hard, pink, yellow, or white nodules in a soft, white or yellow gibbsite matrix.
4. A layer 6–9 feet thick consisting of white or pink stalactitic bauxite in a soft clay matrix. This clay matrix grades directly into the residual kaolinitic clay below.

The mineralogy of deposits at the Montgomery, Nieu Haarden, Maria Elizabeth, and Warababaru mines was investigated by Brindley and Sutton (1957), who used X-ray methods to analyze samples taken at 2-foot vertical intervals. Gibbsite is the principal mineral in all deposits, and some samples contain as much as 95 percent of this mineral. Boehmite is present at all localities; the vertical distribution of this mineral is irregular. Most deposits contain only 1–3 percent boehmite. The highest concentration of boehmite is at the Maria Elizabeth mine, where layers containing 5 percent are common and one sample contained 15 percent. Anatase is uniformly distributed in amounts of 1–2 percent in nearly all the bauxite. Goethite occurs in all deposits but is rarely more than 5 percent, except at Warababaru, where 5–15 percent is present in some layers. Hematite occurs in the bauxite at the Nieu Haarden and Warababaru mines, and one layer contains 10 percent of this mineral.

Very large deposits of aluminous laterite and ferruginous bauxite have been discovered in remote parts of the Pakaraima Mountains (Bateson, 1961). The most extensive deposits are on plateaus at altitudes of 2,200–2,500 feet. Others are at 1,200–1,500 feet and at about 3,000 feet. The aluminous laterites have been investigated in three areas. Deposits in the Kopinang River basin are reportedly 10 feet thick and cover 300 square miles; the average composition of samples from 35 pits is 40.4 percent  $\text{Al}_2\text{O}_3$ , 6.1 percent  $\text{SiO}_2$ , 27.6 percent  $\text{Fe}_2\text{O}_3$ , and 2.1 percent  $\text{TiO}_2$ . Deposits in the Sukabi River basin cover 250 square miles, and the average composition of samples representing the upper 16 feet from three test pits is 34.4 percent  $\text{Al}_2\text{O}_3$ , 16.5 percent  $\text{SiO}_2$ , 25.8 percent  $\text{Fe}_2\text{O}_3$ , and 1.9 percent  $\text{TiO}_2$ . Deposits in the Kamarang-Kukui areas in the basin of the upper Mazaruni River cover 400 square miles, and the average composition of samples representing the upper 14 feet in 16 test pits is 33.3 percent  $\text{Al}_2\text{O}_3$ , 20.3 percent  $\text{SiO}_2$ , and 19.7 percent  $\text{Fe}_2\text{O}_3$ .

Aluminous laterite deposits cap the surface of the Blue Mountains in several places (Bleackley, 1964, p. 85–87). These mountains and a smaller highland nearby, called the Oko Mountains, are about 5 miles west of the Essequibo River. The surface of these highlands slopes about 15 feet per mile from an altitude of 1,000 feet in the south to 400 feet above sea level in the north. Aluminous laterite covers an area of 5–7 square miles, and the amount present is approximately 50 million tons. This area was prospected by Harvey Aluminum Inc., and several patches of laterite containing an average of 50 percent  $\text{Al}_2\text{O}_3$  were located.

Bauxite mined in British Guiana is high grade and is uncommonly low in iron oxide (table 6). Because of its low iron content,

much of it is particularly suited for use in abrasives and refractories (Stockley, 1958, p. 50), and much of the refractory-grade bauxite consumed in the United States and Canada is imported from British Guiana.

Reserves of the Demerara Bauxite Co., Ltd., were reported to be 65 million tons in 1954 (Pollard and Barron, 1954, p. 46), and at that time the company had an extensive exploration program underway. This same report (p. 49, 52) mentioned that the Berbice Co. had "succeeded in locating and to a large extent drilling some 18 orebodies" and that Harvey Aluminum Inc. had found some deposits south of Bartica. Accurate estimates of the total bauxite in British Guiana have not been published. It is probably at least 80 million tons (Wilmot, 1960, p. 21) but may not be as much as the 150 million tons previously estimated (S. H. Patterson, 1963).

Statements published by Bateson (1961) and supported by Dr. R. B. McConnell, Director of the British Guiana Geological Survey Department (McConnell, in Bateson, 1961), indicate that the bauxite in the Pakaraima Mountains covers 1,000 square miles and is generally more than 10 feet thick. These dimensional data and analyses of samples from scattered pits led the author to assume that low-grade bauxite resources in the Pakaraima Mountains were on the order of 1 billion tons (S. H. Patterson, 1963, p. B159). The results of more recent investigations reported by Dr. R. B. McConnell (in Beard, 1963, p. 83) indicate that the Pakaraima Mountain deposits do not contain commercially important bauxites. Accordingly, the 1 billion ton estimate was erroneous, and whether any of the bauxite in this region should be classed as resources is questionable.

Potential resources of bauxite in British Guiana are large, but no accurate estimates have been made. These resources include the following aluminous materials:

1. Bauxitic clay containing less than 50 percent gibbsite (Bleackley, 1964, p. 16) associated with bauxite deposits of the kind now mined. Deposits of this clay are known to be large.
2. Bauxite occurring under overburden exceeding thicknesses that can be mined profitably under existing economic conditions. Such deposits are known to exist in the Canje district (Bleackley, 1964, p. 83), and they undoubtedly occur elsewhere.
3. Deposits too high in iron oxide, too remote, or too low in grade to be of value at present. These deposits include those on Blue Mountain, at Yurowa near the Canje district, and the large low-grade laterite in the Pakaraima Mountains.

Deposits near the Corentyne River, presumably including those in the Canje and Yurowa districts, reportedly contain 200 million tons

of bauxite (Mining World and Eng. Rec., 1962, p. 16). These deposits and those on Blue Mountain are the basis of a tentative estimate of 250 million tons for the potential bauxite resources in British Guiana.

#### FRENCH GUIANA

The most valuable bauxite deposits in French Guiana occur in the nearly flat topped Kaw and Roura Mountains, which extend from near the village of Roura to near Guissambourg (Annales Mines, 1955, p. 3-4). Other deposits occur on the Mahury plateau, which is near the coast and about 10 kilometers southeast of Cayenne (DeMunck, 1956, p. 4), and, reportedly, at St. Laurent-Mana, in the Orapu basin, in the Approuague basin, in the Inery Mountains, and in the Mts. de l'Observatoire near the mouth of the Ouanary River (Bracewell, 1962, p. 191). Deposits in the Kaw Mountains are at altitudes of 750-1,100 feet, those in the Roura Mountains at 600-750 feet, and those on the Mahury plateau at about 450 feet.

The bauxite occurs as lateritic cappings on flat-topped uplands. Some of the laterite deposits are as much as 60 feet thick, but the average thickness is about 18 feet (Annales Mines, 1955, p. 12). The deposits in the Kaw Mountains have weathered from schists and greenstones and are separated from fresh rock by a thick zone of deeply weathered rocks rich in clay minerals. Finely crystalline gibbsite is the principal bauxite mineral, but small amounts of boehmite occur locally (Annales Mines, 1955, p. 7), and noncrystalline aluminous materials are probably also present. Only small amounts of quartz occur in the bauxite, and most of the silica present is in clay minerals. Iron is chiefly in the form of goethite and stilpnosiderite, but X-ray analysis of one sample, presumably from the Kaw Mountains, showed that it was chiefly gibbsite and hematite (Keyser, 1959, p. 980, fig. 4). Minor amounts of rutile, brookite, anatase, ilmenite, zircon, and tourmaline have also been identified in the bauxite.

A considerable number of samples, representative of the 150 million tons of laterite in the Kaw Mountains, were analyzed by the Bureau Minier Guyanais (Annales Mines, 1955, p. 10-12). Results of this work outlined 42 million tons of bauxite with a chemical composition of 41.5 percent  $\text{Al}_2\text{O}_3$ , 1.7 percent  $\text{SiO}_2$ , 30 percent  $\text{Fe}_2\text{O}_3$ , 4 percent  $\text{TiO}_2$ , and 0.8 percent other oxides, and a 22 percent loss on ignition. Much additional prospecting has been done by the Société Guyanaise de Bauxite in the Kaw Mountains, and deposits recently discovered at Lucifer Mountain reportedly contain 10 million tons of bauxite (Baker and others, 1963). Total reserves of bauxite in French Guiana are now estimated to be 70 million tons

(Eng. Mining Jour., 1959a, p. 207). No realistic figure is available for the potential bauxite resources, including low-grade bauxite in the Kaw Mountains and deposits elsewhere; however, the total amount of this material is probably at least 100 million tons.

#### SURINAM

Extensive bauxite deposits in Surinam are associated with planation levels at intermediate altitudes in a belt 20–30 miles from the coast (fig. 6), and other deposits occur on plateaus farther inland. Only deposits at intermediate levels have been mined, but several deposits on plateaus have been prospected. The important Onverdacht, Paranam, Rorac, and Para bauxite deposits are along the Surinam River and its tributary Para River. The Moengo and Rickanau deposits are in the northeastern part of the country. The largest plateau deposits are in the Nassau and Bakhuis Mountains; other deposits are in the Wintiwaai, Hokahin, Lely, and Stoffbroekoe Mountains, according to the Geology and Mines Bureau of Surinam (Schols, 1954, p. 26–27; 1957, p. 22–23).

The deposits mined differ in size; some are small, some large. The Moengo Hill deposit, now mined out, was 3 miles long and half a mile wide and yielded 10 million tons of bauxite. Most deposits are 10- to 20-foot-thick cappings on low flat-topped hills and are overlain by only a thin veneer of soil and sedimentary rock. At Paranam, however, some deposits are overlain by sand and clay as much as 80 feet thick. Overburden more than 100 feet thick has been reported (Harder and Greig, 1960, p. 69). Most deposits rest on transported kaolin that overlies weathered schist and other Precambrian rocks, but a few rest on coarse sand.

Bauxite in the deposits mined has several different lithologies. They are as follows:

1. Dense homogeneous pink to yellowish-white bauxite, some of which is fine grained and some of which consists of gibbsite crystals as much as 4 mm in size. In this type, small vugs filled with white clay are common.
2. Laminated bauxite consisting of alternating layers of gibbsite and kaolin or dense and porous forms of gibbsite.
3. Porous bauxite containing vugs of various sizes and shapes, some of which retain the outline of leached quartz grains.
4. Very thin-walled cellular bauxite consisting chiefly of crystalline gibbsite.
5. Bauxitic clay containing concretions consisting chiefly of dense fine-grained bauxite resembling kaolin, and scattered cylindrical concretions as much as 1.5 cm in diameter.

Gibbsite is the principal bauxite mineral in all the Surinam deposits, but all deposits contain some boehmite and minor quantities of other minerals (Kersen, 1956, p. 317-364). Boehmite contents are about 10 percent in deposits on plateaus and 1 percent in the extensively mined deposits at intermediate levels. Small amounts of kaolinite and halloysite are present in nearly all the bauxite. The titanium is chiefly in cryptocrystalline granular aggregates of anatase. The iron oxide is chiefly in magnetic hematite, but small amounts of goethite are present. Traces of the heavy minerals staurolite, tourmaline, andalusite, rutile, and zircon also occur in the bauxite.

Except for deposits in the Nassau Mountains (described by Doeve (1957) and Kersen (1956, p. 256-264)), bauxite deposits on plateaus in Surinam have only been reconnoitered. The bauxite in the Nassau Mountains occurs as laterite capping plateaus at altitudes of 1,500-1,800 feet. The laterite layer varies considerably in thickness; it is as much as 36 feet thick in places and is completely missing elsewhere. The deposits formed in place and are overlain by only a thin soil; they grade downward through a transition zone, residual clay, and weathered bedrock into fresh hornblende-rich basalt. Dense homogeneous, porous spongelike, laminated, pisolitic, clayey, and brecciated types of bauxite are present. The transition zone between the bauxite and clay ranges from a few inches to about 3 feet in thickness. The lower part of this zone contains nuclei of bauxite and scattered quartz grains. The upper part is chiefly bauxitic clay containing a few bauxitic layers and concretions. The residual clay zone consists chiefly of kaolinite and is commonly 30 meters thick or more. The weathered bedrock zone is mostly clay, but original textures and structures have been preserved. Chlorite is very common in the altered bedrock.

Doeve (1957, p. 25) calculated that reserves of bauxite in the Nassau Mountains total 14 million metric tons, the composition of which is 53.5-55.5 percent  $\text{Al}_2\text{O}_3$ , 3-3.5 percent  $\text{SiO}_2$ , 8.5-10.5 percent  $\text{Fe}_2\text{O}_3$ , and 4-6 percent  $\text{TiO}_2$ , with loss on ignition of 27-29 percent. In addition 6 million tons is present that contains 47.5-49.5 percent  $\text{Al}_2\text{O}_3$  and 17.5-19.5 percent  $\text{Fe}_2\text{O}_3$ .

Bauxite deposits in the Bakhuis Mountains were described by Doeve and Meijer (1963, p. 1160-1161) as follows:

A large number of laterite capped hills and plateaus have been surveyed recently in the Adampada-Kabalebo area in the northern part of the Bakhuis Mountains, Surinam. Here, an aggregate total of 300 to 400 million tons of residual bauxite is inferred with an average of 45% available alumina. The individual deposits vary from a couple of million tons up to 30 and more million tons of bauxite. Of this, a primary selection totalling some 100 million tons of bauxite with somewhat more than 50% available alumina could be

considered as first grade commercial ore. The hydrated alumina occurs nearly completely in the form of trihydrate. The distance from the northernmost deposits to tide-water is approximately 50 miles. Drilling indicates a bauxite thickness of generally more than 10 feet, with an overburden varying from zero up to, for instance, seven feet. Locally, a section of sixty-four feet of bauxite averaging 45% of available alumina has been drilled, including a middle section of twenty-eight feet with nearly 49% available alumina.

Bauxite reserves in Surinam were estimated several years ago (Kurtz and Blue, 1951, p. 182) to be 62–67 million tons, but this estimate included only deposits at Rickanau and Paramam, which are owned by two companies. Since then several companies have carried on exploration programs (Schols, 1953, p. 19–24), and new deposits have been found at Rorac, Onverdacht, Ric a Rac, and other places, and 20 million tons of bauxite has been blocked out in the Nassau Mountains (Doeve, 1957, p. 25). Though figures have not been published for many deposits, total reserves are probably about 200 million tons (Wilmot, 1960, p. 21) and not as large as the 250-million-ton figure previously reported by the author (Patterson, 1963, p. B159). The larger figure included reported reserves in the Bakhuis Mountains, which most authorities who reviewed the preliminary estimates regard as potential resources. The total potential resources are estimated to be 350 million tons, the midpoint of the 300- to 400-million-ton estimate of Doeve and Meijer (1963, p. 1160) for the Bakhuis deposits.

Most bauxite produced in Surinam is high grade (table 6) and is crushed, washed, and dried. A small proportion of that produced is low in iron and is suitable for use in refractories and chemicals. Some deposits are beneficiated by heavy-media separation to reduce iron oxide contents (Bracewell, 1962, p. 192).

#### VENEZUELA

Several companies have explored and tested deeply weathered rocks for bauxite in places along the coast, and the Venezuelan Dirección de Geológica del Ministerio de Minas e Hidrocarburos has explored and reconnoitered several areas inland (Candiales, 1961, p. 1661–1662). No valuable bauxite deposits have been reported near the coast, but large deposits are present inland. The most valuable of these inland deposits are in (1) the Nuria region (fig. 6), which is south of the Orinoco River in the northeastern part of the State of Bolívar and includes parts of the Federal Territory of Delta Amacuro; and (2) the Upata region, in the State of Bolívar, west of the Nuria region. Very large low-grade deposits may occur in the highlands of the Gran Sabana region, which is in the southeastern part of the State of Bolívar near the Brazilian border. The Gran Sabana region, however, has only been reconnoitered, and according to information

now available, bauxite deposits are widely scattered (Candiales, 1961, p. 1679).

Venezuelan bauxite deposits, like others in northern South America, occur on peneplain surfaces. The deposits in the Gran Sabana region are on an upland at altitudes of 3,000–3,300 feet. Those in the Upata and Nuria regions are at an altitude of about 1,800 feet. In the Upata and Nuria regions the bauxite is formed on several types of rocks, including gneiss, amphibolite, granitic rocks, and diabase. At some localities the bauxite is pisolitic, and at others it is compact, massive, cellular, and fine grained. At least some of the deposits in the Upata region have formed in place, inasmuch as lenses of bauxite overlie kaolin and kaolinized gneiss, and original textures of the parent rock are indicated by preserved sericite (Candiales, 1961, p. 1672).

Resources of bauxite in the State of Bolívar have been estimated at 80 million tons (Cabello, 1957, p. 498); a later estimate placed the total bauxite in Venezuela at 103 million tons (Stamper and others, 1961, p. 247). The average partial chemical composition of 16 samples representing the better grade bauxite of the Upata region is 60.12 percent  $\text{Al}_2\text{O}_3$ , 0.94 percent  $\text{SiO}_2$ , and 11.78 percent  $\text{Fe}_2\text{O}_3$ , and the loss on ignition is 27.30 percent (Perfetti and others, 1951, map 3). Deposits in the Nuria region commonly contain approximately 43 percent  $\text{Al}_2\text{O}_3$ ; most of them are high in iron, and only a few are low in silica (Candiales, 1961, p. 1673).

#### OTHER SOUTH AMERICAN COUNTRIES

Bauxite deposits in the Department of Antioquia, Colombia, reportedly are 4–6 meters thick and cover an area 10 by 20 kilometers (Trought, 1940, p. 6). The  $\text{Al}_2\text{O}_3$  content of this bauxite ranges from 40 to 60 percent.

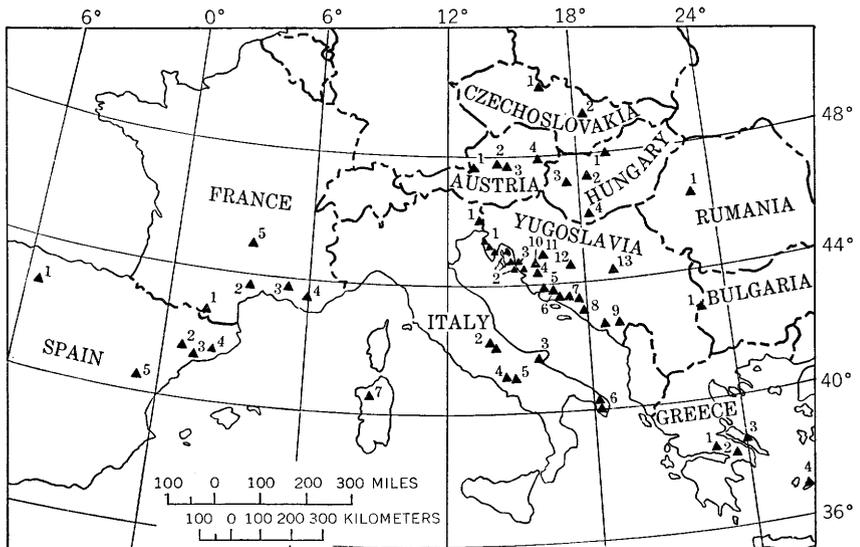
Discovery of bauxite in the province of Sud Yungus and near Suri, LaPaz, Bolivia, has been reported (Mining World, 1955). No information is available on the size and grade of these deposits.

Bauxite deposits occur in several places in the eastern part of Paraguay (Putzer, 1962, p. 124; Eckel and others, 1959). These deposits formed on nepheline-bearing syenite, shonkinite, and basalt, and their occurrence is similar to that of deposits in the Poços de Caldas area, Brazil.

Small deposits of bauxite have been discovered near Montenegro, Chile, approximately 40 kilometers north of Santiago (W. D. Carter, oral commun., 1963).

## EUROPE

The large bauxite deposits in Europe consist predominantly of the mineral boehmite and occur in France, Italy, Yugoslavia, Hungary, and Greece (fig. 8). Small boehmitic bauxite deposits occur in Spain, Austria, and Czechoslovakia. Large deposits of high-grade bauxite consisting predominantly of gibbsite occur only in Hungary, and smaller, lower grade deposits of this type occur in Northern Ireland, West Germany, France, and parts of the U.S.S.R. Extensive diaspore-bearing deposits occur in the Urals region of the U.S.S.R., in Rumania, and in northern Hungary; some deposits in Greece also are predominantly diaspore.



**Austria**  
 1. Untersberg  
 2. Laussa  
 3. Hölgraben  
 4. Dreistatten

**Bulgaria**  
 1. Trun

**Czechoslovakia**  
 1. Rychnov  
 2. Mojtin

**France**  
 1. Department of Ariège  
 2. Department of Hérault  
 3. Department of Bouches-du-Rhône  
 4. Department of Var, including the Brignoles district  
 5. Department of Puy-de-Dôme

**Greece**  
 1. Parnassus-Helikon region  
 2. Region west of Athens  
 3. Euboea Island  
 4. Amorgos Island

**Hungary**  
 1. Börzsöny district  
 2. Vértes district, including the Gant area  
 3. Bakony district, including the Halimba area  
 4. Hars ány district

**Italy**  
 1. Gorizia  
 2. Abruzzi and Molise  
 3. San Giovanni Rotondo  
 4. Benevento  
 5. Spinazzola  
 6. Southeastern Apulia  
 7. Sassari district

**Rumania**  
 1. Bihor Mountains

**Spain**  
 1. Leon  
 2. Lerida  
 3. Ferragona  
 4. Barcelona  
 5. Teruel

**Yugoslavia**  
 1. Istrian Peninsula  
 2. Krk, Rab, Pag  
 3. Gospić  
 4. Gracac  
 5. Drnis  
 6. Sinj  
 7. Imotski  
 8. Mostar  
 9. Nikšić  
 10. Bihać  
 11. Bosanska Krupa  
 12. Jajce  
 13. Vlasenica

FIGURE 8.—Location of principal bauxite deposits in Europe.

**AUSTRIA**

Small bauxite deposits occur in Austria near Salzburg on the northern slope of the Untersberg Mountains, at Laussa (Unterlaussa) in upper Austria, near Höllgraben in northern Styria, and near Dreistatten, south of Vienna. The Laussa deposits are chiefly boehmite; those at the other three localities are gibbsite (Weisse, 1948, pl. 1). The Laussa deposits are between two limestones of Mesozoic age and probably formed during the middle part of the Cretaceous Period (Bracewell, 1962, p. 137). Those at Dreistatten are above the irregular surface of carbonate rocks of Triassic age and are overlain by sandstones, conglomerates, and shales (Dittler and Kuhn, 1936).

The Laussa deposits are the most valuable in Austria. They have been mined on a small scale for several years, but the mines became unprofitable to operate in 1963 (Eng. Mining Jour., 1963a). According to old estimates (Harris and Trought, 1950, p. 4), the bauxite reserves in the Laussa area, including both proved and probable ore of all grades totaled approximately 2 million tons. Present reserves probably total about 1 million tons (Wilmot, 1960, p. 21). The bauxite mined at Laussa contained 45–46 percent  $\text{Al}_2\text{O}_3$ , 2–20 percent  $\text{SiO}_2$ , and 14–32 percent iron oxide.

**CZECHOSLOVAKIA**

Bauxite deposits occur at Rychnov in Bohemia (Konta, 1954, p. 58–60) and near the village of Mojtin, between Zilina and Trencin, in central Czechoslovakia (Orlov, 1937). The bauxite at Rychnov overlies amphibolite schists and probably formed from both the schist and transported material. Three types of bauxite present are (1) dense mixtures of kaolin and boehmite containing minor amounts of gibbsite, (2) pisolitic bauxite that is chiefly boehmite, and (3) porous pisolitic diaspore. The Rychnov deposits are overlain by sedimentary rocks of Late Cretaceous age (Bracewell, 1962, p. 138). The Mojtin bauxite occurs as irregular scattered deposits in limestones of Triassic age and is overlain by Eocene conglomerates. Some of the bauxite probably formed in place as a chemical sediment or as the product of lateritization of clayey material that filled karst depressions. That part of the bauxite composed chiefly of boehmite may have been transported (Orlov, 1939). None of the bauxite in Czechoslovakia appears to be of the grade and size required to support a major aluminum industry, and both alumina and bauxite are imported from Hungary (Bracewell, 1962, p. 139).

**FRANCE**

The principal bauxite deposits in France are in a belt a few miles north of the Mediterranean coast and extending from near the Spanish

border to within about 50 miles of the Italian border. The largest deposits are in the Departments of Var, Hérault, Ariège, and Bouches-du-Rhône, and small deposits are located in Pyrénées-Orientales, Lozère, and in the inland Department of Puy-de-Dôme. The deposits are in discontinuous beds, lenses, and pockets between limestone and dolomite formations that have been folded and faulted. Some deposits are nearly horizontal, others on the limbs of synclines are nearly vertical, and a few have been overturned. Because of their steep dips, many deposits extend to depths below the limits of profitable exploration and mining. The bauxite in Var is underlain by dolomite of Jurassic age (Lapparent, 1930, p. 58) and is overlain by Cretaceous limestones. Deposits in Hérault are underlain by limestone and dolomite of Jurassic age; deposits in Bouches-du-Rhône are enclosed by lacustrine limestone of Late Cretaceous age (Lapparent, 1930, p. 60); and those in Hérault are underlain by limestone and dolomite of Jurassic age.

The typical French bauxite deposit is red in the lower part and grades upward through a rose or pink-mottled zone into white bauxite (Lapparent, 1930). A few deposits are green, and some are gray and contain minor quantities of organic matter. Most deposits are pisolitic or oolitic, some are massive, and a few are layered and brecciated. The bauxite is principally boehmite (Caillère and Pobeguïn, 1962; Valetton and Klint, 1963), but gibbsite is present in variable quantities, and diaspore is a major constituent in some of the white and green bauxite. Some of the better grades of bauxite contain only minor quantities of kaolinite, but the poorer grades contain abundant kaolinite and may grade laterally into bauxitic clay and kaolin. Goethite and hematite are the principal iron minerals in the bauxite. Iron also occurs in the atomic structure of boehmite and diaspore in Ariège (Caillère and Pobeguïn, 1962) and possibly elsewhere in France.

Accurate estimates of bauxite reserves of France are not possible because high- and low-grade bauxite are intermixed in irregularly shaped deposits and because many areas have not been prospected to the depths required to penetrate the deeper deposits. Realistic estimates are also difficult because some deposits are in populated areas, where mining and prospecting rights are expensive or are impossible to obtain in peacetime. One report (Charrin, 1936, p. 1058) states that hundreds of millions of tons of bauxite are present in southern France. A reserve figure of 60 million tons has been quoted several times (Charrin, 1936, p. 1058; Weisse and Louvan, 1956, p. 52). One estimate (Gall, 1961, p. 48) places the bauxite reserves in Var at 25 million tons and notes that small reserves also are present in Hérault and Ariège. A more recent discussion of

bauxite in France (Vidal, 1963, p. 168) states that the reserves in active mines in the Departments of Var, Hérault, and Ariège in 1961 did not exceed 10 years' supply. (French bauxite production was 2.2 millions metric tons in 1961, and nearly all of it came from these three Departments.) This same report indicates that 30 million tons of bauxite containing less than 9 percent silica and 50 million tons containing less than 12 percent silica were discovered in the Department of Bouches-du-Rhône. The estimates for the discoveries in Bouches-du Rhône, however, include bauxite as deep as 600 meters, and much of it cannot be mined profitably. An estimate of 70 million tons (Wilmot, 1960, p. 21; S. H. Patterson, 1963, p. B159) is probably approximately correct for the French bauxite reserves and is intended to include inferred deposits, which are known to be two to three times as great as the measured reserves (*Annales Mines*, 1958, p. 689). The potential resources of bauxite, including high-silica bauxite, bauxitic clays, deposits at depths greater than the limits of profitable mining, and deposits in land unavailable for mining are assumed to be 190 million tons, the figure used in previous estimates (Wilmot, 1960, p. 21).

Most bauxite mined in France is high grade (table 6). The red bauxite is high in iron oxide and low in silica, and the white and gray bauxite is high in silica and low in iron oxide. Some French bauxite contains small quantities of  $P_2O_5$  and  $V_2O_5$  (Denizot, 1961, p. 39). Small quantities of vanadium have been recovered as a by-product from the treatment of bauxite in France (R. P. Fischer, 1961, p. 39).

#### GREECE

The largest bauxite deposits in Greece are north of the Gulf of Corinth and in the mountains of Parnassus and Guione. Small deposits occur in the Eleusis-Mandra area west of Athens, in the northwestern part of Amorgos Island, and on Euboea Island. Thin and small deposits also occur in western Greece. Schistose emery deposits containing aluminous minerals have been found on Naxos and Samos Islands. Most deposits in Greece are of the pocket or Mediterranean type; they occur in irregular masses along the uneven surfaces of limestone or dolomite and are overlain by younger carbonate rocks. The bauxite in the Parnassus-Helikon region is between strata of Early and Late Cretaceous age (Aronis, 1956). Deposits in the Eleusis-Mandra district are on the eroded surface of structurally deformed Upper Tertiary limestones and are overlain by limestone of Late Cretaceous age (Aronis, 1953). The bauxite deposits range in thickness from a few inches to 60 feet, and some are as much as 4,000 feet long and 1,500 feet wide. Red clay is commonly present between the bauxite and the underlying limestone, and

a thin persistent red clay layer occurs between the bauxite and overlying limestone in some districts.

Small bauxite deposits of Eocene age occur at three localities in southern Greece (Papastamatiou, 1964, fig. 1). These deposits are chiefly gibbsite (V. T. Allen, 1960, p. 233).

Both hard massive and soft friable types of bauxite occur in Greek deposits. Nearly all the bauxite is pisolitic, but concretionary, brecciated, and massive types occur locally. Some deposits contain appreciable bituminous material (Aronis and Roch, 1958, p. 941). Boehmite is the principal mineral in metal-grade bauxite, and diaspore is the dominant mineral in some deposits that are used for refractories. Diaspore tends to be most abundant in deposits on the limbs of folds (Kiskyras, 1960, p. 662). Diaspore also occurs in the schistose emery deposits on Naxos and Samos Islands (Lapparent, 1933). Hematite is the principal iron mineral in the bauxite, and magnetite is also present at one locality (V. T. Allen, 1960, p. 233). Anatase is the principal titanium mineral present. Vein calcite is a major impurity in some deposits. The red clay associated with the bauxite is a mixture of hematite and kaolinite at most localities, but in some deposits halloysite is more abundant than kaolinite.

The reserves of bauxite in Greece have been estimated by the Greek Institute of Geology and Subsurface Research to be 84 million tons (Wilmot and others, 1958, p. 253). Another report (Harris and Trought, 1954, p. 5) suggests that total potential bauxite resources in Greece may be hundreds of millions of tons. These resources are probably about 100 million tons, inasmuch as the total proved and inferred bauxite was estimated by Bardossy (1964, table 2) to be 192 million tons. The average composition of a number of samples of Greek bauxite is given in table 6 and is presumably typical of bauxite mined in Greece.

#### HUNGARY

Bauxite occurs in four districts (McCroskey, 1945; Bárdossy, 1961): (1) the Bakony district, including the Iszkaszentgyörgy, Halimba, Nyirád, Szóc, and Sümeg deposits, extending east-northeastward 60–70 miles northwest of Lake Balaton; (2) the Vértes district, including deposits at Gant, near the western end of the Vértes Mountains and 30–40 miles west of Budapest; (3) the Börzsöny district, including the Nézsa deposits, about 25 miles due north of Budapest at the eastern extremity of the Börzsöny Range; and (4) the Harsány district in southern Hungary near the Yugoslavian border. The largest and most active mines are in the Bakony and Vértes districts (Canadian Mining Jour., 1961, p. 41).

Hungarian bauxite deposits are mineralogically complex and variable (Bárdossy, 1959, p. 4–21). Gibbsite makes up as much as 60–70

percent of the Iszkaszentgyörgy and Szöc bauxite deposits, 1–35 percent of the Gant deposits, and commonly less than 20 percent of most other deposits. Most of the gibbsite occurs as submicroscopic crystals in the groundmass of the bauxite, but it also occurs as secondary nodules and crusts. Boehmite commonly forms 60–85 percent of the Nyirád, Halimba, Gant, and Harsány deposits and 10–50 percent of most other deposits. Diaspore forms about 50–70 percent of the Nézsa deposits and an average of about 10 percent of the Harsány deposits; it is not present in identifiable amounts in most other deposits. Corundum, probably occurring as a detrital mineral, has been identified in several deposits. Hematite is the principal iron mineral in the bauxite, and amounts present commonly range from 10 to 20 percent. Goethite is the second most abundant iron mineral; amounts range from 1 to 20 percent. Other iron-bearing minerals, including magnetite, ilmenite, ankerite, chamosite, and nontronite, occur in minor amounts. The silica in the bauxite is chiefly in kaolin minerals, but minor amounts of quartz and traces of many detrital silicate minerals are present. The kaolin minerals are chiefly well-crystallized kaolinite, but disordered kaolinite is abundant locally, and dickite has been identified at a few places. Titanium minerals in the bauxite are chiefly rutile, anatase, and brookite.

Most Hungarian bauxite deposits probably formed in place by alteration of fine-grained aluminous detrital minerals that were transported to basins formed on carbonate rocks. Alteration may have taken place in an alkaline environment that developed under tropical or subtropical conditions (Bárdossy, 1959, p. 1, 24–46). Gibbsite was probably the initial alteration product of the parent sediments, and the change to boehmite and diaspore was by diagenetic processes.

Bauxite in the Bakony and Vértes districts occurs in widespread flat lying deposits in karst depressions formed in dolomite of Mesozoic age. Some deposits are overlain only by unconsolidated sediments; others are overlain by strata of Mesozoic and Tertiary age. Deposits in the Harsány district occur in a steeply dipping series of limestone beds of Mesozoic age. The bauxite is a discontinuous unit consisting of lenses and pockets (Rakusz, 1937). Thicknesses of the bauxite are 6–10 meters in the Bakony district, 2–33 meters in the Vértes district, and 8–10 meters in the Harsány district (McCroskey, 1945, table 14).

The bauxite deposits in the Halimba basin are the largest in Hungary (Erdélyi, 1965, p. 339). They overlie dolomite and limestone of Triassic age. In some places the bauxite grades upward into terrestrial deposits of Late Cretaceous age, and at other places it is unconformably overlain by rocks of Eocene age. Hungarian geologists postulate that the Halimba deposits are reworked and were deposited in their present position in the form of bauxite.

The chemical composition of Hungarian bauxite varies considerably (Bárdossy, 1958a). Most deposits contain 50–60 percent  $\text{Al}_2\text{O}_3$ , but some contain as much as 76.8 percent  $\text{Al}_2\text{O}_3$ , and others are very low grade. In most deposits  $\text{SiO}_2$  amounts to 1–5 percent. Some deposits contain almost no  $\text{Fe}_2\text{O}_3$ , and others consist of as much as 50 percent  $\text{Fe}_2\text{O}_3$ .

Estimates of bauxite reserves in Hungary range from 116 to 400 million tons (Weitz and Trought, 1947, p. 685). A figure of 300 million tons was published by Cardew (1953) and by the Mining Journal (1958, p. 200), and it was used in previous estimates by the author (S. H. Patterson, 1963). Bárdossy, who investigated many Hungarian bauxite deposits, listed the indicated bauxite as 150 million tons (1964, table 2) but gave no figures for proved reserves. Presumably his estimate is more accurate than any previously published and is assumed to be the correct figure for reserves. Estimates for potential bauxite resources are not available, but such resources may be large.

#### ITALY

The largest bauxite deposits in Italy are northeast of Foggia in the San Giovanni Rotondo district, in the nearby Manfredonia area, and at other places on the Gargano promontory. The second most important deposits are near Spinazzola in southern Italy. Other deposits occur in the Gorizia region along the Yugoslavian border, Department of Venetia; near Benevento, north of Naples; in the Apennine region of Abruzzi and Molise; in the southeastern part of Apulia; and in the Sassari district north of Alghero, Sardinia.

The deposits in the San Giovanni Rotondo district occur in solution depressions in limestone of Late Cretaceous age and are overlain by limestone of Eocene age (V. T. Allen, 1960, p. 233). Boehmite is the principal bauxite mineral in these deposits. Hematite and anatase are the most common impurities in the best grade deposits. Kaolinite or halloysite is abundant in low-grade deposits, and calcite is common locally. The composition of four samples (Crema, 1931, p. 11) is 52.27–60.05 percent  $\text{Al}_2\text{O}_3$ , 1.04–3.50 percent  $\text{SiO}_2$ , 20.19–27.67 percent  $\text{Fe}_2\text{O}_3$ , and 1.33–2.35 percent  $\text{TiO}_2$ , and the loss on ignition is 14.10–17.30 percent.

Bauxite deposits occur at several localities on Sardinia. They have been prospected in the Sassari district north of Alghero and in the Olmedo district (Stamper and others, 1961, p. 248). Most deposits occur between limestones of Cretaceous age (Pecorini, 1956). Both pisolitic and massive types of bauxite are present in the area north of Alghero. The composition of three samples of this bauxite (Moretti, 1955, p. 464) is 53.06–65.94 percent  $\text{Al}_2\text{O}_3$ , 6.64–13.14 percent  $\text{SiO}_2$ , 3.04–23.51 percent  $\text{Fe}_2\text{O}_3$ , and 2.97–3.35 percent  $\text{TiO}_2$ , and 13.23–15.15 percent  $\text{H}_2\text{O}$ .

Reserves of bauxite in Italy are estimated at about 24 million tons, half of which is high grade (Wilmot, 1960, p. 21). This estimate may be low for the total reserves in Italy because deposits in Abruzzi alone reportedly contain 11 million tons of bauxite (Baudart, 1959), and the figure does not include the deposits on Sardinia or the recently discovered deposits near Salento, in southern Italy (Higbie and others, 1963, p. 303), for which no estimates are available

#### NORWAY

Deposits of bauxite have been reported on the island of Jan Mayen in the Arctic Ocean. According to one estimate (R. J. Anderson, 1936, p. 337), the deposits contain 30 million tons of bauxite; another estimate (South African Mining and Eng. Jour., 1942, p. 681) gives their size as 32 million tons. Though this reported bauxite resource has been included in several estimates of world bauxite resources it is not listed in the world totals (table 5) inasmuch as no thorough geologic studies of the deposits have been published, and no information on the grade of the bauxite is available.

#### POLAND

Poland has no economic bauxite deposits; however, some low-grade bauxite and bauxitic clays occur near Grudkow (Glaser, 1938) and Tarnowice, in the Silesia region (Spangenberg, 1949). Bauxitic clays overlying lignite deposits are reported (Wilmot and others, 1960, p. 237) to be the raw material that will supply a plant at Gorka which is designed to produce alumina from low-grade materials (Eng. Mining Jour., 1959b). These clays may be the ones from Upper Silesia described by Duchniewski (1958) as occurring between limestone of Triassic age and much younger sediments and consisting of a mixture of kaolin and gibbsite.

#### RUMANIA

Bauxite deposits, associated with limestone of Early Cretaceous age (Vádasz, 1946), occur on the slopes of the Bihor Mountains in the western part of Rumania. The bauxite consists chiefly of diaspore, but minor amounts of boehmite and gibbsite are present. White spongy bauxite contains 42.5 percent  $\text{Al}_2\text{O}_3$ , 39.41 percent  $\text{SiO}_2$ , 1.30 percent  $\text{Fe}_2\text{O}_3$ , and 1.80 percent  $\text{TiO}_2$ ; and gray hard bauxite contains 63.70 percent  $\text{Al}_2\text{O}_3$ , 3.56 percent  $\text{SiO}_2$ , 9.70 percent  $\text{Fe}_2\text{O}_3$ , and 3.20 percent  $\text{TiO}_2$ . According to old estimates, proved reserves containing 53–61 percent  $\text{Al}_2\text{O}_3$  total 2–10 million tons; probable reserves, 40–42 million tons (S. M. Anderson, 1944, p. 42). Total Rumanian reserves probably amount to about 20 million tons containing 57 percent  $\text{Al}_2\text{O}_3$  and 2 percent  $\text{SiO}_2$  (Mining Jour., 1958, p. 200).

## SPAIN

Numerous small irregular bauxite deposits occur near Barcelona, Lerida, Terragona, and Teruel in northeastern Spain; other small deposits occur near Alós de Balaguer in Catalonia; and bauxite has recently been discovered near Leon, in the northwestern part of the country. Deposits at La Llacuma, about 65 kilometers west of Barcelona, have been worked for several years and are presumably typical of the bauxites in Spain. At La Llacuna the bauxite deposits occur in depressions on the surface of carbonate rocks of Triassic age and are overlain by limestones of Paleocene age (Miralles, 1954, p. 211-215). The bauxite is chiefly boehmite, but minor amounts of diaspore, kaolinite, and hematite are also present. Most of the bauxite is pisolitic. The partial composition of 20 samples that have been analyzed (Miralles, 1954, p. 215) is 30.04-70.00 percent  $\text{Al}_2\text{O}_3$ , 3.42-32.76 percent  $\text{SiO}_2$ , 1.60-22.78 percent  $\text{Fe}_2\text{O}_3$ , and 2.1-4.15 percent  $\text{TiO}_2$ .

The small deposits near Leon are of Middle Devonian age and are underlain by clay slate and overlain by fossiliferous limestone (Font-Altaba and Closas, 1960, p. 1288). They consist chiefly of gibbsite but also contain minor quantities of boehmite, diaspore, halloysite, and carbonate impurities. Those near Alós de Balaguer occur between Jurassic and Cretaceous rocks and contain 300,000-400,000 tons of bauxite (Rios and Almela, 1950).

Reserves of bauxite in Spain have been estimated at 6-7 million tons (Heindl and others, 1955, p. 219). A search for large deposits of metal-grade bauxite has been unsuccessful, but probably new discoveries have kept pace with the small quantities mined for refractory products and cement. No information is available on the total potential bauxite resources in Spain; however, they are probably not large.

## U.S.S.R., INCLUDING SOVIET ASIA

A search for new bauxite deposits began with the first 5-year plan (1929-35), and exploration for raw material to supply an expanding Soviet aluminum industry was intensified after World War II. This program resulted in increased knowledge of old deposits and the discovery of many new deposits of bauxite and aluminous rocks and minerals other than bauxite. About 90 occurrences of bauxite are reported in Central Asia alone (Konnov, 1958). Very little information on economic geology is available, and economic data given in this discussion are either old or inferred from vague and sketchy information. Notwithstanding recent discoveries at several localities, the U.S.S.R. is still regarded as a bauxite-deficient nation. This conclusion is supported by the large imports of bauxite in recent years from Greece, Hungary, and Yugoslavia, and by reports

that both much of the present Soviet aluminum industry and planned future expansion are based on raw materials other than bauxite. Nepheline on the Kola Peninsula supplies the Pikalevo alumina plant (Baker and others, 1960b); nepheline supplies the alumina plant at Achinsk in Siberia (Shabad, 1958, p. 17); and alunite deposits in the Zaglik district south of the Caucasian Mountains reportedly supply the plant at Sumgait (Shabad, 1958, p. 17; Baer, 1959, p. 104).

The bauxite deposits in the U.S.S.R. range in age from late Proterozoic to Quaternary and were formed in several ways (Strakhov and Bushinsky, 1958). Most of the bauxite formed during the Devonian, Carboniferous, Cretaceous, and Tertiary Periods. Bauxite deposits formed by lateritic weathering processes are recorded from the Onega district in the marginal belt of the Baltic shield, the southern part of the Ukrainian crystalline massif, the Turgai region, and scattered localities in Soviet Asia. Several different theories of origin of other deposits have been advanced by Russian geologists. Most of the deposits are believed to be of sedimentary origin, and many may have accumulated in lake, swamp, and marine environments. Some Russian geologists apparently believe that sulfuric acid from pyrite plays a major role in bauxite formation. Many of the deposits believed to be marine are associated with ancient karst topography on limestones, and theories of marine origin do not seem adequately substantiated.

*Tikhvin district.*—The Tikhvin district is near Boksitogorsk, east of Leningrad. The bauxite deposits are associated with aluminous clays that occur along an erosional unconformity between rocks of Devonian and Early Carboniferous ages. Most of this bauxite consists of pebbles or pellets enclosed by fine-grained interstitial material. The coarse particles are chiefly boehmite, but they also contain diasporë and corundum (Gladkovsky and Ushatinsky, 1964, p. 154). The interstitial material is chiefly kaolinitic clay, but some secondary gibbsite is also present. The chemical composition of this bauxite is 42–48 percent  $\text{Al}_2\text{O}_3$ , 10–20 percent  $\text{SiO}_2$ , 15–25 percent  $\text{Fe}_2\text{O}_3$ , and 2–2.5 percent  $\text{TiO}_2$  (Latus and others, 1938, p. 28). The bauxite now mined at Boksitogorsk is reported to be 47.7 percent  $\text{Al}_2\text{O}_3$  and 13.2 percent  $\text{SiO}_2$  (Mining Jour., 1960, p. 549). According to an old estimate, the Tikhvin district contains 8.3 million tons of bauxite, including some bauxitic clays. However, considerable mining has been done since that estimate was made, and the results of recent exploration in the district are not available.

*Onega district.*—Bauxite occurs in two zones of Late Devonian to Early Carboniferous age in the Onega River basin. One of the zones is an ancient lateritic weathering surface formed on diabase

porphyry. The second zone is associated with mottled clays and may have formed from transported weathered material derived from the diabase. The bauxite above the diabase is ferruginous and gibbsitic and is reported to be about 7 meters thick. The ferruginous gibbsitic layer is underlain by kaolinite, which in turn grades downward into diabase through a montmorillonitic zone. The bauxite contains 15.40–37.86 percent  $\text{Al}_2\text{O}_3$ , 14.06–42.18 percent  $\text{SiO}_2$ , 7.89–50.77 percent  $\text{Fe}_2\text{O}_3$ , and 0.52–1.64 percent  $\text{TiO}_2$  (Trubina, 1958a, p. 331). No information on the reserves of bauxite in the Onega district is available.

*Southern part of the Moscow basin.*—Low-grade bauxite deposits fill karst depressions on limestone of Early Carboniferous age. The deposits are overlain by coal-bearing clay beds. The bauxite deposits are mixtures of gibbsite, allophane, kaolinite, and halloysite. The largest deposits in the area reportedly occur along the Upa River about 30–40 kilometers south of Tula. Some of the deposits are reported to be 2–3 meters thick and hundreds of meters in diameter (Belousov, 1939). The bauxite contains 31.25–54.90 percent  $\text{Al}_2\text{O}_3$ , 9.40–32.2 percent  $\text{SiO}_2$ , 0.00–10.15 percent  $\text{Fe}_2\text{O}_3$ , and no  $\text{TiO}_2$  (Trubina, 1958b, p. 336).

*Southern Ukraine.*—Bauxite deposits were discovered recently at scattered localities along the southern rim of the Ukrainian crystalline massif in southern Ukraine. The bauxite occurs in the weathered parts of older amphibolite and schist and in clay-rich sediments of middle Eocene age. Both types of deposits consist chiefly of gibbsite and contain small amounts of boehmite (Bass, 1958). Bauxite deposits near the village of Shestunia in the Dneprotrovsk region reportedly extend for 12 miles and are about 200 feet below the surface. Reserves in this area are estimated to be about 20 million tons (Wilmot and others, 1958, p. 253). No information is available on the grade or thickness of the deposits.

*Kazakhstan.*—Bauxite deposits occur in several parts of the Turgai embayment in Kazakhstan. The deposits range in age from Early Cretaceous to Oligocene. Most of the deposits are gibbsitic, but some boehmite is present in a few deposits. Some of the bauxite may have formed by surficial weathering prior to the deposition of marine sediments; other deposits may have been transported and deposited in lakes. The most valuable deposits in Kazakhstan are near Amangeljdinsk (Amangeldy on some maps). These deposits reportedly furnish much of the bauxite processed in the new plant at Pavlodar. Bauxite deposits in the Amangeljdinsk district contain 28.75–58.30 percent  $\text{Al}_2\text{O}_3$ , 1.86–19.94 percent  $\text{SiO}_2$ , 3.73–45.3 percent  $\text{Fe}_2\text{O}_3$ , and 1.40–3.16 percent  $\text{TiO}_2$ , and are composed chiefly of gibbsite (Tjurin, 1958, p. 422).

Deposits of bauxite of Cretaceous age along the western limb of the Turgai depression are of the karst type and represent a continuation of the bauxite belt of the Central Urals (Kuzemkina, 1960). Pisolites in this bauxite range in size from 2 to 22 mm. Unaltered pisolites, investigated by X-ray methods, contain hematite, magnetite, corundum, siderite, pyrite, gibbsite, titanium minerals, and quartz. The corundum occurs in the central parts of the pisolites, and the outer parts are chiefly gibbsite. Kuzemkina believes that the corundum formed in place, because it occurs only in pisolites, and no corundum is present in the cementing materials enclosing the pisolites or in the nonpisolitic bauxite.

*Urals region.*—bauxite deposits occur at several localities on the slopes of the Ural Mountains from Ivdel in the northern part to the vicinity of Orsk near the southern end of the mountain chain. The most valuable deposits are on the east flank of the mountains, but scattered deposits also occur on the west flank. Stratigraphic work (Andronov, 1959) has established that the Ural bauxites occur at three horizons in a sequence of Devonian limestones and shales. Some bauxites of the Urals consist chiefly of diasporite, a few are chiefly boehmite, and others are mixtures of diasporite and boehmite (Gutkin and Skripko, 1963). A few deposits contain chlorite (Rozhkova and others, 1938). Some deposits are dark green and some are red, and most of the bauxite is pisolitic.

The major bauxite deposits in the region and the largest reserves of bauxite in the U.S.S.R. are near the city of Severouralsk (Nalivkin, 1960, p. 57) in the southern part of the Northern Urals. Valuable deposits occur (1) in the Krasnaya-Shapochka district, (2) in the Bogoslovsk (Krasno-Turinsk) district, (3) near Ivdel, and (4) along the Talitza River (Moldavantsev, 1934). According to one report (Latus and others, 1938), the bauxite at Krasnaya-Shapochka contains 58 percent  $\text{Al}_2\text{O}_3$ , 3.7 percent  $\text{SiO}_2$ , and 26 percent  $\text{Fe}_2\text{O}_3$ . Shabad (1960, p. 15) described the bauxite mined in Severouralsk region as the highest grade in the Soviet Union. He reported that it contains 49–59 percent  $\text{Al}_2\text{O}_3$  and 3–7 percent  $\text{SiO}_2$ , and that the ore is a monohydrate type. The deposits have been mined extensively to supply a plant at Krasnoturinsk. The bauxite at one locality in the Northern Urals is reported to extend to depths of 4,500 feet (Metal Industry, 1960). Much of the reserves that can be mined by opencut methods have been exhausted, and the necessity of removing water at depths of 500–2,100 feet has impeded underground mining.

The second most valuable bauxite deposits in the region are in the northern part of the east flank of the Southern Urals. The deposits are near Kamensk and supply the plants in that city. The

bauxite is mainly gibbsitic. It occurs in lacustrine clay of Early Cretaceous age that fills valleys in igneous and sedimentary rock and also karst depressions in limestone (Karczhevskiy, 1958).

*Central and southern Siberia.*—Bauxite occurs at several localities in the Salair Range (Strakhov and Bushinsky, 1958) south of Novosibirsk, and at other localities (Guipp, 1964). Most of the bauxite is diasporic and ferruginous and is associated with limestone of Devonian age. These deposits accumulated on an ancient weathering surface and probably formed in the same way as deposits in the Northern Urals. Deposits of Mesozoic and Oligocene ages are also known to occur in the Salair Range, but detailed information on these deposits is not available.

Bauxite also occurs along the middle reaches of the Yenisey River, in the Angara River valley (Strakhov and Bushinsky, 1958), and at other scattered localities in central and southern Siberia. The bauxite is in terrace deposits of Quaternary age. Some of these deposits are about 5° S. of the Arctic Circle at several localities along the Yenisey River. The bauxite is in pisolitic pebbles as 10 cm in diameter. Some bauxite of Cretaceous age is also present in this region. Gibbsitic bauxite in the lower Angara River valley is associated with lake deposits of Oligocene age. Presumably none of these deposits have been mined.

Bauxite deposits occur in the eastern Sayan Mountains in the general area south of Lake Baikal. Apparently the best bauxite in this region is in the Bokson (Boksonsky) deposits. These deposits are in limestones of Cambrian age and consist chiefly of diasporic, boehmite, and hematite. Some bauxite in this region may also have formed during the continental break following the deposition of marine sediments at the close of the Precambrian. These deposits are the oldest known bauxites. According to the few analyses available, the composition of Bokson bauxites is 31.33–60.18 percent  $\text{Al}_2\text{O}_3$ , 3.88–37.76 percent  $\text{SiO}_2$ , 1.71–28.90 percent  $\text{Fe}_2\text{O}_3$ , and 0.33–2.78 percent  $\text{TiO}_2$  (Orlova, 1958, p. 291).

*Bauxite resources in U.S.S.R.*—Reports on bauxite reserves of the entire U.S.S.R. have not been published, and little information is available on which to base an estimate. A figure of 300 million tons for the indicated reserves of bauxite in the U.S.S.R. was given by Bárdossy (1964, table 2) and is assumed to be of the correct order of magnitude in this report. This figure probably includes considerable bauxite of such low grade that it would be classed as resources instead of reserves in other countries. Any consideration of the bauxite reserves of the U.S.S.R. should not overlook the intensive program carried out in recent years to find new sources of aluminum. Many geologists have been searching for bauxite in several regions

in the U.S.S.R. Information on the quantity of bauxite found has not been released. Also, rocks other than bauxite are used as sources of aluminum in the U.S.S.R. Plants at which alumina and certain byproducts, chiefly soda ash, potash, and raw material for cement, are extracted from nepheline syenite are reportedly operating on a large scale. The reserves of nepheline syenite in the U.S.S.R. are believed to be virtually inexhaustible (Nalivkin, 1960, p. 16; Harris and Trought, 1955, p. 4). A plant utilizing alunite as a source of alumina is also operating (Shabad, 1958, p. 17; Baer, 1959, p. 104). Kyanite, sillimanite, and andalusite also have been investigated as possible sources of alumina (Galaburda, 1958).

#### UNITED KINGDOM

*Northern Ireland.*—Bauxite deposits occur in County Antrim and in the Coleraine area in adjoining parts of County Londonderry. The deposits are in a region of basaltic rocks and are associated with lateritic iron ores of late Miocene or early Pliocene age. Several similarities between the bauxites in Ireland and those in Oregon were noted by V. T. Allen (1960, p. 231). The chief difference between the two is that Oregon deposits are at the surface and Irish deposits, formed during "interbasaltic intervals," are overlain by younger basalt accumulations. The rocks of two "interbasaltic intervals" occur in the northern part of the region; the rocks of only one are present in the southern part (E. M. Patterson, 1955). The deposits associated with the bauxite include lignite, pisolitic iron ore, clays, basaltic lithomarge (saprolite formed from basalt), and weathered rhyolitic debris. Most of the bauxite deposits that were mined were 2–6 feet thick. Three types of aluminous laterites or bauxites present (Eyles and others, 1952, p. 5) are as follows: (1) highly ferruginous red bauxite formed from basalt and commonly containing 20–30 percent  $\text{Fe}_2\text{O}_3$  and 5–10 percent  $\text{SiO}_2$ ; (2) siliceous gray bauxite formed mostly from rhyolitic debris and commonly containing 5–10 percent  $\text{Fe}_2\text{O}_3$  and 20–40 percent  $\text{SiO}_2$ ; and (3) bauxites of mixed origin, which have formed both from basalt and rhyolitic material and are intermediate in composition between the first two types.

Gibbsite is the most common bauxite mineral present (Eyles and others, 1952, p. 39). Boehmite is common in parts of deposits near basalt dikes, and corundum was identified in one sample collected 6 inches from a dike. Hematite is the principal iron oxide mineral in all three types of bauxite; minor amounts of goethite, magnetite, maghemite, and ilmenite are also present (Eyles and others, 1952, p. 39–42), and spherulites of a mineral having the optical properties of siderite were recognized by V. T. Allen (1960, p. 230). Titanium-

bearing minerals in the bauxite and weathered basalt include anatase, brookite, rutile, and ilmenite. The most common clay minerals are kaolinite and halloysite, and a clay mineral that is probably of the chlorite type is also present (Eyles and others, 1952, p. 38, 50-51). The composition of 19 samples of bauxite from the Skerry, Lyles Hill, and Ballynabanish mines (Eyles and others, 1952, p. 63, 66) is 28.70-53.09 percent  $\text{Al}_2\text{O}_3$ , 1.58-12.12 percent  $\text{SiO}_2$ , 17.85-32.30 percent  $\text{Fe}_2\text{O}_3$ , and 2.31-5.20 percent  $\text{TiO}_2$ ; and loss on ignition is 13.54-27.70 percent.

Bauxite in Northern Ireland has been mined intermittently for use in the manufacture of alum, refractory brick, and quick-setting cement; and between 1941 and 1945 the British Aluminum Co. produced 300,000 tons in behalf of the Ministry of Aircraft Production (Bracewell, 1962, p. 84). According to one estimate (Daniels and Derbyshire, 1959), the amount of bauxite containing about 10 percent  $\text{SiO}_2$  and 45 percent  $\text{Al}_2\text{O}_3$  that remains is 2.5-3 million tons. This bauxite should be considered as resources because it is in thin deposits that must be mined by underground methods and cannot compete with imported bauxite in peacetime.

*Scotland.*—The Ayrshire bauxitic clay occurs along the west coast of Scotland in a belt extending about 15 miles from Saltcoats eastward to Kilwinning, and at other places as far south as Stranraer. In most places the clay rests on mafic lava flows and is overlain by the lowest coal bed of the Coal Measures. The clay is in a discontinuous and lenticular bed, and deposits range from a few inches to 30 feet in thickness and from 30 to several hundred feet in lateral extent. Boehmite and diaspore mixed with kaolinite have been identified in the clay (Lapparent, 1936), and the more aluminous minerals are commonly in pisolites. Samples contain 26-60 percent alumina, 29-60 percent silica, and 5-10 percent iron oxide (Wilson, 1922, p. 9). The deposits are used in making refractories by several companies, and they are also used in the manufacture of alum (Bracewell, 1962, p. 86). No estimates of reserves are available.

#### WEST GERMANY

Small bauxite deposits occur at several localities on the slopes of the Vogelsberg Mountains in Hesse (Harrassowitz, 1922). The deposits formed on basaltic lavas and tuffs of Miocene age, probably by weathering in Pliocene time. Gibbsite, the principal bauxite mineral, occurs as nodules scattered throughout red clay and weathered rock. J. Lang (1884, p. 2893) reported that the bauxite contains 49.02-50.85 percent  $\text{Al}_2\text{O}_3$ , 5.14-10.27 percent  $\text{SiO}_2$ , and 25.88-27.03 percent  $\text{Fe}_2\text{O}_3$ . The deposits have been mined intermittently and used in the manufacture of abrasives and chemicals. They are

too small to furnish supplies of bauxite for aluminum; bauxite used by the West German aluminum industry is imported.

#### YUGOSLAVIA

Large deposits of bauxite are scattered throughout a belt about 40 miles wide extending along the Adriatic Coast from the Istrian Peninsula to near the Albanian border. Other deposits occur farther inland, and small deposits occur on the offshore islands (fig. 8). Deposits in the coastal belt occur (1) in an area extending across the central part of the Istrian Peninsula; (2) west of Gospić and north of Gracáč, Bosnia; (3) in the Drnis district; (4) near Sinj; (5) north of Imotski; (6) in a large area surrounding Mostar; and (7) in the Nikšić region, Montenegro. The inland deposits occur (1) south of Bihać; (2) near Bihać; (3) near Bosanska Krupa; (4) in the Jajce region; and (5) near Vlasenica. The offshore deposits are on the islands of Krk, Rab, and Pag. Most deposits occur as irregular lenses and pockets filling karst depressions in limestone and are overlain by younger carbonate rocks. Some of the karst depressions are as much as 200 feet deep (V. T. Allen, 1960, p. 232). The bauxite and enclosing strata are folded into deep synclines, and some deposits extend to depths of more than 2,000 feet. Bauxite is worked at depths of 1,300 feet in the Kalun mine near Drnis (Bracewell, 1962, p. 164).

Bauxite in Yugoslavia occurs in rocks ranging in age from Middle Triassic to Eocene; deposits formed during 10 different geologic intervals (Jurković and Sakač, 1964). Deposits of Middle Triassic age occur at Gracáč, and deposits of both Middle and Late Triassic ages occur in Montenegro. Deposits of Late Jurassic age that are large enough to be of economic significance occur only in Montenegro. Bauxites of Jurassic and Early Cretaceous age occur chiefly in the Istrian Peninsula, but small deposits of this age occur at several places. Most valuable deposits at Bosanska Krupa are of Early Cretaceous age, but deposits that may be Jurassic are also present. Deposits in the Jajce and Vlasenica districts are of Late Cretaceous age. Deposits of Paleocene and Eocene ages occur in an extensive belt near the coast. Most of the valuable deposits in the Gospić, Drnis, Sinj, and Imotski districts are presumably of Eocene age (Grubić, 1964, p. 65).

The mineralogical composition of bauxites in Yugoslavia varies with their age. The deposits of Eocene age, the youngest, are mixtures of gibbsite and boehmite (Jurković and Sakač, 1964, p. 261; Weisse, 1948, p. 116), and goethite is the most common iron-bearing mineral. Bauxite of Paleocene and Cretaceous ages is chiefly boehmite and contains only minor quantities of gibbsite; iron occurs both as

goethite and hematite. Bauxite of Triassic age is chiefly boehmite but contains abundant diaspore locally. Almost all iron in these deposits is in the form of hematite. Kaolinite is the most abundant clay mineral in all Yugoslav bauxite deposits. Halloysite occurs locally in some deposits of Eocene age but has not been identified in older deposits. Anatase has been identified as the principal titanium mineral in Yugoslav bauxites (V. T. Allen, 1960, p. 232).

Reserves and resources of bauxite in Yugoslavia are difficult to calculate because of the irregular shapes of deposits and their common occurrence at depth. One estimate (Baker and Diggs, 1957a) places the total reserves at about 300 million tons; according to a more recent estimate (Mining Jour. 1962) they amount to 290 million tons. Both figures may include very large deposits that have not been mined because of high silica content (5–13 percent) and low grade. The 10 million tons along the Dalmatian Coast is in the second category because the  $Al_2O_3$  content is only 47–48 percent (Franotovic, 1955, p. 84). An estimate of 200 million tons for the inferred bauxite reserves in Yugoslavia (Bárdossy, 1964, table 2) is probably approximately correct, and potential bauxite resources probably exceed 100 million tons. The average composition of bauxite mined in Yugoslavia is listed in table 6.

#### OTHER EUROPEAN COUNTRIES

Small bauxite deposits occur in Albania, and presumably they are similar to those in Montenegro, Yugoslavia, to the northwest. An estimate of 1 million tons for the inferred bauxite in Albania was listed by Bárdossy (1964, table 2).

Small deposits of bauxite occur in Bulgaria near Trun, which is 38 miles west of Sofiya. The deposits are reported to be of low grade (McCroskey, 1944, p. 16), but they were worked prior to World War II (Bracewell, 1962, p. 138).

Bauxite deposits that are high in silica and presumably small occur between rocks of Triassic and Jurassic ages in Switzerland (Badoux and Weisse, 1959).

#### AFRICA

The largest and most valuable deposits of bauxite that have been mined in Africa are in Guinea and Ghana (fig. 9), but small deposits in Sierra Leone are now being mined, development is planned for deposits in Angola, and small deposits in Mozambique have been worked for refractory materials for many years. Very large potential bauxite resources are present in Cameroon, and deposits in Mali and Upper Volta and in the Congo (Léopoldville) may also be of moderate size or larger; however, these deposits are in remote areas or conditions are otherwise unfavorable for mining, and they probably will not be

developed for many years. Bauxite deposits that are small, low grade, incompletely explored, or unfavorably located for development occur in Senegal, Portuguese Guinea, Ivory Coast, Southern Rhodesia, Malagasy Republic, Tanganyika region of Tanzania, and other countries.

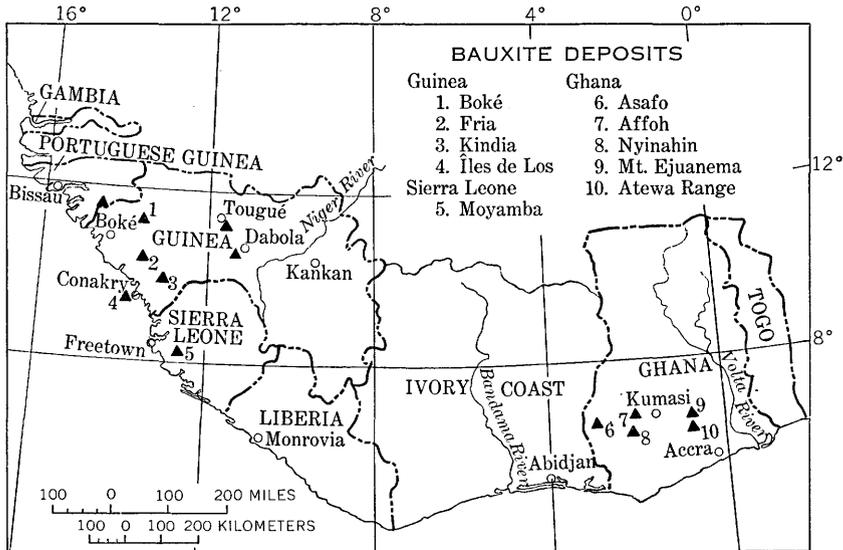


FIGURE 9.—Location of principal bauxite deposits in West Africa.

Most of the valuable bauxite deposits in Africa are of the lateritic type and occur at the surface or under shallow overburden. Gibbsite is the chief bauxite mineral in all these deposits, but minor amounts of boehmite are present in much of the bauxite.

#### ANGOLA

A contract for the exploration of bauxite in Angola, between the Government of Portugal and N. V. Billiton Maatschappij of The Hague, Netherlands, was announced in 1957 (Baker and Diggs, 1957. (b). A more recent report (Mining World, 1960) notes that a Portuguese aluminum company has developed bauxite deposits in the Dondo district where an aluminum plant having a capacity of 50,000 tons a year is planned. No information is available on the size and grade of the deposits; however, reserves and resources of at least small tonnages must be present if the report of development and intended plant construction is correct.

#### CAMEROON

Bauxite deposits occur at several places in Cameroon. Very large deposits of lateritic bauxite have recently been discovered near the villages of Minim and Martap, about 120 kilometers southwest of

Ngaoundéré. The deposits cap the Ngaoundal plateau at altitudes of more than 1,200 meters. Thicknesses of the laterite layers range from 3 to 15 meters, the approximate average  $\text{Al}_2\text{O}_3$  content is 42 percent, and the  $\text{SiO}_2$  content is between 1 and 4 percent (Cedat, 1961, p. 21). Over 2,500 hectares had been prospected by the end of 1959, and an estimated 500 million tons of lateritic bauxite containing 44 percent  $\text{Al}_2\text{O}_3$  and 3 percent  $\text{SiO}_2$  had been discovered (Cedat, 1961, p. 10). By the end of the following year the total area prospected by the Bureau de Recherches Géologiques et Minières had been doubled and the resource estimates increased to 900 million tons (Cedat, 1961, p. 28). Of this tonnage, more than 100 million tons contains only 1–2 percent  $\text{SiO}_2$ . In this area, total bauxite resources containing 40 percent  $\text{Al}_2\text{O}_3$  may total as much as 2 billion tons (Wilmot and others, 1960, p. 238).

Bauxite deposits also occur at several places in the Deschang region. Deposits at Fongo Tongo contain approximately 46 million tons of bauxite, from which 34 million tons of coarse material containing 45 percent  $\text{Al}_2\text{O}_3$  and 4 percent  $\text{SiO}_2$  could be recovered (Cedat, 1961, p. 20). Deposits at Bamboutos contain 4 million tons of lateritic bauxite that is 46 percent  $\text{Al}_2\text{O}_3$  and 4.3 percent  $\text{SiO}_2$ . Deposits in the Bangam sector are approximately the same size as those at Fongo Tongo, but the bauxite minerals are more irregularly distributed and the quality is lower.

The total inferred bauxite in Cameroon was estimated by Bárdossy (1964, table 1) to be 1.5 billion tons, and this figure is probably of the right order of magnitude. All this bauxite is considered to be a potential resource rather than a reserve, because none of it is mined; the plant at Edea uses imported alumina, and most deposits are in remote areas. However, construction of a railroad inland from the coastal city of Douala has been proposed, and should these plans materialize, Cameroon would possess one of the world's major bauxite reserves.

#### CHAD

Bauxite deposits cap plateaus in a few areas in southwestern Chad. Deposits on the Koro plateau near Lai have an average thickness of 17 feet. They formed on kaolinitic rocks of Tertiary age. The best deposits according to De Kun (1965, p. 307) contain 3.5 million tons, and this bauxite is 57.3 percent  $\text{Al}_2\text{O}_3$ , 8.2 percent  $\text{Fe}_2\text{O}_3$ , 3.8 percent  $\text{TiO}_2$ , and 3.7 percent  $\text{SiO}_2$ . An estimate of 30 million tons of inferred bauxite was listed by Bárdossy (1964, table 2) for the total in Chad. This figure is assumed to be correct in this report.

#### CONGO (LÉOPOLDVILLE)

Several efforts have been made to find bauxite deposits to supply a proposed plant that would utilize the hydroelectric power potential

at Inga on the Congo River. The deposits investigated include (1) aluminous laterite overlying granitic rocks on a high plateau between the Ituri, Bima, and Rubi Rivers (Sluys, 1946); (2) extensive laterite deposits northeast of Mayumbe, approximately 60 kilometers north of Inga (Stas, 1959); and (3) Laterite near the village of Kinzauki on the Sumbi-Isanghila road (Grosemans, 1959). The  $\text{Al}_2\text{O}_3$  contents of a number of samples from several localities (Vanderstappen and Cornil., 1955, p. 693) range from 34 to 52 percent and the  $\text{SiO}_2$  from 26 to 42 percent. These samples are chiefly kaolin clays containing minor amounts of gibbsite. Another suite of composite samples from several pits representing deposits 4–5 meters thick was investigated by Keyser (1959), who found that the laterite was a mixture of gibbsite, hematite, goethite, and small amounts of kaolinitic clay. The silica content of these samples is less than 6 percent, but iron oxide and titania contents are high, and  $\text{Al}_2\text{O}_3$  is only about 40 percent. According to one estimate (Refractories Jour., 1959), the amount of bauxite in the Congo (Léopoldville) is at least 50 million tons and may be as high as 100 million tons. The larger figure was used for inferred bauxite by Bárdossy (1964, table 2) and is assumed to be correct for potential bauxite resources in this report.

#### GHANA

Bauxite was discovered in Ghana in 1914 by Sir Albert Kitson, former Director of the Gold Coast Geological Survey (Cooper, 1936, p. 6). Mining began in 1941, and the average yearly exports during the period 1955–59 were 159,000 tons (Bracewell, 1962, p. 89). The deposits are scattered across a belt 150 miles long and 50 miles wide, 80–100 miles north of the coast. They cap flat-topped remnants of highly dissected plateaus. The major deposits are grouped in the following areas (fig. 9): (1) Nyinahin, Ashanti Region; (2) Affoh, near Sefwi Bekwai, Western Region; (3) Asafo near Asempanaiye, Western Region; (4) Mount Ejuanema near Nkawkaw; and (5) Atewa Range, Eastern Region.

The deposits in the Ashanti and Western Regions rest on steeply dipping folded and sheared phyllites, lavas, ashes, and tuffs of probable Precambrian age. These rocks locally contain grits, conglomerates, and granitic intrusions that weather to bauxite rich in silica or iron. The Ejuanema deposits and others in the Eastern Region formed on flat-bedded shales of Carboniferous age.

The Nyinahin bauxite deposits are scattered over an area 20 miles long, about 40 miles west of Kumasi. They cap a highly dissected plateau at an altitude of 2,000 feet. Most deposits support only grass and scrub vegetation, but trees grow in a few places where soil is adequate. Deposits range in thickness from 20 to 50 feet and are overlain by a rubbly soil as much as 6 feet thick. The bauxite

is mostly vermicular, but cemented and pisolitic types are also present. Most bauxite at the surface is very hard, and that at depth is soft. The bauxite is cream colored, yellow, orange, pink, red, and purple. Reserves of bauxite in the Nyinahin area are estimated to be 168 million tons (Cooper, 1936, p. 30). The compositions of 18 samples for which analyses were given by Cooper are as follows: 41.40–62.89 percent  $\text{Al}_2\text{O}_3$ , 0.20–3.13 percent  $\text{SiO}_2$ , 1.16–30.93 percent  $\text{Fe}_2\text{O}_3$ , 1.49–5.30 percent  $\text{TiO}_2$ , and 21.6–30.99 percent  $\text{H}_2\text{O}$ .

Affoh bauxite deposits are north of Sefwi Bekwai town and about 55 miles west of Dunkwa. The deposits cap nearly flat hills at altitudes of 1,000–1,800 feet. Laterite cappings range from 20 to 60 feet in thickness. Quartz veins and stringers are common in some deposits, and both gold and silver are associated with the quartz and would be valuable byproducts if the bauxite were mined (Cooper, 1936, p. 20). Total bauxite in the Affoh area was estimated by Cooper (1936, p. 22) at 31,400,000 tons and deposits in other nearby hills at 1,030,000 tons. The range in composition of eight samples from the Affoh bauxite deposits is listed in table 6. The Kanaiyerebo deposits in the Affoh Group have been worked by the British Aluminum Co. Ltd., since early in World War II (Bracewell, 1962, p. 91). These deposits are chiefly gibbsite, but they contain sufficient monohydrate bauxite for profitable recycling at higher temperatures and pressures after the alumina trihydrate has been extracted at low temperatures.

Asafo bauxite deposits occur in hills east of the Bia River, 40 miles north of Wiawso and about 100 miles by road from Dunkwa. Observed thicknesses of the deposits range from 25 to 38 feet. They are estimated to contain a bauxite reserve of 25 million tons (Cooper, 1936, p. 30). Of this reserve 20 million tons is approximately 50 percent  $\text{Al}_2\text{O}_3$  and 20 percent  $\text{Fe}_2\text{O}_3$ , and 15 million tons is 55 percent  $\text{Al}_2\text{O}_3$ .

Mount Ejuanema bauxite deposits are on a flat highland along the excarpment of the faulted and dissected Kwahu plateau. They are at an altitude of 2,500 feet and about 1,700 feet above the railway at Nkawkaw 2 miles away. This town is 112 miles by railway from the port at Accra. The bauxite has weathered from a bed of shale in the upper part of a thick section of sedimentary rocks of probable Carboniferous age. The following section, which is typical of the deposits in general, is a modification of Cooper's section (1936, p. 18), which was based on earlier work by Kitson (1925, p. 17–22).

	<i>Thickness (feet)</i>
Red soil (finely granular bauxite) -----	2.7
Massive bauxite boulders and blocks, partly pisolitic -----	12.6
Rubbly bauxite -----	8.0
Bauxitic clay, grading downward through partially altered shale into fresh shale -----	2.2

Kitson (in Cooper, 1936, p. 19) estimated that the Mount Ejuanema deposits contain 4 million tons of bauxite. These deposits were mined during World War II (Bracewell, 1962, p. 91). The following analyses of Ejuanema bauxite were given by Cooper (1936, p. 18) :

	Mean of 17 analyses of various types of bauxite	Mean of 3 analyses of 3 lots of 176 pieces of bauxite from surface blocks	Mean of 7 samples of different grades from various depths of shaft 36
Al <sub>2</sub> O <sub>3</sub> -----	60. 55	60. 97	52. 29
Fe <sub>2</sub> O <sub>3</sub> -----	9. 75	9. 60	18. 44
TiO <sub>2</sub> -----	2. 21	1. 85	1. 58
SiO <sub>2</sub> -----	1. 42	. 62	2. 02
CaO-----	} . 73	{ . 59	} Not determined.
MgO-----			
H <sub>2</sub> O-----	25. 59	26. 40	25. 53

The Atewa Range bauxite deposits occur on the flat-topped summits of low mountains. These deposits overlie and presumably formed from rocks of Precambrian age (J. M. Hunter, 1961). The deposits were once thought to be only minor occurrences (Cooper, 1936, p. 7), but significant tonnages of low-grade bauxite have since been discovered.

The reserves of bauxite in Ghana are incompletely known but are estimated to be 290 million tons. This figure includes the total of 230 million tons estimated by Cooper (1936) and an estimate of 60 million tons for recently discovered deposits in the Atewa Range near Kibi (J. E. Cudjoe, Director, Ghana Geol. Survey, written commun., 1963). One recent unconfirmed report (Eng. Mining Jour., 1963b) states that more than 400 million tons of bauxite has been discovered at Hinahini and elsewhere in Ghana. (Hinahini is probably a variation of Yenahin, as used by Cooper (1936); the official name is now Nyinahin (S. Bracewell, geologist, Overseas Geol. Surveys, written commun., 1963). Potential resources of bauxite in Ghana are arbitrarily considered to be 110 million tons, the difference between the reserve estimates and the figure given in the Engineering and Mining Journal (1963b). This potential resource figure may be very conservative, inasmuch as several minor bauxite occurrences were listed by Cooper (1936, p. 7, 31-32), and he noted that many hills, not investigated, represent parts of high peneplains and are capped by laterite of considerable thickness.

#### GUINEA

Small deposits of bauxite occur in the Îles de Los near the port of Conakry, and extremely large deposits occur at several places on the mainland. Large mainland deposits are in the Boké, Dabola, Kindia-

Friguiagbé, Badi-Konkouré (Fria), and Tougué-Dabola regions. Nearly all mainland deposits occur on plateaus characterized by open or brushy, gently rolling uplands incised by wooded stream valleys. This type of country is known as "bowes" or the singular "bowal." The "bowes" are at altitudes ranging from 900 feet at Boké to about 3,500 feet near Dabola. The large lateritic bauxite deposits vary considerably in composition (table 6).

*Îles de Los.*—The bauxite deposits in the Îles de Los consist of an upper layer 1–3 meters thick cemented by ferruginous material and an underlying red concretionary layer 5–10 meters thick (Bonifas, 1959, p. 82–91). The concretionary layer, in turn, grades downward into fresh nepheline syenite, from which the bauxite has weathered, through a porous layer that is only 5–10 cm thick. Gibbsite is the principal mineral in the deposits, but some hematite and anatase are also present. The washed bauxite from these deposits contains an average of 54 percent  $\text{Al}_2\text{O}_3$ , 6 percent  $\text{SiO}_2$ , and 11 percent  $\text{Fe}_2\text{O}_3$ , and 28 percent  $\text{H}_2\text{O}$ . Proved reserves in the Îles de Los were reported by Moyal (1956, p. 1059) to be 5 million tons on Kassa Island and 4 million tons on Tamara Island. Bauxite was mined on Kassa Island for several years and reserves are now virtually exhausted; therefore the total reserves in the Îles de Los probably do not exceed 5 million tons.

*Badi-Konkouré (Fria).*—Large bauxite deposits occur near the junction of the Badi and Konkouré Rivers. These deposits now supply the new alumina plant at Fria to which a railroad was built to provide access to the port of Conakry.

Extensive drilling and test pitting on 150-meter centers in an area of more than 3,000 acres have revealed bauxite reserves conservatively estimated at 150 million tons (Annales Mines, 1958, p. 690). A more recent estimate places the bauxite reserves of the entire Fria district at 300 million tons (Wilmot and others, 1960, p. 238).

Laterite deposits 25–30 feet thick formed on a dolerite sill that overlies schist along the Konkouré River (Lajoinie and Bonifas, 1961). The laterite consists of red gibbsitic earth containing hard lumps and crusts and is underlain by a red clay zone. This clay is underlain by a yellow clay in which the structures of the dolerite are preserved; residual dolerite boulders occur in the lower part of this zone. Gibbsite is the only bauxite mineral in these deposits. Goethite is the most abundant iron mineral, but hematite is common, particularly in the uppermost part. Kaolinite is the principal clay mineral, but chlorite also occurs in the least weathered part of the laterite. One sample (Lajoinie and Bonifas, 1961, p. 27) consisted of 47 percent  $\text{Al}_2\text{O}_3$ , 0.45 percent  $\text{SiO}_2$ , 22.40 percent  $\text{Fe}_2\text{O}_3$ , and 3 percent  $\text{TiO}_2$ , and the loss on ignition was 25.60 percent. Much of the bauxite contains

40–45 percent  $\text{Al}_2\text{O}_3$  and less than 2 percent  $\text{SiO}_2$  (Barrand and Gadeau, 1964, p. 28).

*Boké*.—Boké is a village on the tidal Nunez River. The very large bauxite deposits of the region are on both sides of the Congon River, and their center is about 55 miles northeast of Boké. Development of the deposits will require the construction of about 75 miles of railroad from the deposits to a harbor site at the mouth of the Nunez River (Bracewell, 1962, p. 169).

The bauxite occurs in the capping laterite layer of "bowes" at altitudes of 900–1,000 feet. The lower slopes of stream valleys between the "bowes" are generally covered by soil and forest, but laterite extends down into the valleys locally. Rock outcrops and boulders in the streams are chiefly gabbroic diabase that is believed to be part of a large diabase sill forming the parent rock of the laterite (Harder, 1952, p. 55). The diabase is fine grained and consists chiefly of andesine-labradorite, augite, and minor amounts of biotite and perthitic quartz-orthoclase intergrowths. Nearly horizontal thin-bedded sandstone and micaceous siltstone and shale of probable early Paleozoic age crop out in the Congon River and its deeper tributaries. These rocks presumably are part of the host rocks into which the diabase sill was intruded.

A typical section of the bauxite and laterite is 40–50 feet thick and consists of an upper iron-rich crust underlain by a softer bauxitic laterite that grades downward into a ferruginous bauxite layer. In a few areas the ferruginous bauxite rests on fresh diabase, but generally a layer of variegated clay and decomposed rock 30 feet thick or more intervenes between the laterite and fresh rock. The bauxite consists chiefly of gibbsite and hematite with minor amounts of goethite, boehmite, quartz, and kaolinite. Boehmite makes up as much as 4–5 percent of the bauxite at the surface. Harder (1952, p. 56) suggested that it formed by dehydration of more hydrous forms of aluminum under the hot tropical sun. The minor quartz in the laterite commonly, but not everywhere, decreases in quantity with depth. Kaolinite is most abundant in the lower parts of the laterite and presumably is a major constituent of the clay-rich layer below the laterite.

Reserves of bauxite in the Boké region amounting to several hundreds of millions of tons were expected to be outlined in systematic prospecting (Annales Mines, 1958, p. 690). According to a recent estimate, the reserves of bauxite in this region are approximately 700 million tons (Wilmot and others, 1960, p. 238). Some of this bauxite is as much as 55 percent  $\text{Al}_2\text{O}_3$ . Some of it must also be low in silica and iron oxide, as chemical and calcined abrasive and refractory grades produced from these deposits have been offered for sale by the Compagnie des Bauxite de Guinée (World Mining, 1965).

*Dabola.*—The town of Dabola is on the Conakry-Kankan railroad in central Guinea, about 250 miles from the coast. Bauxite deposits in this region are on “bowes” at altitudes of about 3,500 feet, between the Niger and Tinkisso Rivers. The deposits on the Ouroussa “bowal” near Dabola formed on diabase; elsewhere in this region laterite formed on mica schist (Lacroix, 1913, p. 283).

Extensive drilling on the Oursa (Ouroussa) and Sinseri “bowes” 1 or 2 miles north of Dabola (Moyal, 1956, p. 1062) and on other “bowes” 20 miles east and 30 miles west of Dabola has revealed very large deposits of bauxite. Total reserves of bauxite containing very little silica are reported to be well over 100 million tons.

*Kindia-Friguiagbé.*—Kindia is on the Conakry-Kankan railroad about 95 miles inland from Conakry, and Friguiagbé is about 12 miles southwest of Kindia. The bauxite deposits in this area cover nearly 2,000 acres, and their average thickness is 4–8 meters (Annales Mines, 1958, p. 690). By 1958, 85 million tons of bauxite had been proved. This bauxite is 40–45 percent  $\text{Al}_2\text{O}_3$  and 5–6 percent  $\text{SiO}_2$ , and about one-third of the silica is in kaolinite (Barrand and Gadeau, 1964, p. 29).

One sample of bauxite weathered from sericite schist was taken 3 meters below the surface on a plateau a few kilometers southwest of Kindia. It was investigated by Alexander and Cady (1962, p. 27–29, table 6), who used X-ray and petrographic microscope techniques. This sample is approximately 80 percent gibbsite and contains identifiable quantities of boehmite and quartz and a moderate amount of hematite. The gibbsite occurs in both concretions and light-colored matrix. The concretions are dark red, pale red, yellowish pink, and white with red bands. Many of the concretions consist of alternate irregular bands of pure crystalline gibbsite and iron-impregnated material. The matrix consists chiefly of unoriented aggregates of gibbsite crystals that are less than 10 microns in size. Quartz grains are scattered throughout the bauxite, and some grains are loose and occupy round holes. The quartz has either formed secondarily or the matrix has shrunk away from grains during dehydration.

*Tougué-Dabola.*—Extensive bauxite deposits occur between Tougué and Dabola in Guinea. These deposits were reconnoitered by Goloubinow (1938), and those somewhat farther south by Chermette (1949). Bauxite of good grade is present in both areas. Only a few of the plateaus have been prospected; however, several hundred million tons of bauxite is known to be present (Annales Mines, 1958, p. 690). The bauxite is 15–30 feet thick, and most deposits are 40–44 percent  $\text{Al}_2\text{O}_3$  and less than 3 percent  $\text{SiO}_2$  (Barrand and Gadeau, 1964, p. 29).

*Bauxite reserves and resources in Guinea.*—Bauxite reserves listed in the foregoing discussion are as follows: (1) Îles de Los—5 million

tons; (2) Boké—700 million tons; (3) Dabola—more than 100 million tons; (4) Kindia-Friguiagbé—85 million tons; and (5) Badi-Konkouré—300 million tons. Total reserves of bauxite are approximately 1.2 billion tons.

Total potential bauxite resources are also very large. They include the marginal and submarginal deposits in the five regions containing reserves, as well as the very large deposits in the Tougué-Dabola region and other parts of the country which have not been adequately prospected. Though no realistic estimates of the total potential bauxite resources in Guinea are available, the total amount is probably as much as the 2.4-billion-tons figure published by Wilmot (1960, p. 21), and it may be much larger.

#### IVORY COAST

Bauxite deposits occur in several places in the Ivory Coast. Deposits have been prospected in the Bondoukou region, about 300 miles north-northeast of Abidjan (Baker and others, 1960a). Other deposits occur in the Lakota region, 125 miles northwest of Abidjan (Arnaud, 1945, p. 80-82), and at Tombokro on the White Bandama River and in the Kaya region of the Haute Côte (Bracewell, 1962, p. 171).

#### MALAGASY REPUBLIC (MADAGASCAR)

Deeply weathered rocks containing scattered bauxite deposits occur in several places in the Malagasy Republic. Ferruginous bauxite deposits on the Analavory and Marangaka plateaus at altitudes of 4,800-5,500 feet are 0.5-6.3 meters thick (Emberger, 1957). The deposits overlie granitic rocks from which they presumably have weathered. Much of the bauxite is in irregular porous and pisolitic ferruginous concretions scattered throughout fine-grained ferruginous rock; however, massive bauxite blocks are also present. The Analavory deposits are estimated to contain 4 million tons that is 54 percent  $\text{Al}_2\text{O}_3$  and the Marangaka 40 million tons that is 38 percent  $\text{Al}_2\text{O}_3$  (Besairie, 1960). Very ferruginous bauxite deposits occur at a number of places on the Tampoketsa plateau (Hottin, 1960). Some of these deposits are on basalt and others on sedimentary rocks. Much of this bauxite contains only 36-38 percent  $\text{Al}_2\text{O}_3$ , but scattered deposits contain as much as 50 percent  $\text{Al}_2\text{O}_3$ . D'Ankazobe deposits are estimated to contain approximately 800,000 tons, those at Fenoarivo 3.8 million tons, and the D'Analamaitso deposits as much as 5 million tons of bauxite.

Bauxite deposits overlying rocks of several types have recently been discovered in the Fort Dauphin-Isandra region in the southeastern part of the Malagasy Republic (Besairie, 1962). Rocks

below the bauxite include Precambrian leptynites and granites, basalt and rhyolite of Cretaceous age, and continental sediments of late Tertiary age. The economic appraisal of these deposits has not been completed, but considerable quantities of bauxite that contain 50–56 percent  $\text{Al}_2\text{O}_3$  are probably present. A recent report (Mining Jour., 1965b, p. 197) notes that a French aluminum company has discovered 70–75 million metric tons of bauxite in the Manantenina district, which is north of Fort Dauphin.

According to figures now available, the total bauxite in the Malagasy Republic, including much low-grade material, is approximately 120 million tons. No development of the deposits has been reported, and all this bauxite is considered to be a potential resource.

#### MALI

Many plateau areas in the western part of Mali are underlain by ferruginous laterites, and bauxite deposits occur along the Niger River. One old report (Bur. d'Études Géol. et Minières Coloniales, 1933) describes bauxite deposits near Koulouba, Kita, the Bassaro Plateau, M'Pébougou, along the Niger River, near Ségou, and at Quenkoro. Deposits from M'Pébougou reportedly contain 70–75 percent  $\text{Al}_2\text{O}_3$ , 1–2.6 percent  $\text{SiO}_2$ , and 2.0–2.8 percent  $\text{Fe}_2\text{O}_3$ . Part of the laterites along the Niger River are alluvial deposits (Jodot, 1934). The bauxite near Koulouba and Ségou is chiefly in pisolites of boehmite, but some gibbsite is also present (Lapparent and Hocart, 1938). Recent exploration has resulted in the discovery of a bauxite deposit in the Fantofa Plateau area where the bauxite is reported to contain 45 percent  $\text{Al}_2\text{O}_3$  (Wilmot and other 1960, p. 238). The total low-grade bauxitic laterite in parts of Mali near the Guinea border, containing 39–44 percent  $\text{Al}_2\text{O}_3$ , is estimated to be 550 million tons (De Kun, 1965, p. 79). Though these deposits are very large, they have little value because of their remote location and low grade.

#### MOROCCO

A possible bauxite reserve of 20 million tons containing 70 percent alumina was reportedly (Claiborne, 1928; Echo Minès et Métallurgie 1928) discovered in the Atlas Mountains of Morocco. A complete summary of the geology and distribution of minerals in Morocco, however, does not mention bauxite. One chapter of this summary (Jeannette, 1952) contains information on andalusite, semirefractory clays, and syenite. Some of these aluminous materials may have been erroneously referred to as bauxite in the earlier report.

#### MOZAMBIQUE

Small bauxite deposits at an altitude of about 6,000 feet occur near Penhalonga along the border between Mozambique and Southern

Rhodesia. The bauxite is in the form of gibbsite nodules intermixed with aluminous clays. Rock containing the deposits is weathered to depths of more than 100 feet.

Penhalonga deposits have been mined intermittently by hand-cobbing methods for a number of years. The bauxite is used for refractory brick and in the manufacture of aluminum sulfate. The average chemical composition of bauxite mined to 1941 was 61 percent  $\text{Al}_2\text{O}_3$ , 10 percent  $\text{SiO}_2$ , and 1-2 percent  $\text{Fe}_2\text{O}_3$  (Colin, 1942, p. 329); other analyses published by the Southern Rhodesia Geological Survey (Rhaup, 1937, p. 79) report that nodules of this grade are present. The reserves of bauxite in the Penhalonga deposits are 2.4 million tons, according to one estimate (Colin, 1942, p. 331). Of this amount only 68,000 tons was considered to be of commercial grade.

#### NYASALAND (NOW MALAWI)

Residual bauxite deposits derived from syenite of the Mlanje massif occur on the Lichenya Plateau. The deposits underlie rolling grassy and wooded uplands at altitudes of more than 6,000 feet. The deposits have been investigated by both government and private interests and are estimated to contain 60 million tons of bauxite (Cooper, 1957, p. 15-16). The average partial composition of 250 analyses is 42.73 percent  $\text{Al}_2\text{O}_3$ , 13.93 percent  $\text{Fe}_2\text{O}_3$ , and 1.57 percent  $\text{TiO}_2$ ; the bauxite contains 15.65 percent quartz and 2.2 percent other silicates. Gibbsite is the principal aluminous mineral in these deposits (Stephen, 1963), and it occurs in fine grains that are intermixed with kaolin minerals, quartz, and feldspar, as well as goethite, ilmenite, and several other heavy minerals. Quartz is particularly abundant where the bauxite is derived from pegmatite veins. The deposits have not been exploited, but sufficient attention has been given them to justify their classification as reserves instead of potential resources. Other bauxite deposits in Nyasaland are known to occur on the Chambe, Sombani, and Little Ruo Plateaus, in the Sombani and Ruo Valleys, and on the flanks of Manene Peak (Dixey, 1925), but apparently these are small or low grade.

#### PORTUGUESE GUINEA

Lateritic bauxite, of the type that is widespread in Guinea, occurs on "bowal" plateaus between Casamance and the Guinea border. The deposits rest on dolerite sills that overlie impure sandstone (Hose, 1960, p. 239). The laterite was described by Weisse (1954, p. 176) as consisting of a hard cemented surficial layer 2-3 meters thick overlying a brick-red vesicular layer 10-12 meters thick. These two layers are separated from the underlying weathered dolerite by a clayey concretionary layer and a bleached clay zone having a total

thickness of 3–5 meters. Gibbsite is the principal mineral in the deposits, but some boehmite is also present, as identified by differential thermal analysis. Mottled bauxite from these deposits contains 53.73–53.82 percent  $\text{Al}_2\text{O}_3$ , 0.89–1.25 percent  $\text{SiO}_2$ , 14.87–16.40 percent  $\text{Fe}_2\text{O}_3$ , 1.68–1.79 percent  $\text{TiO}_2$ , and 26.24–28.74 percent loss on ignition; a white bauxite contains 63.42 percent  $\text{Al}_2\text{O}_3$  (Weisse, 1954, p. 177). Bauxite deposits in Portuguese Guinea have been investigated by aluminum interests (South African Mining and Eng. Jour., 1958, p. 839), and potential resources are estimated to be approximately 10 million tons (Bárdossy, 1964, table 2).

#### SIERRA LEONE

Low-grade bauxite and small moderate-grade deposits at several localities have been mentioned in the Annual Reports of the Sierra Leone Geological Survey since 1920 (Bracewell, 1962, p. 97–98). Lateritic deposits in areas of “grassfields flats” on the narrow coastal plain of the Freetown Peninsula are derived from sedimentary clays and sands of Pleistocene age. Deposits along the boundary between Freetown Peninsula and Northern Province are derived from ijolite, an alkali-rich igneous rock. Large lateritic deposits in a range of hills east of Waia apparently formed from talc and amphibolite schist of the Kambui Series. Less combined silica was found in the laterite derived from schist than in laterite from mafic igneous rock. Laterite deposits are also known on dolerite in the northwestern part of the country and on the surface of a sand formation on the Great Plateau in the northeastern part.

Four samples of laterite representing intervals in sections 10–420 cm below the surface at a locality near York south of Freetown, contain 23.60–46.55 percent  $\text{Al}_2\text{O}_3$ , 3.60–7.76 percent  $\text{SiO}_2$ , 22.36–51.37 percent  $\text{Fe}_2\text{O}_3$ , and 1.28–3.00 percent  $\text{TiO}_2$  (Alexander and Cady, 1962, p. 16–17). These samples, except one very high in iron, are chiefly gibbsite. They contain 10–20 percent kaolin; goethite is the principal iron mineral.

Probably the best bauxite in Sierra Leone is in the Gbangbama neighborhood of the Mokañji Hills (Bracewell, 1962, p. 98). Bauxite in Moyamba district of this region was discovered by the Sierra Leone Geological Survey in 1959. This bauxite formed on anorthosite. Subsequent mapping revealed a belt extending along the watershed between the Chiefdoms of Banta and Dasse. This deposit is derived from a feldspathic band in hypersthene gneiss. The bauxite belt is not more than 150 yards wide, but it is known to extend along the strike for 18 miles. Its thickness is reported to be variable, and the maximum known is 50 feet. This deposit is now under development by the Sierra Leone Ore and Metals Co., a subsidiary of a Swiss aluminum company.

Bauxite has recently been discovered by the Sierra Leone Geological Survey in the Krim-Kpaka Chiefdom just south of the town of Pujehun (Sierra Leone Geol. Survey Dept., 1964, p. 13). The deposits occur on flat hilltops and overlie weathered feldspathic gneiss. They have only been reconnoitered but are known to cover about 1 million square yards. The few drill holes and test pits that have been sunk in the bauxite reveal that the deposits are 30–35 feet thick.

Most of the bauxite in Sierra Leone is too inadequately prospected to provide reserve and grade information. One report (Daniels and Derbyshire, 1959) describes deposits north of Bumbuna as probably containing 25–30 million tons of bauxite that is about 40 percent  $\text{Al}_2\text{O}_3$ . These deposits, those in the Freetown Peninsula, Mokanji Hills, and in the Kpaka Chiefdom, probably provide a total bauxite reserve of at least 30 million tons in Sierra Leone.

#### SOUTHERN RHODESIA

Alumina-rich clays, gibbsite-rich nodules, and laterite occur in Southern Rhodesia on the slopes of ridges along the Southern Rhodesia-Mozambique border and in the area north of Umtali. Deposits north of Penhalonga are unsuitable for refractory brick but can be used for aluminum sulfate. One partial chemical analysis (South African Mining and Eng. Jour., 1941), showed 64.91 percent  $\text{Al}_2\text{O}_3$ , 5.86 percent silica, and 1.09 percent iron. The only available estimate of resources of bauxite is 2 million tons (Rhodesian Mining Jour., 1957) in deposits near the Southampton mine about 5 miles north of Umtali.

#### TANZANIA

Large areas favorable for bauxite in Tanganyika region of Tanzania have only been partly explored. Several small deposits have been reported, and the outlook is favorable for additional discoveries. The best bauxite that has been reported (Teale and Oates, 1946, p. 70–71) is on the Usambra highlands near the town of Amani, which is about 50 miles west of the port of Tanga. At this locality, the bauxite overlies hornblende-pyroxene granulite and garnet-biotite-pyroxene gneiss. One of three samples from Amani that were analyzed (Teale and Oates, 1946, p. 71) contained 57.7 percent  $\text{Al}_2\text{O}_3$ , 10.53 percent  $\text{SiO}_2$ , 1.15 percent  $\text{Fe}_2\text{O}_3$ , and 1.66 percent  $\text{TiO}_2$ , and 26.8 percent  $\text{H}_2\text{O}$ , but the other two samples were high in  $\text{SiO}_2$  and low in  $\text{Al}_2\text{O}_3$ .

#### OTHER AFRICAN COUNTRIES

Bauxite deposits in Liberia occur near Zigida in the Western Province and in the Careysburg district in the Central Province (Bracewell, 1962, p. 171). Extensive laterite deposits in Nigeria

were reconnoitered for bauxite by the British Aluminum Co. (Bracewell, 1962, p. 94); however, no valuable bauxite was discovered. Bauxite occurs at Kaya, Sikasso, and Bobo-Dioulasso in Upper Volta (De Kun, 1965, p. 306). The occurrence of bauxitic material on the Seychelles Islands has been known for many years (Bauer, 1898), but these deposits reportedly have very little economic value (Fox, 1932, p. xxix). Bauxite has been discovered on Agu Mountain in Togoland (Robertson, 1921, pp. 40-41) about 60 miles northwest of the port of Lome. This bauxite contains 46-53 percent  $\text{Al}_2\text{O}_3$  and 18-30 percent  $\text{Fe}_2\text{O}_3$  (Arnaud, 1945, p. 84). Low-grade lateritic bauxite has been reported in Uganda in the Northern and Eastern Provinces and Buganda (Wayland, 1921, p. 54), and diaspore occurs on Kawere Island in Lake Kyogo (Bisset, 1943, p. 18). Deposits of ceramic-grade diaspore and pyrophyllite containing 51.7 percent  $\text{Al}_2\text{O}_3$  occur in Swaziland (De Kun, 1965, p. 308). Aluminous deposits in the Phalaborwa area have been explored, but no large deposits of bauxite have been found (Mining Jour., 1965b, p. 185). Lateritic accumulations are also reported to occur on the Cape Verde Islands and in the Congo (Brazzaville), Kenya, Egypt, and Algiers (Fox, 1932, p. 95-103). Most of these deposits are probably ferruginous laterites and have little value as bauxite. Very large deposits of weathered aluminous phosphatic rocks in Senegal have been called laterite (Bruckner, 1957, pp. 248-250); however, this rock is quite different in composition from typical laterites and will be discussed with potential sources of aluminum other than bauxite (p. 118).

#### ASIA (EXCLUDING U.S.S.R.)

Extensive deposits of bauxite occur in India and mainland China; deposits of small or moderate size occur in Indonesia, Malaysia, including Peninsular Malaysia and Sarawak, Pakistan, and North Viet Nam; and low-grade laterite is common on some of the islands in the Philippines. In addition, large areas of Southeast Asia lie in the tropics, and many extensive areas favorable for bauxite have been inadequately explored. Accordingly, significant bauxite discoveries may be made in the future in Cambodia, Laos, and South Viet Nam, as well as in countries in which bauxite is now known to occur. Bauxite is now mined for aluminum in India, Indonesia, Malaysia, including both Peninsular Malaysia and Sarawak, and mainland China. Small tonnages of bauxite were mined in North Viet Nam for aluminum during World War II, and minor quantities of bauxite in Pakistan have been used in making cement.

## CHINA (MAINLAND)

Very large bauxite deposits occur in several provinces of mainland China (fig. 10). Some of these deposits have been discovered recently during a large-scale search for raw material to supply an expanding aluminum industry. Very little detailed information on the geology of the deposits is available, and much of the information on grade, size, and location of the deposits is inferred. Most of the bauxite is in rocks of Paleozoic age, and much of it is in clays and shales. Nearly all the bauxite is chiefly diaspore or boehmite. Alumina content of these bauxites is generally higher than that of most bauxite now processed in other countries; however, bauxites consisting of diaspore and boehmite cannot be treated by the Bayer process, and more expensive alumina-extraction processes are required.

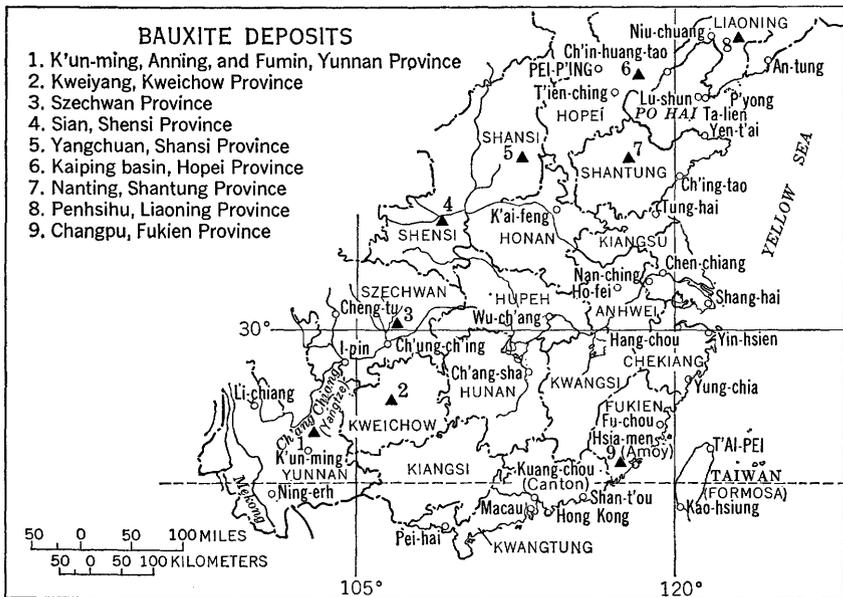


FIGURE 10.—Location of principal bauxite deposits in China (mainland).

*Yunnan Province.*—Very large deposits of bauxite occur near K'un-ming, and other deposits are present in the Anning and Fumin districts in Yunnan Province. The deposits occur between rocks of Devonian and Carboniferous ages. The bauxite is reported to be composed of both diaspore and boehmite. Dr. P. F. Kerr of Columbia University identified boehmite in one sample by X-ray methods (Li and Hsieh, 1946, p. 4); available information on the identification of diaspore is less reliable. The deposits were described as similar to the bauxites in Kweichow Province. Bauxite reserves in

the vicinity of K'un-ming are estimated at 100–150 million metric tons, and 20 million metric tons of this reserve is considered to be high-grade bauxite (K. P. Wang, 1959, p. 75). The high-grade ore is 70 percent  $\text{Al}_2\text{O}_3$ , 6 percent  $\text{SiO}_2$ , and 11 percent  $\text{Fe}_2\text{O}_3$ , and the average grade is 52 percent  $\text{Al}_2\text{O}_3$ , 33 percent  $\text{SiO}_2$ , and 3 percent  $\text{Fe}_2\text{O}_3$ .

*Kweichow Province.*—Very large deposits of bauxite occur in the vicinity of Kueiyang, in the central part of Kweichow Province. The deposits are above dolomitic limestones of Ordovician age and are overlain by a Lower Carboniferous coal series. The bauxite deposits form a rather persistent bed about 8 meters thick. They consist chiefly of diaspore, and the identification of this mineral has been confirmed in one sample by Dr. P. F. Kerr of Columbia University (Li and Hsieh, 1946, p. 3). The reserves of bauxite in this district are approximately 200–500 million metric tons, and at least 50 million metric tons is high grade (K. P. Wang, 1959, p. 75). The high-grade bauxite is reported to contain 70 percent  $\text{Al}_2\text{O}_3$ , 9 percent  $\text{SiO}_2$ , 1 percent  $\text{Fe}_2\text{O}_3$ , and 2 percent  $\text{TiO}_2$ .

*Szechwan Province.*—Bauxite clays occur in the southern part of Szechwan Province. The clays are in lenses and pockets in the upper part of a coal series of Permian age, and they are overlain by limestone. Alumina contents of this clay range from 48 to 78 percent (Li and Hsieh, 1946, p. 4). No estimates of the amount of bauxitic clay in this province are available.

*Shensi Province.*—Bauxitic deposits have been discovered recently in the vicinity of Sian. Detailed information on the geology, location, and size of these deposits is not available, but they probably supply the new alumina plant at Sian. The deposits are undoubtedly extensive and probably consist of aluminous shale, some of which is of good grade (K. P. Wang, 1959, pp. 75–76).

*Shansi Province.*—High-alumina shale deposits reportedly occur in the vicinity of Yangchuan, Shansi Province (K. P. Wang, 1959, p. 75). The deposits are reported to contain 45–55 percent alumina. The size of the deposits is unknown, but they are probably at least moderately extensive.

*Hopei Province.*—Bauxitic clays and high-alumina shales occur in several places in the Kaiping basin, Hopei Province. The deposits are estimated to contain 100–400 million metric tons of aluminous rock, and at least 30 million metric tons is probably high grade (K. P. Wang, 1959, p. 75). The rock is 50–70 percent  $\text{Al}_2\text{O}_3$ , 5–27 percent  $\text{SiO}_2$ , 1–15 percent  $\text{Fe}_2\text{O}_3$ , and 1–3 percent  $\text{TiO}_2$ .

*Shantung Province.*—The most productive bauxite mines in mainland China are near the Tsingtoa-Tsinan railroad in the general vicinity of Nanting, Shantung Province. Bauxite was mined from

these deposits during Japanese occupation, and the deposits now supply the alumina plant at Nanting (Kleinbans, 1948, p. 4). The most productive areas are reported to extend over 800 square kilometers.

The bauxites and associated bauxitic clays and shales are in a coal series of Paleozoic age. Bauxitic rocks occur in seven different beds or seams, but only two beds, which have been referred to as beds A and G, are of major economic importance (Kleinbans, 1948, p. 4). These beds are irregular in thickness, and the best bauxite occurs near the middle of the thicker parts of the bed. Diaspore is the principal bauxite mineral present, and kaolinite occurs in the upper and lower parts of the deposits. The best grade bauxite is reported to be 60 percent  $\text{Al}_2\text{O}_3$ , 13 percent  $\text{SiO}_2$ , 10 percent  $\text{Fe}_2\text{O}_3$ , and 2 percent  $\text{TiO}_2$ . Reserves and resources are estimated to be between 100 and 300 million metric tons; at least 30 million metric tons is high-grade bauxite (K. P. Wang, 1959, p. 75) and possibly as much as 68 million tons (C. C. Wang, 1932, p. 30).

*Manchuria.*—High-alumina shale deposits occur at several places in Manchuria, and the deposits have been mined at several places in Liaoning Province. Beds A and G are both present in coal fields in Manchuria. Bed A is 200–500 meters above bed G (Sakamoto, 1951). Bed A is in the upper part of a productive coal-bearing formation of Permian age. Bed G is at the base of a formation of mid-Carboniferous age, and it rests unconformably on limestone or dolomite of Ordovician age. The high-alumina shale is in lenses 0.5–6 meters thick which are associated with deposits of kaolinitic flint clay. Diaspore and boehmite are present in the shale, and both kaolinite and halloysite occur in the flint clay. Alumina shale in the vicinity of Penhsihu, Liaoning Province, contains 50–100 million metric tons, and possibly 20 million metric tons is high grade (K. P. Wang, 1959, p. 75). The grade of the rock mined is 53 percent  $\text{Al}_2\text{O}_3$ , 20 percent  $\text{SiO}_2$ , 10 percent  $\text{Fe}_2\text{O}_3$ , and 3 percent  $\text{TiO}_2$ . Sakamoto (1951) gave an analysis of the shale that is considerably higher in alumina than analyses given by Wang, but no information on the amount of the high-grade material is available.

*Inner Mongolia.*—Small alumina reserves have been reported recently as occurring on the Ordos grasslands in Inner Mongolia. These deposits were found during extensive work by many teams of prospectors. No detailed information on the deposits is available. However, Sakamoto (1951) mentioned that bed G occurs in Inner Mongolia, and the deposits are probably aluminous shales associated with coal-bearing rocks.

*Fukien Province.*—Small bauxite deposits consisting chiefly of gibbsite occur in the Changpu district along the coast southwest of

Amoy. The deposits were discovered shortly after World War II. These deposits are virtually the only ones in China suitable for treatment by the Bayer process. The bauxite is associated with red clay and laterite and probably formed from the weathering of basalt. The deposits are at the surface and could easily be mined. Apparently they have never been fully explored; however, they are reported to contain 500,000 tons of bauxite (Kleinhans, 1948, p. 7).

*Resources of bauxite in mainland China.*—High-grade bauxite reserves in Shantung, Liaoning, Kweichow, Hopei, and Yunnan Provinces total approximately 150 million tons (K. P. Wang, 1959, p. 75). Total potential bauxite resources are estimated at between 400 million and 1.3 billion tons, plus large deposits in Shensi and Shansi Provinces, for which no estimates are available (K. P. Wang, 1959, p. 75). Because of wide range in the estimates and the absence of information on many deposits, the resources of bauxite are considered to be 1 billion tons.

#### CHINA (FORMOSA)

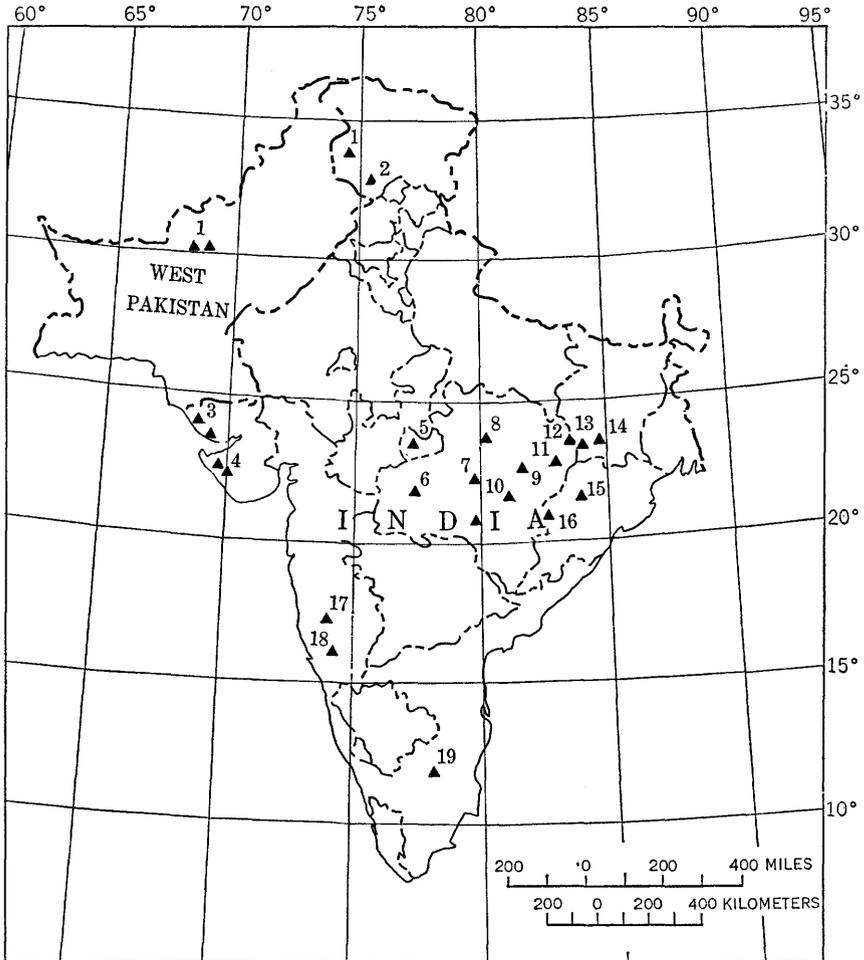
Small deposits of bauxite were discovered on the island of Chinmen (Quemoy) in 1948. The bauxite occurs in irregular deposits that are mostly less than 1 meter thick. The deposits are associated with clays overlying weathered basalt. Contents of  $\text{Al}_2\text{O}_3$  in the bauxite range from 40 to 50 percent, and both iron and silica are abundant in most of the deposits. Reserves in these deposits were estimated at 150,000 metric tons (U.S. Bur. Mines, 1948), and 2,000 tons was shipped in the early 1950's to the Taiwan Aluminum Corp. plant on Taiwan (Formosa) for testing. The reserve estimate was probably overly optimistic (S. Rosenblum, oral commun., 1963), and the quality of the bauxite is not competitive with that of imports from Malaysia and Indonesia.

#### INDIA

High-alumina laterites were first recognized in India in 1883, and production of bauxite began about 1910 (Bracewell, 1962, p. 119). In 1960, nearly 377,500 tons of bauxite was produced and used in making abrasives, alumina, cement, chemicals, petroleum catalysts, and refractories, and in purifying kerosene. Planned expansion of the aluminum industry will probably increase bauxite mining considerably in the next decade.

Bauxite deposits of several types occur in India. Most deposits are in blankets capping plateaus at 900–4,500 feet above sea level. These deposits are scattered throughout the central part of the peninsular shield. The plateau deposits are aluminous laterite, and gibbsite is the principal bauxite mineral. The largest and best grade

plateau bauxite deposits are in the following districts: (1) Ranchi and Palamau, Bihar (fig. 11); (2) Jabalpur, Mandla, Balaghat, Bilaspur, and Surguja (Sarguja), Madhya Pradesh; (3) Kalahandi, Orissa; and (4) Kolhapur and Kolaba, Maharashtra. Small or low-grade plateau deposits occur in Bhopal; Madhya Bharat; on the Seoni Plateau and other localities in Madhya Pradesh; scattered areas in Bihar; Sambalpur, Orissa; Bababudan Hills and Belgaum, Orissa;



**West Pakistan**

1. Ziarat

**India**

1. Punch, Kashmir

2. Riasi, Kashmir

3. Kutch, Gujrath

4. Saurashtra, Gujrath

5. Bhopal

6. Madhya Bharat

7. Seoni Plateau, Madhya Pradesh

8. Jabalpur, Madhya Pradesh

9. Mandla, Madhya Pradesh

10. Balaghat, Madhya Pradesh

11. Bilaspur, Madhya Pradesh

12. Surguja (Sarguja), Madhya Pradesh

13. Palamau, Bihar

14. Ranchi, Bihar

15. Kalahandi, Orissa

16. Sambalpur, Orissa

17. Kolhapur and Kolaba, Maharashtra

18. Bababudan Hills and Belgaum, Mysore

19. Salem, Madras

**FIGURE 11.**—Location of principal bauxite deposits in India and West Pakistan.

Mysore; Salem district, Madras; and at other localities. Low-level laterite deposits, also consisting chiefly of gibbsite, underlie coastal areas in Kutch and Saurashtra, Gujrath. Deposits consisting chiefly of diaspore occur in the Punch and Riasi areas of Kashmir.

The main laterite deposits are in regions of flat-topped ridges and plateaus with narrow intervening valleys. Individual plateaus are as much as 20 miles long and a few miles wide. Most of them are uninhabited grassy tablelands with sheer scarps on their margins. The capping laterite is fairly uniform in thickness, averaging 60–70 feet in most places where parts have not been eroded. Laterite deposits also occur locally on the slopes and in the valleys between plateaus. Many of these deposits contain large blocks of laterite, and all of them probably formed by slumping of high-level deposits (Roy Chowdhury, 1955, p. 198).

*Bihar.*—The most valuable bauxite deposits in India are in highlands of the Ranchi district and adjoining parts of the Palamau district, Bihar State (Roy Chowdhury, 1958, p. 29). Extensive laterite-type bauxite deposits cap plateaus and ridges at altitudes of 2,900–3,350 feet, and accumulations of detrital laterite occur at scattered localities in valleys. Most of the bauxite is a residual weathering product of the Deccan trap of Cretaceous age. Total reserves of bauxite in Bihar containing more than 50 percent  $\text{Al}_2\text{O}_3$  are conservatively estimated at more than 10 million tons (Roy Chowdhury, 1958, p. 29). Small low-grade deposits occur in the Kharipur Hills, Monghyr district, Bihar (Anandalwar, 1962). These deposits contain about 1.5 million tons of bauxite. Most of it is only 35–40 percent  $\text{Al}_2\text{O}_3$ , but some higher grade bauxite is also present.

*Gujrath.*—Belts of laterite as much as 30 miles long and a few miles wide occur along the margins of the Deccan trap in Saurashtra and Kutch (Roy Chowdhury, 1955, p. 213). The belts are most common in the coastal parts of Bhabhanagar, Junagadh, Porbandar, and Nawanagar. Much of the laterite is covered by younger alluvial deposits, and in places the laterite is overlain by about 2 feet of rocks referred to as the "Milliolite Limestone." Thicknesses average about 50 feet and are as much as 250 feet in a few places. The lateritic bauxite in the Nawanagar district is associated with fuller's earth, clays, and yellow and red ochres. Some of the bauxite is gray to white, hard, and pisolitic. Some good-quality bauxite is present, but much of the material is low in alumina and high in iron. Deposits in Saurashtra containing 55–65 percent  $\text{Al}_2\text{O}_3$  and 2–3 percent  $\text{SiO}_2$  are estimated to be about 1 million tons (Bracewell, 1962, p. 121–122), and more recent estimates published by the United Nations (U.N. Econ. Comm. Asia and Far East, 1962, p. 9) give a figure of 11 million tons of bauxite containing more than 50 percent  $\text{Al}_2\text{O}_3$  for the amount present in Saurashtra and Kutch.

*Kashmir*.—Deposits of bauxite having very high alumina contents occur in several areas near the town of Riasi, Jammu Province and in the Punch area. These deposits are stratigraphically above a rock unit known as the "great limestone" and are overlain by a series of coal-bearing rocks of Eocene age (Roy Chowdhury, 1955, p. 214). The bauxite is in areas of dipping strata, and altitudes range from 3,600 to 5,600 feet. Thicknesses of the bauxite range from 3 to 20 feet. Both massive and pisolitic types are present, and diaspore is reported to be the principal mineral. In these deposits the bauxite grades downward into a clay zone above the "great limestone." Best grade deposits are restricted to areas where the coal series has been eroded, and the bauxite is replaced laterally by clay where deposits extend under thick overburden, which suggest that the bauxite formed by weathering at or near the surface after erosion of the coal-bearing rocks.

Deposits in five areas in the Riasi district are estimated to contain 2 million tons of bauxite that is 75–82 percent  $\text{Al}_2\text{O}_3$  and 1–5 percent  $\text{SiO}_2$  (Roy Chowdhury, 1959, p. 26). These deposits are associated with approximately 10 million tons of bauxite that is 65–75 percent  $\text{Al}_2\text{O}_3$  and 6–15 percent  $\text{SiO}_2$ . Deposits in the Punch area of Kashmir contain 600,000–800,000 tons, most of which contains more silica than the better grade bauxite in the Riasi district.

*Madhya Bharat and Bhopal*.—Scattered laterite deposits occur in several areas in the Shivpuri, Guna, Bhilsa, Rajgarh, Shajapur, and Mandsaur districts of Madhya Bharat (Roy Chowdhury, 1958, p. 254). The deposits occur along the northern and eastern marginal regions of the Deccan trap, which in this area is known as the Malwa trap. Most deposits are in low mounds, but a few occur in flat ground, and some have marginal scarps. The northernmost deposits are 60 miles north of Shivpuri and rest on shales of the Gwalior Series. These deposits are at lower altitudes than others in the region, and the Deccan trap, which may have been the parent material, has been removed by erosion. Samples of the bauxite from Madhya Bharat contain more than 50 percent  $\text{Al}_2\text{O}_3$  and are low in silica and iron oxide but uncommonly high in titania. Approximately 80,000 tons of good-quality bauxite is present in this district according to one estimate (Roy Chowdhury, 1958, p. 255); however, the districts in this region have not been investigated sufficiently to permit accurate estimates.

Laterite cappings on basalt plateaus occur in parts of Bhopal. Most of these cappings are ferruginous, but aluminous material is known to be present at a few localities.

*Madhya Pradesh*.—Bauxite occurs at more than 100 localities in Madhya Pradesh State, but the major deposits are in the (1) Jabal-

pur district; (2) Amarkantak and Baihar Plateau areas; and (3) eastern Bilaspur, Surguja (Sarguja), and Jashpur highlands (Pathak, 1958, p. 34-35). The deposits in the Jabalpur district are near the Jabalpur-Katni section of the Central Railway, and they have been mined for several years for use by the chemical, refractory, and abrasive industries. The deposits in the other two districts are in highlands and are less favorable for development. Total estimated reserves of bauxite in Madhya Pradesh are more than 18 million tons (Pathak, 1958, p. 97). Thickness of bauxite mined in the Jabalpur district is as much as 20 feet, and the  $\text{Al}_2\text{O}_3$  contents of several deposits in this district range from 55 to 70 percent (Pathak, 1958, p. 35-38). High-grade bauxite is also present in the other two districts in Madhya Pradesh, and resources of high-iron bauxite are very large.

*Madras.*—The bauxite deposits in Madras are in the Shevaroy Hills, Salem district. They are on scattered hilltops in an area 16 miles long and 12 miles wide, about 8 miles south of the town of Salem. The bauxite is restricted to hills where the underlying rock is leptynite, and no bauxite is present where charnockites form the hills. The bauxite deposits are 20-30 feet thick, and the quantity present is estimated to be 6-7 million tons (Roy Chowdhury, 1955, p. 210). The average  $\text{Al}_2\text{O}_3$  content of the bauxite is 50 percent; silica and titania are low, but most of the bauxite contains more than 8 percent  $\text{Fe}_2\text{O}_3$ . The bauxite is chiefly gibbsite; limonite, ilmenite, quartz, and kaolin are the principal impurities.

*Maharashtra.*—Extensive aluminous laterite deposits occur in several places in Maharashtra. The best deposits are in the Kolhapur district, but others occur in the Kolaba district, and bauxite in the Kaira district near Bombay has been mined for many years for use in the purification of kerosene and in the manufacture of cement (Bracewell, 1962, p. 122). The deposits in the Kolhapur district cap plateaus at altitudes of 2,000-4,000 feet and overlie the Deccan trap. The bauxite ranges in thickness from 8 to 24 feet. It is overlain by ferruginous laterite 1-8 feet thick and underlain by 12-30 feet of soft porous laterite that is, in turn, overlain by 6-20 feet of soft lithomarge, and 40-60 feet of kaolinized basalt. The bauxite is chiefly gibbsite but contains minor quantities of boehmite (Mathad and Altekari, 1960). The reserves of high-grade bauxite in the Kolhapur district are estimated at 6.7 million tons and the total resources exceed 21 million tons (Roy Chowdhury, 1955, p. 207-208). The average partial chemical composition of the better grade bauxite is 55.54 percent  $\text{Al}_2\text{O}_3$ , 1.13 percent  $\text{SiO}_2$ , 7.45 percent  $\text{Fe}_2\text{O}_3$ , and 7.17 percent  $\text{TiO}_2$ , and the loss on ignition is 27.73 percent.

*Mysore.*—High-level lateritic bauxite occurs at several localities in the Bababudan Hills and in the Belgaum district, and small deposits occur elsewhere in Mysore. The deposits in the Bababudan Hills contain about half a million tons of bauxite of various grades and include 100,000 tons containing more than 55 percent  $\text{Al}_2\text{O}_3$  (Rama Rao, 1962, p. 69). The  $\text{TiO}_2$  content of this bauxite ranges from about 4.5 to 10 percent, and the  $\text{SiO}_2$  from less than 1 percent to about 6 percent. The deposits in the Belgaum district overlie Deccan trap, as shown on a mineral map by Rama Rao (1962). The total bauxite in Mysore as listed by the United Nations Economic Commission for Asia and the Far East (1962, p. 6) is approximately 1.25 million tons.

*Orissa.*—Bauxite deposits in Orissa occur in laterite cappings of hills and plateaus in the Karalapat, Kashmir, and Mahulpatna Zamindaries of the Kalahandi district (Roy Chowdhury, 1955, p. 211). The hills and plateaus rise above an altitude of 3,250 feet. They are underlain by rocks of the Khondalite Series, a group of metamorphosed sediments containing garnet-quartz-sillimanite rocks, graphite schists, and other rock types. Bauxite deposits in these areas were very conservatively estimated to contain more than half a million tons. This estimate was based on examination and sampling of only a few outcrops, and the quantity present may be very much greater. Most of the bauxite in these areas is ferruginous and low in silica and titania.

The best deposits in the Khariar highlands, Sambalpur district, are in a hill area called Bara Kondomal and in the depression between Bara and Sana Kondomal (Roy Chowdhury, 1955, p. 212). The bauxite in these areas is of varying purity and occurs as lenses and pockets beneath cappings of lateritic soil. At least 300,000 tons of bauxite containing more than 50 percent  $\text{Al}_2\text{O}_3$  is present at these two localities. Other deposits have not been adequately investigated for tonnage estimates.

*Reserves and resources of bauxite in India.*—Several estimates of the bauxite reserves in various parts of India and for the entire country have been published since World War II. Considerable variation in the estimates exists, because of differences in the amount of inferred bauxite classified as reserves. Also, several deposits have been explored in recent years, and the information available on deposits is increasing. The reserves of bauxite in India were conservatively estimated to be 28 million tons in 1958 (Roy Chowdhury, 1958, p. 28), and in that same year another estimate placed the total bauxite at 58.1 million tons (Pathak, 1958, p. 32). An estimate by Fox (1947, p. 13) of 250 million tons for the total bauxite in India is widely quoted and presumably includes both reserves and resources

as used in this report. A recent estimate by the United Nations Economic Commission for Asia and the Far East (1962, p. 6) based on publication by the India Geological Survey and other sources follows.

The present reserves of high-grade bauxite (with more than 50 percent  $Al_2O_3$ ) have been estimated to be of the order of 31 million tons, with possible reserves of 33 million tons and the inferred reserves of various grades of aluminous laterite and bauxite around 190 million tons, thus bringing the total estimated reserves of the country around 254 million tons.

These occur principally in the following areas:

- (i) Ranchi and Palaman districts of Bihar (13 million tons).
- (ii) Saurashtra and Kutch areas of Gujarath (11 million tons).
- (iii) Riasi and Punch areas of Kashmir (13 million tons).
- (iv) Jabalpur, Balaghat, Mandla, Bilaspur Sarguja district and other areas in Madhya Pradesh (16 million tons).
- (v) Kolhapur and Kolaba areas of Maharashtra (7 million tons).
- (vi) Kalahandi and Sambalpur area, Orissa (0.75 million tons).
- (vii) Shevaroy hills and Salem district, Madras (2 million tons).
- (viii) Bababudam hills and Balgaum areas, Mysore (1.25 million tons).

Total in all the above areas: 64 million tons.

Total reserves of bauxite in India are assumed to be 64 million tons, the figure listed by the United Nations report. Potential resources are at least 190 million tons, and this estimate is probably very conservative, inasmuch as the Amarkantak and the Uprora-Mainpat-Jashpur districts in Madhya Pradesh probably contain 100 million tons of ferruginous bauxite each (Pathak, 1958, p. 100, 102), and several other districts may contain very large low-grade deposits.

#### INDONESIA

The major bauxite deposits in Indonesia are on the small islands of the Riau Archipelago, and recent discoveries have been made in Kalimantan (Indonesian Borneo) (fig. 12). The largest deposits, which have been mined since 1935, are on Bintan Island (fig. 12) approximately 60 miles southeast of Singapore. Smaller deposits occur on Bangka (Banka) (fig. 12), Batam, Singkep, Kundur, Belitung, Kojang, Dendang, and Angkut Islands (Harrington, 1948, p. 9; Bracewell, 1962, p. 197). The deposits in Kalimantan are reported to be in the Singakawang region (Stamper and others, 1961, p. 248).

The bauxite on Bintan is in a laterite layer that ranges from 2 to 10 meters in thickness; the average thickness is approximately 4 meters. The bauxite consists of layers of hard lateritic concretions dispersed in a soft mottled clay. The concretions are about 1-4 inches in longest dimension. They are chiefly gibbsite and goethite, but minor amounts of silica-bearing minerals are also present. Interstitial clay makes up one- or two-fifths of the total laterite mass (Bemmelen, 1940, p. 112). This clay is higher in silica content than

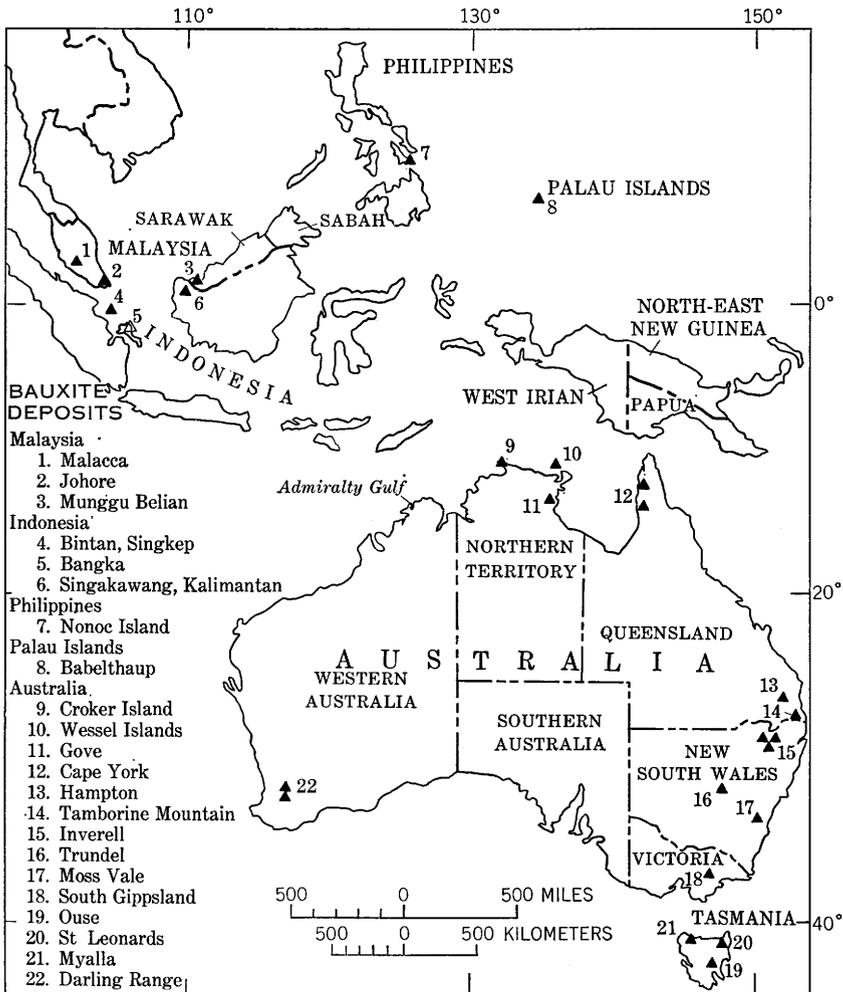


FIGURE 12.—Location of principal bauxite deposits in southeastern Asia and Australia.

the concretions; therefore, the quality of the bauxite can be improved by washing out the clay. A black aphanitic hornfels of probable Triassic age is the parent rock of the bauxite. A section of the bauxite and underlying rocks that is presumably typical of the bauxite areas was described by Bemmelen (1941, p. 635). In modified form, it is as follows: (1) Surficial bauxite, 7 meters thick; (2) clay, 45 meters thick, upper part structureless, lower part contains streaks of intensely weathered siliceous rocks, lowermost 4 meters contains blocks of unweathered parent rock; (3) black hornfels parent rock.

Several small bauxite deposits on five small islands near Bintan and Batam were intensively prospected in 1962 by the Indonesian Government with technical assistance from the U.S. Agency for International Development. These deposits are very similar in occurrence to those on Bintan. During this work, syenite intrusives, volcanic rocks, and phyllite were found to be favorable for the formation of a good grade of bauxite (but only thin low-grade deposits form on sandstone and shale. Approximately 1.6 million tons of washed bauxite was found during this prospecting, of which 1 million tons is as good or better in grade than that now mined on Bintan (R. F. Johnson, written commun., 1963). The percentage of gibbsitic concretions in this bauxite recoverable by washing ranges from 54 to 64 percent.

The bauxite deposits in Indonesia are on a low deeply weathered surface referred to as the Sunda shelf. Only a very small percentage of the Sunda shelf has been prospected for bauxite, and therefore very little is known about the total bauxite in the country. Reserves on Bintan and surrounding islets were estimated before World War II to be 10–20 million tons (Bemmelen, 1941, p. 631). Japanese geologists working during the war estimated the washed bauxite on Bintan at 23 million tons total in proved, probable, and possible categories and low-grade bauxite in the same three categories at 10 million tons (Harrington, 1948, p. 11–12). This bauxite contains 53–55 percent  $\text{Al}_2\text{O}_3$ , 4.3–4.5 percent  $\text{SiO}_2$ , and 9.1–13.2 percent  $\text{Fe}_2\text{O}_3$ . Recent additions to the bauxite reserves include the 1 million tons in the small islands near Bintan outlined by the Indonesian Government in 1962 and about 2 million tons found in the western part of Kalimantan by Japanese interests (R. F. Johnson, written commun., 1963). Total reserves of bauxite in Indonesia are assumed to be approximately 20 million tons. No basis is available for estimating the potential bauxite resources in the country, but they probably greatly exceed the 10 million tons of low-grade bauxite estimated by the Japanese geologists.

#### IRAN

Deposits of bauxite occur at Mahan, 38 kilometers southeast of Kerman, and at Zirkan, 110 kilometers southeast of Yezd. The deposits at Mahan were reported to contain 14–15 million tons that is 30–50 percent  $\text{Al}_2\text{O}_3$ , 10–20 percent  $\text{SiO}_2$ , and 10–30 percent  $\text{Fe}_2\text{O}_3$  (Harris and Trought, 1949). According to Dr. Nasrollah Khadem, Director of the Iranian Geological Survey (oral commun., 1963), most of the bauxite in these deposits contains less than 50 percent  $\text{Al}_2\text{O}_3$ . Previous estimates for Iran (S. H. Patterson, 1963, p. B159) were, therefore, overly optimistic, and the bauxite in Iran is listed only as a small potential resource (table 5).

## MALAYSIA

*Peninsular Malaysia.*—Bauxite deposits in Peninsular Malaysia have been worked discontinuously since the first mining by Japanese interests in 1936. During World War II, Japanese operated bauxite mines in southeastern, southern, and western parts of Johore State and near the coast in Malacca State, and several small deposits have been exhausted. The most valuable remaining deposits are near Pengerang in southeastern Johore (fig. 12), approximately 30 miles east of Singapore. The bauxite deposits in Malacca are small (Harrington, 1948, p. 14). Scattered bauxite deposits in Selangor, Pahang, and Trengganu States have not been thoroughly investigated, but the presence of some good grade bauxite is indicated by a few analyses (Bracewell, 1962, p. 127). Bauxite deposits in Peninsular Malaysia formed from the Pahang Volcanic Series that is partly late Paleozoic and partly Triassic in age (Harder, 1952, p. 62–63) and from shales and hornfels of Triassic age (Hayakawa, 1957). Weathered rocks are as much as 60 feet thick. The bauxite occurs as gibbsite and goethite concretions ranging in size from 1 to 5 inches. The concretions are scattered through a zone of red clay that is 10–20 feet thick. The bauxitic clay zone is separated from the unweathered country rocks, consisting of rhyolite, trachyte, and andesite, by red and yellow clay and greenish-brown saprolite zones.

Reserves of bauxite in Peninsular Malaysia are estimated at 10 million tons, and potential bauxite resources, including low-grade bauxite, of 40 million tons are present (Foreign Service Dispatch 408, Kuala Lumpur, Apr. 24, 1959, H. T. Ellis, Drafting Officer). Washing is required for the recovery of all the bauxite because of its occurrence as concretions scattered through red clay. In most places the bauxitic zone is overlain by only a thin soil, but at a few localities the overburden is as much as 20 feet thick. The composition of the bauxite mined in Johore, Peninsular Malaysia, is given in table 6.

*Sabah (formerly British North Borneo).*—Bauxite has been discovered in a number of shallow pits dug in an area about a mile west of Kaibu (Collenette, 1961). This bauxite appears to have been derived from coarse-grained basalt. It is considered to be of medium grade, but the amount present is unknown, and it is unfavorably situated for development. Extensive deposits of laterite are also known to occur on penepains near Darvel Bay on the east coast; however, the few analyses that were made of soils in this area indicate that they are low in alumina and high in iron (Bracewell, 1962, p. 117).

*Sarawak.*—Bauxite was discovered in Sarawak in 1949, and by 1959 more than 20 deposits had been found. A local company began mining bauxite in 1957, and within 2 years bauxite became the country's most valuable mineral product (Wolfenden, 1961, p. 972). The best deposits are at Munggu Belian, Sematan, and at Bukit Gebong, about 5 miles southeast of Sematan, and ferruginous bauxite deposits occur at Tanjong Serabang.

The bauxite at Munggu Belian formed by weathering of andesite. The deposits are on hills less than 100 feet high that are flanked by terrace alluvium and alluvial swamp deposits. The bauxite is chiefly gibbsite and minor amounts of quartz, kaolin minerals, and iron and titanium minerals. The bauxite occurs as hard pink-brown and gray nodules  $\frac{1}{4}$ -12 inches long. The nodules are scattered through a buff or brownish-red clayey saprolite, and part of the bauxite occurs as fillings of vesicles preserved from the parent andesite. Microcrystalline gibbsite is commonly a pseudomorphic replacement of plagioclase laths. Mixtures of gibbsite and iron minerals replaced pyroxene, and magnetite and rutile of the parent andesite are unaltered (Wolfenden, 1961, p. 975).

Scattered bauxite deposits other than those at Munggu Belian formed from several types of rocks. Gabbro and diorite are the parent materials of deposits at Bukit Gebong. Deposits at Bukit Giol formed from quartz diorite and are high in silica, and other deposits formed from plagioclase amphibolite, saussuritized gabbro, and several types of altered intermediate and mafic volcanic rocks.

Reserves of easily accessible washed bauxite were originally about 5.5 million tons (Wolfenden, 1961, p. 972), and unappraised resources of bauxite underlie alluvium at Munggu Belian and probably at several other localities in Sarawak. One grade of washed bauxite recovered from the deposits at Bukit Gebong was 52.10 percent  $\text{Al}_2\text{O}_3$ , 4.66 percent  $\text{SiO}_2$ , 13.14 percent  $\text{Fe}_2\text{O}_3$ , and 0.49 percent  $\text{TiO}_2$ , and the loss on ignition is 29.61 percent; a second grade is 46.97 percent  $\text{Al}_2\text{O}_3$ , 7.27 percent  $\text{SiO}_2$ , 18.02 percent  $\text{Fe}_2\text{O}_3$ , and 0.57 percent  $\text{TiO}_2$ , and the loss on ignition is 27.17 percent. The washed bauxite produced at Munggu Belian contained an average of 56 percent  $\text{Al}_2\text{O}_3$ , 2.8 percent  $\text{SiO}_2$ , and 9 percent  $\text{Fe}_2\text{O}_3$ , and the loss on ignition was approximately 30 percent (Bracewell, 1962, p. 118). The best deposits in Sarawak were nearing exhaustion in 1965 (Mining Jour., 1965b).

#### NORTH VIET NAM

A few small scattered bauxite deposits in Tonkin near the Chinese border were discovered by Japanese geologists in 1941. Other deposits occur in Annam. Small tonnages have been mined from deposits at Lang Sen near Dong Dang and Dai Phat in Tonkin (Har-

rington, 1948, p. 14; Bracewell, 1962, p. 205). According to an old estimate made by Japanese geologists (Harrington, 1948, p. 15), the reserves of bauxite at Lang Sen were 200,000 tons, and at Dai Phat, 100,000 tons. Analyses of 13 samples from near Dong Dang indicated an average of 51.46 percent  $\text{Al}_2\text{O}_3$ , 5.98 percent  $\text{SiO}_2$ , 26.04 percent  $\text{Fe}_2\text{O}_3$ , and 2.65 percent  $\text{TiO}_2$ , and 12.0 percent  $\text{H}_2\text{O}$  (Harrington, 1948, p. 15). No estimates or information on the grade are available for the bauxite in Annam.

#### PAKISTAN

Though laterite is known to be extensive in West Pakistan, field, mineralogical, and chemical investigations that have been made are not adequate to determine the number of bauxite deposits or the extent of known deposits. Most of the laterite and bauxite deposits that are now known in West Pakistan (M. G. White, geologist, U.S. AID Mission, Quetta, West Pakistan, written commun., 1962) occur in the following areas: (1) Ziarat-Harnai, Quetta Division; (2) Salt Range, Sargodha, and Mianwali districts, Sargodha Division; (3) Surg, Campbellpur district, Rawalpindi Division; (4) Margala Hills, Rawalpindi district; (5) Garhi Habibullah and Nathiagali-Abbottabad areas, Hazara district, Peshawar Division; (6) Lakhra, Dadu district, Hyderabad Division; (7) Nagar Parker, Thar Parker district, Hyderabad Division; (8) Muzaffarabad, Kashmir; and (9) Kotli Tehsil, Kashmir. Mr. White supplied partial chemical analyses of these deposits; they are as follows:

Area	Average percentage				Number of samples analyzed
	$\text{SiO}_2$	$\text{Al}_2\text{O}_3$	$\text{TiO}_2$	$\text{Fe}_2\text{O}_3$	
Ziarat Kathwai .....	12. 20	35. 41	2. 39	36. 92	9
Central Salt Range .....	17. 9	39. 7	1. 76	26. 1	3
Surg .....	13. 05	47. 37	1. 83	22. 46	29
Margala Hills .....	23. 51	50. 61	2. 19	9. 72	22
Muzaffarabad .....	31. 97	44. 84	2. 24	3. 02	47
Kotli Tehsil .....	30. 56	40. 92	2. 46	5. 66	47

Bauxite deposits at Muzaffarabad, Kashmir, are pisolitic and are associated with black clay and pockets of coal of Eocene age (Crookshank, 1955, p. 8). Deposits in the Campbellpur district are also pisolitic, and they occur in the lower part of shales of Paleocene age and overlie limestone of Triassic and Early Jurassic age (Crookshank, 1955, p. 10). The age of deposits at several other localities is uncertain. Although the deposits occur in Eocene rocks, and may therefore be Eocene, they could have formed after the rocks were exposed at the surface—thus, during any post-Eocene interval (M. G. White, written commun., Sept. 1962).

Investigations of bauxite deposits in Pakistan are not adequate to provide information for accurate resource estimates; however, one estimate (U.N. Econ. Comm. Asia and Far East, 1963, p. 29) lists reserves of 250,000 tons for the Campbellpur district and more than 15 million tons for the Ziarat Kathwai district. In this report, all bauxite in Pakistan is considered to be potential resources, and none is classified as reserves, even though small tonnages have been used in making cement.

#### PHILIPPINES

Three deposits of low-grade aluminous ferruginous laterite on Nonoc Island, Surigao Mineral Reservation, were investigated by the Philippines Bureau of Mines. The potential resources in these deposits, Conico, Northern Conico, and Lutawon Peak, were estimated to be 28 million metric tons (Esguerra, 1961, p. 6), and according to a more recent estimate (U.N. Econ. Comm. Asia and Far East, 1963, p. 29), the total low-grade laterite exceeds 100 million metric tons. Most of this laterite contains only 20–25 percent  $\text{Al}_2\text{O}_3$  and is 35–40 percent  $\text{Fe}_2\text{O}_3$  and 2–3 percent  $\text{SiO}_2$ . The aluminous laterites formed by weathering of clastic sedimentary rock derived mainly from serpentinized dunite and pyroxene peridotites. Other ferruginous laterites in the same mineral reservation are nickel bearing.

#### TURKEY

The principal bauxite deposits in Turkey are (Göksu, 1954; Nahai 1958; Baker and others, 1965) (1) at Kokaksu, 3 kilometers south of Zonguldak on the Black Sea, and (2) near Akseki and Seydişehir in the West Taurus Mountains between Antalya and Konya. Small bauxite deposits occur at Sebilköy in the Central Taurus Mountains and at Kân in the East Taurus Mountains. Diaspore deposits occur at (1) Milâs and Muğla in the southwestern part of the country, (2) Alanya on the southern coast, (3) Bolkardag in the central Taurus Mountains, and (4) Saimbeyli in the East Taurus Mountains. Low-grade iron-rich bauxite occurs at Amanos Dag (Islahiye-Payas) northeast of the Gulf of Alexandretta. Emery deposits occur in the southeastern part of the country in a belt approximately parallel to the Aegean coast. The first production of bauxite in Turkey was in 1964 when the Turkish Mineral Research and Exploration Institute mined and shipped 800 tons of high-silica bauxite from the Akseki deposits for use as refractories in metallurgical furnaces near Antalya.

The deposits at Kokaksu near Zonguldak are at altitudes of 300–850 feet. They occur along an unconformity cutting a dark limestone and are overlain by sandstone; the sandstone and limestone are both of Cretaceous age. The bauxite is a mixture of diaspore and boehmite.

One type present is soft and is similar to terra rossa, and the other type is hard and pisolitic. The chemical composition of the two types of bauxite (Göksu, 1954, p. 195) is as follows:

	Percentage				
	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	Loss on ignition
Hard bauxite-----	55.00	5.00	20.00	3.00	13.00
Soft bauxite-----	40.00	30.00	10.00	2.50	15.00

The bauxite deposits near Akseki and Seydisehr occur on a karst surface along an unconformity between limestones of Turonian and Senonian age. Deposits at Seydisehr are at an altitude approximately 5,000 feet, and those at Akseki range from 2,400 to 6,000 feet above sea level. The bauxite in the Akseki deposits is grayish brown, red, and cream colored, and much of it is pisolitic. Boehmite is the principal mineral in these deposits. According to available analyses (Göksu, 1954, p. 190), the bauxite is 50.32–66.71 percent Al<sub>2</sub>O<sub>3</sub>, 0.95–16.11 percent SiO<sub>2</sub>, 3.95–19.86 percent Fe<sub>2</sub>O<sub>3</sub>, 1.20–3.45 percent TiO<sub>2</sub>, and 12.00–15.34 percent H<sub>2</sub>O.

Deposits at Amanos Dag (Islahiye-Payas) are underlain by limestone of Late Jurassic and Early Cretaceous age and are overlain by a limestone series of Middle and Late Cretaceous age. Much of the bauxite is pisolitic and dark brown, and all of it is rich in iron. Of 110 samples analyzed (Göksu, 1954, p. 193), 48 contained more than 50 percent Al<sub>2</sub>O<sub>3</sub>, and 23 contained more than 45 percent Al<sub>2</sub>O<sub>3</sub>. The Fe<sub>2</sub>O<sub>3</sub> contents in these samples ranged from 15 to 17.41 percent.

Most of the diaspore in Turkey occurs in metamorphosed material that formed by the alteration of mafic tuffs and associated rocks on a karst surface. The deposits occur in rocks that are transitional between the Permian and Triassic Systems, and that probably were metamorphosed mostly in the Late Triassic.

The reserves of bauxite in Turkey have been estimated by the Turkish Mineral Exploration Institute (Baker and others, 1965, p. 7) at a rounded figure of 30 million metric tons. Of this tonnage, 28.17 million is near Seydisehr, 3.1 million is near Akseki, and approximately 150,000 tons is near Zonguldak. The best grade deposits are in the Dogan Kuzu area near Seydisehr and contain 18 million tons. This bauxite is 60 percent Al<sub>2</sub>O<sub>3</sub>, 5.4 percent SiO<sub>2</sub>, 14 percent Fe<sub>2</sub>O<sub>3</sub>, and 2.7 percent TiO<sub>2</sub>. Diaspore deposits in Turkey amount to 67 million metric tons. The Al<sub>2</sub>O<sub>3</sub> contents of the diaspore deposits range from 50.2 to 57.4 percent. This diaspore and low-grade

bauxite deposits in Islaiye-Payas that were reported by Göksu (1954, p. 193) to contain 40 million tons are considered to be potential bauxite resources in this report, and the total is rounded at 100 million tons.

The bauxite at Akseki is in complexly folded and faulted rocks. The deposits occur between two carbonate formations of Cretaceous age. The bauxite is grayish brown, red, and cream, and it is commonly pisolitic. Boehmite is the principal mineral in these deposits. According to available analyses (Göksu, 1954, p. 190), the bauxite is 50.32–66.04 percent  $\text{Al}_2\text{O}_3$ , 0.95–16.11 percent  $\text{SiO}_2$ , 3.95–19.86 percent  $\text{Fe}_2\text{O}_3$ , and 1.20–3.45 percent  $\text{TiO}_2$ , and 12–15.34 percent  $\text{H}_2\text{O}$ .

Deposits at Amanos Dag (Islahiye-Payas) are underlain by limestone of Late Jurassic and Early Cretaceous age and are overlain by a limestone series of middle and Late Cretaceous age. Much of the bauxite is pisolitic and dark brown, and it is all rich in iron. Of 110 samples analyzed (Göksu, 1954, p. 193), 48 contained more than 50 percent  $\text{Al}_2\text{O}_3$ , and an additional 23 contained more than 45 percent  $\text{Al}_2\text{O}_3$ . The  $\text{Fe}_2\text{O}_3$  contents in these samples ranged from 15 to 17.41 percent.

#### OTHER ASIAN COUNTRIES

In Aden, a thin zone of bauxitic rock associated with lignite and gypsum occurs in variegated shales between sandstones of Cretaceous age and massive limestones of middle Eocene age (Little, 1925, p. 105, 136–137). The aluminous rock and associated strata crop out in cliff faces north of the port of Makalla. The bauxitic zone is about 3 feet thick and white to pink. At the surface it is brittle to powdery, and the hard parts break with a conchoidal fracture. At one locality the bauxite contained 46 percent  $\text{Al}_2\text{O}_3$ ; at another, 67 percent  $\text{Al}_2\text{O}_3$  and small quantities of iron, lime, magnesium, potassium, and silica.

Occurrences of bauxite in the alluvium-filled Mae Khlaung and Khwae Noi valleys in Thailand were described by Richardson (1947). These deposits, reported to be 6 feet thick, consist of irregularly shaped gray concretions. Laterite, which is probably high in iron, also occurs in Cambodia (Pendleton, 1941).

Laterite deposits overlying basalt occur in plateau areas in the lower Mekong Basin in South Viet Nam. Investigation of these deposits was begun in 1961 by the United Nations Economic Commission for Asia and the Far East (1962, p. 18). No reports on the results of this work or the alumina content of the laterite are available.

Small bauxite deposits have reportedly been discovered in Israel (Chem. Age, 1956). These deposits are in the Ramon area in the Negev region.

## AUSTRALIA AND PACIFIC ISLANDS

### ADMIRALTY ISLANDS

Small bauxite deposits occur on Manus Island (Owen, 1954, p. 222-234), part of the Admiralty group administered by the Territory of Papua and New Guinea. One form of bauxite consists of tabular nodules embedded in a matrix of bauxitic clay that grades downward into kaolinitic tuff. Some of these nodules are as much as 60 percent alumina. A second type of bauxite consists of rounded irregular white to red nodules in brown clay. The origin of this type of bauxite is unknown, but it may be residual from tuff beds and dacite. A third type of bauxite consists of gritty earthy brown rock that underlies the rounded nodular bauxite. The gritty bauxite rests on dacite from which it has been derived. The resources of bauxite in two deposits on Manus Island are estimated to be 600,000 long tons (Owen, 1954, p. 231). This figure is based on the results of reconnaissance investigations in a few areas on one island, and the bauxite resources in the Admiralty group may be much larger.

### AUSTRALIA

Bauxite was first recognized in Australia in 1899 at Wingello, New South Wales (Owen, 1954, p. 28). Deposits are now known to exist in every state except South Australia. Deposits in Victoria, Queensland, and New South Wales have been mined and used on a small scale for chemical and refractory purposes for a number of years. Large-scale development of bauxite for aluminum followed the discovery of the large deposits in the Cape York Peninsula, Queensland, in 1955. Deposits in both the Cape York Peninsula and the Darling Range in Western Australia are now mined, and the development of the large deposits in the Gove area, Northern Territory, is being considered by several companies.

### WESTERN AUSTRALIA

Extensive lateritic bauxite deposits occur in the Darling Range northeast, east, and southeast of the city of Perth. The deposits are in numerous outliers of a dissected peneplain and are scattered throughout a belt about 200 miles long and 25 miles wide, lying 20-

60 miles inland from the west coast of Australia. Most of the deposits are 1,000–1,200 feet above sea level. They are underlain by complex rocks of the Precambrian shield from which they are believed to have weathered in Miocene or Pliocene time (Carroll and Jones, 1947, p. 1). The rocks from which the laterite formed consist of quartz dolerite (Terrill, 1950, p. 108), granite, and greenstone (Owen, 1954, p. 147). The typical laterite consists of a thin surficial layer of sand or sandy soil underlain by a massive, generally pisolitic aluminous laterite that is, in turn, underlain by a kaolin-rich and kaolinized rock that may retain the original rock texture. Much of the laterite that formed on dolerite contains relict texture of the parent rock formed by the replacement of original minerals by gibbsite and a mixture of clachite, hematite, and limonite (Terrill, 1950, p. 109).

The lateritic bauxite in the Darling Range varies in quality, but the best grade present is 45–52 percent  $\text{Al}_2\text{O}_3$  (Tomich, 1964, p. 127), and presumably this grade is the material now being mined. Gibbsite is the principal bauxite mineral, but small quantities of boehmite are also present in this bauxite. Bracewell (1962, p. 130) reported that the lateritic bauxite contains 35–45 percent available alumina; however, the mining of these deposits now underway suggests that the grade is somewhat higher. Proved and indicated reserves in the Jarradale-Dwellingup area are reportedly nearly 80 million tons, and scout drilling has indicated the presence of an additional 100 million tons (Bracewell, 1962, p. 130). Exploration for bauxite in Western Australia is far from complete, and total resources are probably much larger than the figures now indicate.

Bauxite is reported (Mining Jour., 1965a) to have been discovered in the Kimberley Ranges near Admiralty Gulf (fig. 12), in the northern part of Western Australia. The extent and grade of these deposits had not been determined when this report was prepared.

#### NORTHERN TERRITORY

The largest bauxite deposits in the Northern Territory are in the vicinity of Gove (fig. 12). The bauxite exploration in this area has continued for several years, but little geological information is available. According to a report of a brief reconnaissance (Owen, 1954, p. 169), the Gove bauxites are pisolitic and overlie tubular laterite. They formed on flat-lying feldspathic sediments (Fisher, 1958, p. 135). The laterite and bauxite formed from sedimentary rocks that are partly sandy and overlies coarse garnetiferous granite. The re-

erves of bauxite at Gove are reported to be "considerably over 100 million tons" (Fisher, 1958, p. 135). A later newspaper article (Menzies, 1963) gives the proved reserves in the "Gove field" as 300 million tons and states that plans for development of the Gove deposits are in an advanced stage. Some of this bauxite is as much as 50 percent  $\text{Al}_2\text{O}_3$  (Owen, 1954, p. 169).

Eight deposits of bauxite on Marchinbar Island in the Wessel Islands group have been described by Owen (1954, p. 150-168). The bauxite is in laterite resting on quartzite, massive sandstone, and shale of Precambrian age. The bauxite probably formed during the Tertiary Period. It is partly covered by a layer of windblown sand as much as 1 foot thick. Reserves of bauxite on Marchinbar Island are reported to be 9.7 million tons. The bauxite contains 47.7-53.3 percent  $\text{Al}_2\text{O}_3$ , 4.1-8.8 percent  $\text{SiO}_2$ , and 6.4-17.2 percent  $\text{Fe}_2\text{O}_3$  (Owen, 1954, p. 15).

Bauxite also has been reported on Crocker and Truant Islands and at localities on the mainland of the Northern Territory other than Gove. The deposits on Crocker Island were described as containing "less than 5 million tons" indicated reserves (Bracewell, 1962, p. 132), but information on the size or grade of deposits on the Truant Islands and on the mainland other than at Gove is not available.

#### QUEENSLAND

One of the largest deposits of bauxite in the world occurs on the Cape York Peninsula, and there are small bauxite deposits at two other places in Queensland.

*Cape York Peninsula.*—The deposits on the west side of the Cape York Peninsula, commonly referred to as the Weipa deposits, are part of an extensive laterite area extending from Vrilya Point to Archer Bay, a distance of 150 miles, and extending inland as much as 30 miles. The bauxite occurs in flat or gently dipping laterites that range in thickness from a few feet to 30 feet (Evans, 1959, p. 52). The upper part of the laterite is pisolitic and is generally sharply separated from the underlying nodular zone, which contains some sandy clay nodules. The nodular zone grades downward into unlateritized sediments. The laterite is underlain at most places by sedimentary rocks of Cretaceous or Tertiary age, consisting of kaolinitic sandstones, sandy clays, and silts. In a few places the laterite rests on older sedimentary rocks, granites, and schists. Kaolinitic sandstones are the parent material of most of the bauxite. These rocks may be weathered arkoses, but no feldspar and only very small quantities of alkalis have been found in them (Loughnan and Bayliss, 1961, p. 211).

The bauxite apparently formed by weathering and leaching of parent rocks that were 90 percent silica and as little as 4 percent alumina. The deposits are in an area of low relief, where the mean temperature is 82°F and rainfall, 60 inches per year, is concentrated between December and March. The pH of ground water in the bauxite, which presumably has leached constituents other than alumina, is approximately 5.5, and with increasing depth it increases to nearly 7.0 (neutral) below the water table (Loughnan and Bayliss, 1961, p. 211-212).

The Weipa bauxites are mixtures consisting chiefly of gibbsite and minor amounts of boehmite (table 7). Boehmite contents range from 5 to 10 percent in much of the bauxite, but some bauxite contains as much as 40 percent. Generally boehmite is most abundant near the surface and decreases sharply with depth. According to the results of detailed studies of samples from three localities by Loughnan and Bayliss (1961), gibbsite remains fairly constant to depths of about 15 feet and decreases as kaolinite increases with greater depths. Kaolinite is very abundant in a zone 15-20 feet thick below the bauxite, and at greater depths quartz is more abundant than kaolinite. Hematite and goethite are the principal iron minerals. Gibbsite and the iron minerals occur in rounded pisolites and nodules that range from 1 to 20 mm in diameter. The quartz and kaolin in the bauxite occur mostly in the interstices between the nodules, but some quartz grains are also present in the outer shells and interior parts of the nodules. Typical variations in chemical and mineral composition with depth, except for uncommonly low boehmite, are shown in table 7.

The Weipa deposits are so large that they are not expected to be fully explored for several years. Laterite is known to cover 500 square miles, and the area containing bauxite of economic grade is at least 200 square miles. Estimates of the tonnage of bauxite in these deposits vary considerably. Approximately 600 million tons of economic-grade bauxite has been proved, and total resources may amount to several billion tons (Hibbard, 1963, p. 117). According to the few published analyses of Weipa deposits (Evans, 1959, p. 54-55; Loughnan and Bayliss, 1961, p. 214), much of the bauxite is 45-52 percent  $\text{Al}_2\text{O}_3$ , 5-15 percent  $\text{SiO}_2$ , 10-20 percent  $\text{Fe}_2\text{O}_3$ , and 1-2 percent  $\text{TiO}_2$ .

*Tamborine Mountain.*—The bauxite deposits at Tamborine Mountain are about 35 miles south-southeast of Brisbane. The bauxite is in laterite deposits formed from the weathering of andesitic and basaltic lavas of probable Eocene or Oligocene age. Most of the laterite caps high ridges, but some of it also occurs at intermediate altitudes. The bauxite in these deposits has been mined for use in

TABLE 7.—*Variation in chemical and mineral composition of Weipa bauxite and underlying rocks with depth*

[From Longhnan and Bayliss (1961, p. 213-214)]

Depth (feet)	Chemical analysis (percent)									Mineral composition (percent)						
	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	K <sub>2</sub> O	Na <sub>2</sub> O	H <sub>2</sub> O+	H <sub>2</sub> O-	Total	Boehmite	Gibbsite	Hematite	Goethite	Kaolinite	Quartz	Others
1-4	9.9	47.1	13.1	2.1			24.6	2.2	99.0	4	61	4	10	12	5	4
4-7	10.0	46.9	12.9	2.1			24.5	2.2	98.6	4	61	4	10	12	5	4
7-10	10.6	48.8	11.5	2.2			24.5	2.2	99.8	4	63	7	5	12	5	4
10-13	10.5	49.4	9.6	2.2			25.3	2.3	99.3	4	65	3	7	12	5	4
13-16	9.6	50.0	9.2	2.2			26.6	2.1	99.7		70	1	10	10	5	4
16-19	16.9	36.1	25.4	1.2			19.1	1.4	100.1		40	11	16	26	5	2
19-22	19.4	34.3	26.3	1.2			16.6	1.2	99.0		33	22	6	32	5	2
22-25	26.5	31.5	26.1	.9			13.4	1.2	99.6		20	21	6	46	5	2
25-28	31.5	28.6	25.8	.9			11.4	1.0	99.2		6	22	5	60	5	2
28-29	73.1	17.9	2.8	.7			5.6	.6	100.7			3		42	54	1
31-32	92.9	4.1	.5	.2			1.0	.0	98.7					10	89	1
33-34	91.1	5.2	.5	.3	0.2	0.7	1.8	.0	99.8					13	86	1
35-36	93.2	3.9	.2	.2	.1	.8	1.4	.0	99.8					10	89	1

aluminum sulfate. The size and grade of the deposits are incompletely known; however, they are 27 feet thick at one locality, and they are estimated to contain 473,000 long tons of proved and 1,020,000 long tons of indicated bauxite (Owen, 1954, p. 15). The bauxite is 37.3–41.0 percent  $\text{Al}_2\text{O}_3$ , 4.0–7.0 percent  $\text{SiO}_2$ , and 22.0–24.0 percent  $\text{Fe}_2\text{O}_3$ .

*Hampton.*—The bauxites at Hampton, northwest of Brisbane, are presumably similar in occurrence to the Tamborine Mountain deposits. Hampton deposits contain 250,000 long tons of indicated bauxite whose partial composition is 1.9 percent  $\text{SiO}_2$ , 37.8 percent  $\text{Al}_2\text{O}_3$ , and 32.7 percent  $\text{Fe}_2\text{O}_3$  (Owen, 1954, p. 15).

#### NEW SOUTH WALES

The Inverell area contains many separate bauxite deposits (Owen, 1954, p. 29–63). The bauxite is in laterite that is derived from basalt and is overlain by younger basalts of Pliocene age. The deposits range in thickness from 16 to 42 feet. The bauxite is pisolitic and earthy in texture and grades downward into clay-rich weathered rocks in which basaltic textures have been preserved. Proved reserves of bauxite in the Inverell area are 9,610,000 long tons, and indicated reserves are 5,960,000 long tons (Owen, 1954, p. 15). The composition of this bauxite is 35.7–42.9 percent  $\text{Al}_2\text{O}_3$ , 2.7–6.6 percent  $\text{SiO}_2$ , and 26.3–31.1 percent  $\text{Fe}_2\text{O}_3$ .

Bauxite occurs in surficial laterite derived from basalt in several places in the Moss Vale area. Some deposits are as much as 50 feet thick, but most are less than 20 feet thick. The upper part of most deposits is dark-red pisolitic laterite, which is separated from fresh basalt by layers of variegated red and buff kaolinized basalt. Some of the bauxite in the Moss Vale area has been used in the manufacture of aluminum chemicals. The Moss Vale area is estimated to contain 518,000 tons of proved and 3,600,000 long tons of indicated bauxite, having 31.0–53.9 percent  $\text{Al}_2\text{O}_3$ , 2.9–7.5 percent  $\text{SiO}_2$ , and 5.7–37.4 percent  $\text{Fe}_2\text{O}_3$  (Owen, 1954, p. 15).

Several small deposits of bauxitic laterite occur in the Trundle area. These deposits are estimated to contain 40,000 long tons of bauxite (Owen, 1954, p. 15); however, at the time this estimate was made the deposits were only partly explored.

#### VICTORIA

Most of the bauxite deposits in Victoria are scattered over the part of County Buln Buln that is south of the Gippsland railway. The bauxite is derived from basalt and is probably of early or middle Eocene age. According to Bell (1961), the distribution of the deposits is controlled by a major fault system, and the origin of the

bauxite is apparently related to ground-water movement along the faults. Bauxite reserves in County Buln Buln were estimated to be 785,000 long tons proved and 116,000 long tons indicated (Owen, 1954, p. 15). No significant new deposits were found during an exploration program carried on by Reynolds Metals Corp. in 1959 (Bell, 1961, p. 51). The bauxite is 60–70 percent gibbsite, 5 percent boehmite, 15–25 percent kaolinite, and 10 percent ilmenite and hematite. It is 43.8–53.0 percent  $\text{Al}_2\text{O}_3$ , 3.7–11.5 percent  $\text{SiO}_2$ , and 3.5–16.1 percent  $\text{Fe}_2\text{O}_3$  (Owen, 1954, p. 15).

#### TASMANIA

Laterite and ferruginous bauxite occur in the Ouse area in a layer of weathered rock derived from dolerite. After the formation of the laterite the rocks were faulted, tilted, eroded, and buried by fresh-water sediments and basalt flows. The bauxite is associated with remnants of the former land surface uncovered by erosion. Reserves of bauxite are estimated to be 627,000 long tons having 38.6–41.0 percent  $\text{Al}_2\text{O}_3$ , 5.6–6.1 percent  $\text{SiO}_2$ , and 25.7–30.2 percent  $\text{Fe}_2\text{O}_3$  (Owen, 1954, p. 15).

Small deposits of bauxite resting on dolerite occur in the St. Leonards area near the city of Launceston. The deposits contain 142,000 long tons of proved bauxite having 40.9–41.7 percent  $\text{Al}_2\text{O}_3$ , 5.6–7.1 percent  $\text{SiO}_2$ , and 25.7–27.4 percent  $\text{Fe}_2\text{O}_3$ .

Several small deposits of bauxite derived from basalt occur near Myalla. These deposits are estimated to contain 190,000 long tons of bauxite.

#### BAUXITE RESOURCES IN AUSTRALIA

Several reports (Mining Mag., 1959, p. 83; Higbie and others, 1962, p. 328; and Wardrop, 1961) give a total of 3 billion tons for the bauxite in the Weipa and Gove deposits, of which 2 billion tons is expected to be of metal grade. In an article by the Prime Minister of Australia (Menzies, 1963), the proved reserves in the Weipa field are given as more than 600 million tons; the additional potential bauxite is placed at 2 billion tons, and proven reserves in the Gove field at 300 million. The total for the deposits near Perth, Western Australia, is 180 million tons (Bracewell, 1962, p. 130). The amount of bauxite in various scattered deposits (Owen, 1954, p. 15) is as follows: Tamborine Mountain and Hampton, Queensland, 1.7 million tons; several localities in New South Wales, 19.7 million tons; two localities in Victoria, 901,000 tons; three localities in Tasmania, 959,000 tons; and Marchinbar Island, Northern Territory, 9.7 million. Total reserves of measured, indicated, and inferred bauxite in Australia are probably at least 2 billion tons, and potential bauxite resources, chiefly in Weipa and Gove deposits, are approximately 1 billion tons.

### FIJI ISLANDS

The possibilities for commercial bauxite deposits have been investigated on the main islands of Viti Levu and Vanua Levu and 13 of the Lau islands. Bauxite deposits have been found on most of these islands (Bracewell, 1962, p. 134). The aluminous materials occur as 1) irregular gibbsite nodules as much as 6 inches in diameter scattered throughout surface gravels, 2) brown earthy saprolitic bauxite, occurring chiefly as exfoliated shells of weathered basalt, and 3) earthy phosphatic bauxite associated with limestone. The gibbsite nodules contain an average of 57 percent  $\text{Al}_2\text{O}_3$ , 9 percent  $\text{SiO}_2$ , 4.5 percent  $\text{Fe}_2\text{O}_3$ , and 0.8 percent  $\text{TiO}_2$ , and their loss on ignition is 29 percent; brown earthy bauxite contains 51 percent  $\text{Al}_2\text{O}_3$ , 3 percent  $\text{SiO}_2$ , 16 percent  $\text{Fe}_2\text{O}_3$ , and 1.7 percent  $\text{TiO}_2$ , and its loss on ignition is 28 percent.

The largest deposits, in the northwestern part of Viti Levu, occur near the surface of dissected peneplain remnants that slope seaward from an altitude of 550–180 feet. Other deposits occur north of Vakambuli and elsewhere in the Lautoka-Mba region. The bauxitic layer ranges in thickness from 6 to 21 feet. Washing would be required to obtain an acceptable grade, and preliminary tests indicate that recovery would range from 20 to 30 percent. Total resources of bauxite in the Fiji Islands is estimated by the Geological Survey of Fiji to be more than a million tons (Guest, 1959).

### NEW ZEALAND

Red and brown soils derived from mafic volcanic rocks in North Auckland contain appreciable quantities of gibbsite. Most of these soils contain kaolin minerals and are high in iron oxides and titania. This bauxitic soil is very similar to deposits in Hawaii, and apparently the deposits in the two areas formed under similar conditions (Kear and others, 1962, p. 5). Potentially valuable bauxitic soils cover 5 square miles, and very low grade bauxitic clays cover an additional 30 square miles. The soils richest in alumina are in an area of a little more than a square mile near the town of Kerikeri. They were investigated by Swindale (1959) and by Kear, Waterhouse, and Swindale (1962, p. 11), who found that deposits in seven areas are 10–15 feet thick and contain an estimated 20 million tons of bauxite. The probable average composition of this bauxite is 37.4 percent  $\text{Al}_2\text{O}_3$ , 5.5 percent  $\text{SiO}_2$ , 25.6 percent  $\text{Fe}_2\text{O}_3$ , and 6.4 percent  $\text{TiO}_2$ , 23.6 percent water loss on ignition. The probable extractable alumina content is 30.6 percent.

### PALAU ISLANDS

Bauxite deposits occur south and southeast of the village of Ngardmau and in the northwestern part of Babelthaup Island of the

Palau Group. The bauxite occurs in deeply weathered andesitic agglomerates. Deeply weathered rocks support only a dense fern growth, and generally areas are heavily forested only where fresh rock is at or near the surface; therefore, the distribution of fern growth outlines areas worth prospecting. According to Bridge and Goldich (1948, p. 22), the vertical sequence of weathered rocks containing the bauxite is typically as follows: (a) A surface bauxitic gravel bed 4–6 inches thick; (b) a reddish- or yellowish-brown clay 6–12 inches thick, containing small bauxite concretions; (c) concretionary dark-reddish-brown clay 4–6 feet thick at most places, containing concretions and hard beds of bauxite as much as 2 feet thick; (d) a mixed zone of reddish-brown clay and variegated kaolinitic clay 1–2 feet thick, containing a few sheets and layers of ferruginous gibbsite along joints; (e) variegated purple, red, brown, yellow, and gray clay having an estimated maximum thickness of 40 feet and retaining ghosts of structures and textures of parent rock; and (f) volcanic agglomerate parent rock.

Gibbsite is the chief bauxite mineral present, and hematite is the chief impurity. Minor amounts of boehmite and goethite and appreciable quantities of kaolinite and halloysite are also present in the bauxite. The average chemical composition of unwashed samples from one locality representing a bauxite layer 24 feet thick is 35.89 percent  $\text{Al}_2\text{O}_3$ , 10.33 percent  $\text{SiO}_2$ , 20.75 percent  $\text{Fe}_2\text{O}_3$ , and 0.7 percent  $\text{TiO}_2$ , and the loss on ignition is 32.56 percent (Bridge and Goldich, 1948, p. 26).

A Japanese company produced approximately 370,000 tons of washed bauxite on Babelthaup from 1938 through part of 1944, when operations were terminated by American bombing. The composition of this washed bauxite was 51 percent  $\text{Al}_2\text{O}_3$ , 2.5 percent  $\text{SiO}_2$ , and 16 percent  $\text{Fe}_2\text{O}_3$  (Bridge and Goldich, 1948, p. i).

Japanese geologists have estimated that 2–3 million tons of washed bauxite can be recovered from deposits in which the recoverable concentrate is 30 percent by weight. The reserves increase to 5 million tons if the washed concentrate requirement is reduced to 20 percent of the bauxite in the ground. Very tentative estimates place the total potential bauxite resources on Babelthaup at 40–50 million tons (Bridge and Goldich, 1948, p. 6–8).

#### OTHER ISLANDS

Bauxite or aluminous laterite occurs on several Pacific islands. The occurrence of bauxitic laterite on Santa Cruz and Vanikero in the British Solomon Islands was reported by Owen (1954, p. 234). Hose (1960, p. 246) reported an analysis of bauxite from Mare Island, New Caledonia. Prospecting for bauxite has been reported

on Misool Island off New Guinea (Higbie and others, 1962, p. 327) and in the Western District of Papua (Mining Jour., 1963b, p. 279). Several samples of laterite from Samoa contain 33-38 percent  $Al_2O_3$  (Seelye and others, 1938), but no estimates of the amount of this rock on the island have been made. Bauxitic soils overlie limestone on Guam (Carroll and Hathaway, 1963, p. F39-F40), but deposits on this island are probably too small to be of value for bauxite (Tracey and others, 1964, p. A74). Small deposits of bauxite also occur on several islands of the Caroline group other than Palau (p. 116). Bauxite deposits covering 63 acres on Witipon and small deposits on Meon in the Truk Islands have been described by Stark and Hay (1963, p. 13). Bauxite also occurs on Ponape and Saipan (Bridge, 1948, p. 224) and on Yap and Kausaie (Watanabe, 1939); deposits on Ponape contain an estimated 300,000 tons of low-grade bauxite (Fischer, in U.S. Bur. Mines, 1953, III-45).

#### ALUMINUM SOURCES IN ROCK AND MINERALS OTHER THAN BAUXITE

Aluminous rocks and minerals other than bauxite that have been used or considered for use as a source of alumina include alunite, high-alumina clay, aluminous shale, aluminum phosphate rock, saprolite, igneous rocks rich in feldspar or feldspathoids, and minerals of the sillimanite group. Large quantities of the aluminous mineral dawsonite has been found recently in oil shale in Colorado. This mineral and some metamorphic rocks that are uncommonly rich in alumina may also be possible sources of alumina. The only present significant industrial use of these rocks as a source of aluminum is in the U.S.S.R., where nepheline syenite and alunite are processed (Baer, 1959, p. 102; Shabad, 1958, p. 17). During World War II when several aluminum-producing countries were cut off from their normal supplies of bauxite, many attempts were made to use other raw materials. Some attempts were successful under the economic conditions existing during the war, but no other raw material has been able to compete with bauxite since the war. Alumina was recovered from clay in Germany, and andalusite was concentrated from mine waste in Sweden (Bracewell, 1962, p. 43). Minor quantities of aluminum were produced in Japan from Korean and domestic alunite, domestic clay, and Chinese, Manchurian, and Korean shale (Harrington, 1958, p. 2). In the United States, four experimental plants were built by the Government to test the feasibility of extracting alumina from nonbauxitic materials. The location of plants and raw materials tested were: (1) Laramie, Wyo., Laramie Range anorthosite; (2) Harleyville, S.C., South Carolina

kaolin; (3) Salt Lake City, Utah, alunite from the Marysvale district, Utah; and (4) Salem, Oreg., clay in Oregon and Washington. Prior to World War II, a small plant was built in Norway to recover alumina from labradorite feldspar, and one was built in Italy to recover alumina as a byproduct of potash recovery from leucite. Neither plant was able to operate profitably.

In recent years, attention has again focused on the nonbauxite material because of the increased demands for aluminum, the depletion of very high grade bauxite reserves in several countries, and other economic and political reasons. Intense research on methods of profitably extracting alumina from materials other than bauxite is underway in several countries (Domaas, 1961). In addition to the plants that use nepheline syenite and alunite in the U.S.S.R., a plant is being considered in Uzbekistan to extract alumina from clay (Mining Jour., 1963a). A plant is presumably in operation in Poland for the extraction of alumina from clay (Wilmot and others, 1960, p. 237). In the United States, the North American Coal Corp. constructed a pilot plant at Powhatan Point, Ohio, for the recovery of aluminum sulfate from shaly coal mine waste (Higbie and others, 1963, p. 291). The Anaconda Co. built a pilot plant at Anaconda, Mont., to test the feasibility of extracting alumina from aluminous clay in Latah County, Idaho (Wilmot and others, 1957, p. 243). This company announced that the results of the tests were favorable, and it investigated kaolin deposits in Warren, Glascock, and McDuffie Counties, Ga. (Georgia Geol. Survey, 1963), which are known to be considerably higher in alumina content than those in Idaho. The 1964 annual report of the company stated that design of a plant for the extraction of alumina from clay has started (Anaconda Co., 1965, p. 10).

The aluminous materials other than bauxite in the United States, including aluminous shale, aluminum phosphate rock, alunite, dawsonite, high-alumina clays, igneous and metamorphic rocks, minerals of the sillimanite group, and saprolite, vary considerably in occurrence, physical properties, alumina content (table 8), and in location of deposits (fig. 13). Some of these materials are soft and occur in large deposits that could be mined cheaply. Others are hard or are deeply buried and would be costly to mine. Some occur in large uniform masses and are not suitable for beneficiating, and others occur as minerals that are disseminated through other rocks and would have to be concentrated to be of value. Recovery of alumina from some of these materials might yield byproducts; recovery from others would not. Some of the materials have no present use, and others are now mined for purposes other than alumina extraction.

TABLE 8.—Aluminous rocks and minerals other than bauxite in the United States

Rock or mineral	Principal aluminous minerals	Common mineral impurities	Al <sub>2</sub> O <sub>3</sub> content (percent)	Remarks
Aluminous shale.....	Kaolinite (OH) <sub>3</sub> Si <sub>4</sub> Al <sub>4</sub> O <sub>10</sub> ..... Illite (OH) <sub>2</sub> K <sub>2</sub> (Si <sub>6</sub> Al <sub>2</sub> )Al <sub>4</sub> O <sub>20</sub> Montmorillonite (OH) <sub>2</sub> Si <sub>3-34</sub> Mg. <sub>0.66</sub> O <sub>20</sub> .	Quartz, miscellaneous clay and nonclay minerals, and organic matter.	14-23.....	Soft rock; virtually inexhaustible resources.
Aluminum phosphate rock.	Crandallite CaAl <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> (OH) <sub>5</sub> ·H <sub>2</sub> O Millsite (NaK)CaAl <sub>6</sub> (PO <sub>4</sub> ) <sub>4</sub> (OH) <sub>6</sub> ·3H <sub>2</sub> O Wavellite Al <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> (OH) <sub>3</sub> ·5H <sub>2</sub> O Kaolinite (OH) <sub>3</sub> Si <sub>4</sub> Al <sub>4</sub> O <sub>10</sub>	Quartz.....	6-15.....	Large resources occur in unconsolidated overburden above calcium phosphate rock in Florida. Several million tons of this rock is discarded yearly in overburden removal. The alumina content of much of this rock could be increased two- to three-fold by removing 150-mesh quartz.
Alunite.....	Alunite K <sub>2</sub> Al <sub>6</sub> (OH) <sub>12</sub> (SO <sub>4</sub> ) <sub>4</sub> .....	Quartz, kaolinite, and feldspar.	High grade >30; low grade 20-30.	Resources are small; commonly mixed with other fine-grained minerals and minable only by underground methods.
Dawsonite.....	Dawsonite NaAl(OH) <sub>2</sub> CO <sub>3</sub> .....	Oil shale.....	Pure dawsonite is 35 percent acid extractable Al <sub>2</sub> O <sub>3</sub> .	Locally oil shale as much as 300 feet thick is 25 percent dawsonite, by weight.
High-alumina clay: High grade.....	Kaolinite (OH) <sub>3</sub> Si <sub>4</sub> Al <sub>4</sub> O <sub>10</sub> .....	Quartz, feldspar, mica, and clay minerals other than kaolinite.	30-40.....	Resources of high-grade high-alumina clay are large, and those of moderate and low grade are very large. Many deposits are near the surface; others are deeply buried.
Low grade.....	Kaolinite (OH) <sub>3</sub> Si <sub>4</sub> Al <sub>4</sub> O <sub>10</sub>	Quartz, feldspar, and mica in some deposits; the minerals in aluminous shale in others.	20-30.....	
Igneous rocks: Anorthosite.....	Plagioclase feldspar NaAlSi <sub>3</sub> O <sub>8</sub> , CaAl <sub>2</sub> Si <sub>2</sub> O <sub>8</sub> .	Ferromagnesian minerals.....	25-30.....	Hard rock; resources are inexhaustible.
Nepheline syenite	Orthoclase feldspar (K, Na)AlSi <sub>3</sub> O <sub>8</sub> .....		15-25.....	
Metamorphic rocks...	Nephelite (Na, K)AlSi <sub>4</sub> O <sub>10</sub> Muscovite KAl <sub>3</sub> Si <sub>3</sub> O <sub>10</sub> (OH) <sub>2</sub> .....	Quartz.....	25-30.....	Resources of aluminous metamorphic rocks are probably very large, but the Al <sub>2</sub> O <sub>3</sub> in them is tightly bonded in silicate structures and would be difficult to extract.
Saprolite.....	Kaolinite (OH) <sub>3</sub> Si <sub>4</sub> Al <sub>4</sub> O <sub>10</sub> .....	Chiefly iron oxide minerals; locally quartz and mica.	25-35.....	Soft rock; large resources occur at surface.
Sillimanite group minerals.	Gibbsite Al(OH) <sub>3</sub> Hallowysite (OH) <sub>3</sub> Si <sub>4</sub> Al <sub>4</sub> O <sub>10</sub> Andalusite..... Kyanite..... Sillimanite..... } Al <sub>2</sub> SiO <sub>5</sub> .....	Associated with mica and other minerals occurring in schist, gneiss, and quartzose metamorphic rocks, pegmatites, and placer deposits.	Andalusite, kyanite, and sillimanite are 63.2 percent Al <sub>2</sub> O <sub>3</sub> , but these minerals are disseminated through hard schists and gneisses.	Resources in Southeastern States are large, and large resources may occur elsewhere. Minerals of this group must be concentrated.

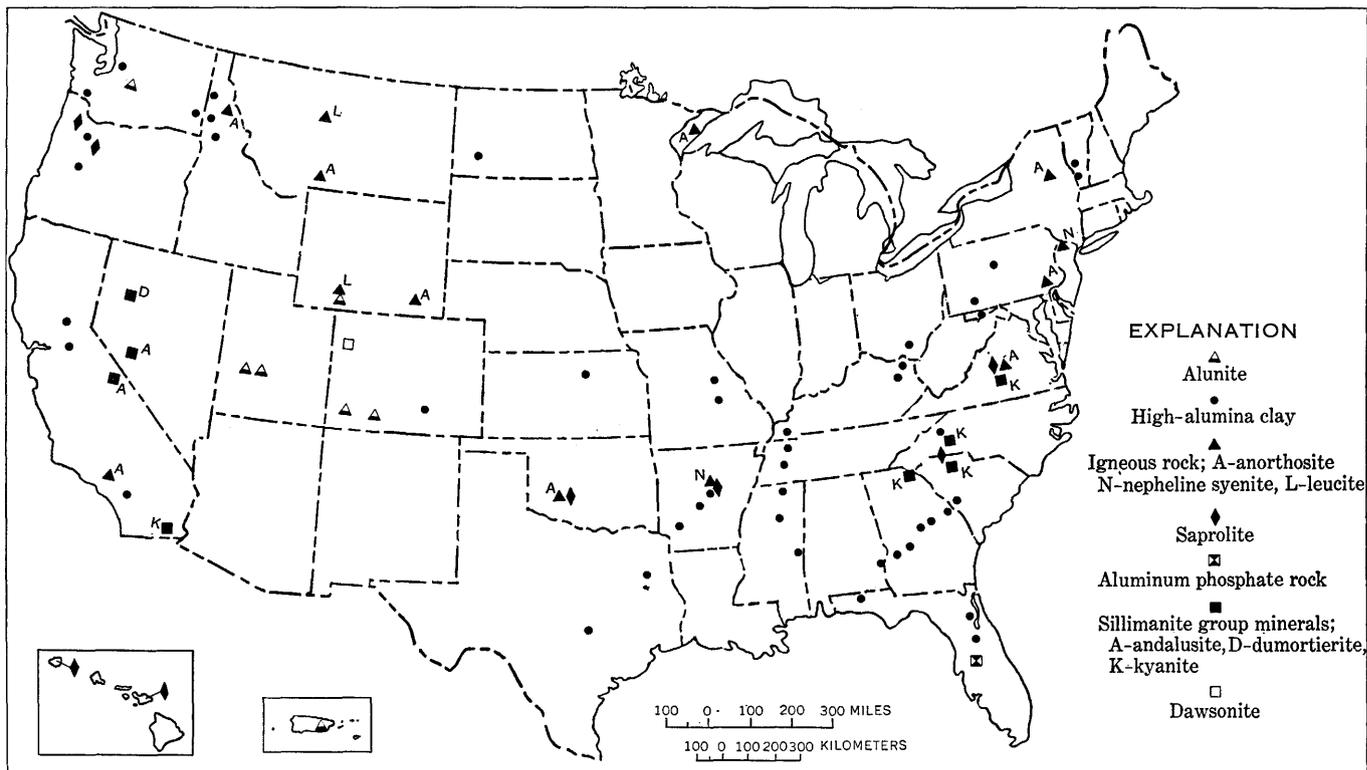


FIGURE 13.—Location of potential sources of aluminum other than bauxite in the United States.

In evaluating the resource potential of aluminous materials other than bauxite, many complex and interrelated geologic and economic factors must be considered. Among these are alumina content and size of the resources; costs of acquiring reserves and mining; costs and efficiency of a method of alumina extraction; costs of plant construction, power, and chemicals required for processing; location of deposits with respect to markets or captive plants using alumina and possible byproducts, and so on.

Though each of the aluminous materials other than bauxite in the United States has some favorable characteristics, none ideally meets all requirements for a bauxite substitute. Probably high-alumina clay fulfills more of the requirements of a substitute for bauxite than other materials, because it contains more aluminum than most other nonbauxitic materials and does not require beneficiation; also, many large deposits can be mined cheaply. According to estimates by the U.S. Bureau of Mines (1953, p. VII-5), aluminum can be made from such clays at approximately 1.5 cents more per pound than from bauxite, and more recent efforts may have reduced this margin. High-alumina clay now appears to be the most likely source of alumina other than bauxite, but regardless of technological advances, the clay has limitations that may prevent it from becoming a major long-range competitor of bauxite. High-grade clay is much in demand for use in refractories, paper coater and fillers, ceramics, fillers, and other uses. Many of the best grade clay deposits that are favorable for mining are now earmarked for such uses, and increased competition for clay reserves is expected. Total resources of high-alumina clay are large, but by no means all of the clay occurs where it could be mined cheaply. Low- and moderate-grade alumina clay (20-30 percent  $\text{Al}_2\text{O}_3$ ) resources are very large, but their low alumina content reduces their potential as a source of alumina.

Anorthosite and other igneous rocks occur in extremely large masses, but they are hard and would be more costly to mine and process than other aluminous materials. Probably alumina extraction from igneous rocks would have to be supported by a salable byproduct, such as portland cement. According to estimates by St. Clair and others (1959, p. 80), aluminum made from anorthosite would cost approximately 2.5 cents per pound more than from bauxite.

The aluminum phosphate rock in Florida is extremely fine grained, and the recovery of alumina, uranium, and phosphate byproducts from it may never be more than an interesting possibility. Large tonnages of this rock are discarded in phosphate mining each year, and the resources may not exist or may be reduced greatly when economic conditions are favorable for the extraction of alumina from it.

Aluminous shale is much lower in alumina content than some of the other nonbauxitic materials, but large deposits are favorably located with respect to transportation facilities, power, and markets. Aluminous shale would also be a cheap raw material because large tonnages are now removed in coal mining.

High-grade alunite resources are not large, and low-grade deposits would be costly to mine and process. Accordingly, alunite is not likely to be a major substitute for bauxite in the United States.

Though the alumina content of the sillimanite group minerals is very high, the occurrence of these minerals limits their potential as a source of alumina. Large pure deposits of these minerals are not known to exist, and they would be difficult to mine and concentrate at a cost competitive with bauxite.

Some large saprolite deposits are nearly as rich in alumina as high-alumina clay, and they also could be mined cheaply; however, they are commonly rich in iron and are composed of mixtures of aluminous materials and would therefore require a complicated process for the recovery of alumina.

#### ALUMINOUS SHALES

Though the Japanese recovered alumina during World War II from shales in Manchuria and northern China, little attention was given to this possible source of aluminum until recently. The most intense effort to use shale for an aluminous product was by the North American Coal Corp., which built a pilot plant at Powhatan Point, Ohio, to process shaly coal mine waste rock chiefly from roof stone above the Pittsburgh coal bed. This plant had an annual capacity of 40,000 tons and produced a small quantity of aluminum sulfate in 1962 (Higbie and others, 1963, p. 291); however, profitable extraction was not achieved, and the plant was dismantled (Am. Metal Market, 1964). The use of Canadian aluminous shales has been investigated by the Canada Department of Mines and Technical Surveys (Thomas and Ingraham, 1959), and some possibility of developing a commercial process may exist (Canadian Chem. Processing, 1962).

The aluminous-shale resources of the United States and Canada are extremely large, but most of them are not exceptionally high in alumina content. The shales of Pennsylvanian age removed in coal and clay mining amount to several million tons a year and are, therefore, attractive as possible sources of aluminum. The grade of the shales used in the Powhatan Point, Ohio, pilot plant has not been published; however, other shales of Pennsylvanian age are known to contain only 20–22 percent  $\text{Al}_2\text{O}_3$  (F. W. Clarke, 1924, p. 552; S. H. Patterson and J. W. Hosterman, 1962, table 8). The shales

investigated in eastern Canada contain 23.01 percent  $\text{Al}_2\text{O}_3$  (Thomas and Ingraham, 1959, table 1). Total resources of shale in the eastern parts of Canada and the United States are virtually inexhaustible. Extremely large resources of shale also occur in rocks of Cretaceous and Tertiary age in the western parts of both countries, and presumably much of the 125 billion tons of aluminous clay in Kansas containing 20–30 percent  $\text{Al}_2\text{O}_3$  (Jewett and others, 1942, p. 101, 133) is actually shale of Pennsylvanian age. Extraction of  $\text{Al}_2\text{O}_3$  from the Pierre Shale in South Dakota has been considered (Gries, 1942, p. 63–66; Rothrock, 1944, p. 65–66), and chemical engineering students at the South Dakota School of Mines and Technology have studied this problem (Miller, 1959, p. 26). The Pierre Shale, however, cannot be considered a good potential source of aluminum, because it contains only 12–18 percent  $\text{Al}_2\text{O}_3$  (Tourtelot, 1962, table 7).

### ALUMINUM PHOSPHATE DEPOSITS

#### UNITED STATES

Very large aluminum phosphate deposits occur in a belt extending from west-central peninsular Florida northward into southern Georgia. These deposits contain large potential resources of aluminum, uranium, and phosphate, and the recovery of all three commodities offers attractive possibilities. The utilization of these deposits is also attractive because they occur in the overburden that is removed in mining calcium phosphate, and an estimated 15 million tons is stripped and discarded each year (Calver, 1957, p. 52). This overburden may be as much as one-fourth aluminum phosphate rock. Research has been conducted on the recovery of alumina from these deposits (Mining World, 1953; Altschuler and others, 1956, p. 503). A method for recovery of uranium and fertilizer from this rock has been developed (Hignett and others, 1957), but no commercial extraction of any of the three commodities has been attempted.

The largest and best known aluminum phosphate deposits are in the land-pebble phosphate district, Florida, which is east of the Tampa Bay region in Polk, Hillsboro, and adjoining Counties. The aluminum phosphate rock occurs in a friable, leached, phosphatic sand above the calcium phosphate zone in the Bone Valley Formation of Pliocene age. The aluminum-bearing minerals are crandallite  $\text{CaAl}_3(\text{PO}_4)_2(\text{OH})_5 \cdot \text{H}_2\text{O}$ , millsite,  $(\text{NaK})\text{CaAl}_6(\text{PO}_4)_4(\text{OH})_9 \cdot 3\text{H}_2\text{O}$ , wavelite,  $\text{Al}_3(\text{PO}_4)_2(\text{OH})_3 \cdot 5\text{H}_2\text{O}$ , and kaolinite,  $(\text{OH})_8\text{Si}_4\text{Al}_4\text{O}_{10}$ . In addition to the aluminous forms, some of the phosphate occurs as carbonate-fluorapatite,  $\text{Ca}_{10}(\text{PO}_4\text{CO}_3)_6\text{F}_{2-3}$  (Altschuler and others, 1956, p. 499). The aluminum phosphate minerals form 20–30 percent of the rock, and more than 60 percent is quartz sand. The quartz is coarser than 150 mesh (0.1 mm), and virtually all the phosphatic material is finer than 150 mesh or can be disaggregated to this size.

The aluminum phosphate zone underlies several hundred square miles in the Peace and Alafia River valleys in the land-pebble district, and its average thickness is 6-7 feet. Known reserves of aluminous phosphate rock in this field alone exceed 800 million tons (McKelvey and others, 1953). The potential resources of aluminum in this field, in the hard-rock phosphate district farther north in Florida (Espenshade and Spencer, 1963), and in deposits in southern Georgia amount to hundreds of millions of tons. Though much of this rock contains only 8-15 percent  $\text{Al}_2\text{O}_3$  (table 9), the alumina content as well as the phosphate and uranium can be increased threefold by removing the plus 150-mesh quartz sand (Cathcart, 1963, p. D46).

TABLE 9.—*Chemical analyses, in percent, of seven samples from the aluminum phosphate zone in the Bone Valley Formation, Florida (Alischuler and others, 1956, p. 501)*

[Analyst, F. Cuttitta, U.S. Geol. Survey]

	Percent						
$\text{SiO}_2$ .....	51.48	62.60	40.92	57.24	69.46	68.08	51.32
$\text{Al}_2\text{O}_3$ .....	8.26	5.98	12.48	14.17	8.16	9.40	14.91
$\text{Fe}_2\text{O}_3$ <sup>1</sup> .....	2.76	2.86	2.61	2.17	1.32	1.33	2.19
MnO.....	.70	.53	2.14	.16	.16	.14	.13
MgO.....	.01	.01	.01	.01	.01	.01	.01
CaO.....	8.98	8.25	8.00	3.10	.90	.20	1.20
$\text{Na}_2\text{O}$ .....	.23	.13	.12	.15	.06	.04	.03
$\text{K}_2\text{O}$ .....	.00	.00	.00	.00	.00	.00	.00
$\text{TiO}_2$ .....	.37	.40	.63	.63	.31	.42	.65
$\text{P}_2\text{O}_5$ .....	19.72	13.60	20.79	12.79	11.61	11.32	16.35
Loss on ignition <sup>2</sup> .....	6.76	6.09	11.72	9.96	7.91	9.18	13.24
$\text{CO}_2$ .....	.80	.24	.26	.05	.02	.02	.05
F.....	1.15	.52	.63	.59	.51	.70	.53
Cl.....	.03	.02	.04	.01	.03	.02	.01
$\text{SO}_3$ <sup>3</sup> .....	.01	.01	.01	.01	.01	.01	.01
$\text{Cr}_2\text{O}_3$ .....	.01	.01	.01	.01	.01	.01	.01
$\text{V}_2\text{O}_5$ .....	.00	.00	.00	.00	.00	.00	.00
U.....	.01	.03	.02	.01	.01	.01	.01
Total.....	101.28	101.28	100.39	101.06	100.49	100.89	100.65
Less F=O.....	.48	.22	.27	.25	.22	.30	.22
Less Cl=O.....	.01	.01	.01	.00	.01	.01	.00
Corrected total.....	100.79	101.05	100.11	100.81	100.26	100.58	100.43
$\text{H}_2\text{O}$ (110°C).....	.35	.49	1.13	.64	.73	.39	.88

<sup>1</sup> This represents total iron, some of which may be present as ferrous iron.

<sup>2</sup> These figures include adsorbed water ( $\text{H}_2\text{O}$ -) and exclude  $\text{CO}_2$ .

<sup>3</sup> This represents total sulfur; no sulfides were found.

<sup>4</sup> Uranium is reported as a metal, as its valence state was not determined.

#### OTHER COUNTRIES

Large deposits of aluminous phosphatic laterite are located in the Thiès district of Senegal (Bruckner, 1957, p. 248-250; Capdecemme, 1953), 60 kilometers east of Dakar. These deposits formed on gently dipping marls, argillaceous limestone, and calcium phosphate rock. Augelite, crandallite, and an unidentified phosphate mineral are the principal minerals in the deposit, and, like the phosphate deposits in Florida, the Thiès deposits contain radioactive minerals. Very large tonnages of rock that is 25-27 percent  $\text{Al}_2\text{O}_3$  and 28-30 percent  $\text{P}_2\text{O}_5$  are present in these deposits (Arnaud, 1945, p. 86), and some of the augelite contains as much as 49.35 percent  $\text{Al}_2\text{O}_3$  (Capdecemme and

Pulou, 1954). Appreciable tonnages of crude and dehydrated alumina phosphate were mined in the Thiès district in 1964 (Mining Jour., 1964, p. 202) but were used for fertilizer rather than alumina.

Deposits of aluminous phosphatic rock occur in several other countries. Deposits of phosphatic bauxite near the mouth of the Maracassume River, Maranhão, Brazil, are reported to contain 20 million tons (Oliveira, 1943) that is 31 percent  $\text{Al}_2\text{O}_3$  and 30 percent  $\text{P}_2\text{O}_5$  (Paiva and others, 1937). Small deposits of aluminous phosphate occur in Fiji (Bracewell, 1962, p. 134). A phosphatic band is present locally between the bauxite and the underlying limestone in Jamaica (Eyles, 1958, p. 1367). Deposits of some economic potential occur near Cayenne, French Guiana, in the Los Islands, Guinea, and in the Abeokuta Province, Nigeria (Arnaud, 1945, p. 85–86, 91). The deposits in Nigeria contain 25–29.7 percent  $\text{Al}_2\text{O}_3$  and 26.3–33 percent  $\text{P}_2\text{O}_5$ . Phosphorite in Japan containing 20–30 percent  $\text{Al}_2\text{O}_3$  was investigated as a source of aluminum during World War II (Sato and others, 1956, p. 197); however, a commercially successful process was not developed. An association of phosphate and bauxite has also been noted in Jurassic rocks in the northern Urals, U.S.S.R. (Bushinsky and Bogolyubova, 1960).

### ALUNITE

#### UNITED STATES

Alunite,  $\text{KAl}_3(\text{OH})_6(\text{SO}_4)_2$ , which is 37 percent  $\text{Al}_2\text{O}_3$ , 11.4 percent  $\text{K}_2\text{O}$ , 38.6 percent  $\text{SO}_3$ , and 13 percent  $\text{H}_2\text{O}$ , occurs as nearly pure veins and as disseminated particles or masses in altered volcanic rock. Most alunite is white or pale shades of gray, red, brown, or yellow, and it occurs as coarsely crystalline aggregates and as dense earthy masses resembling clay.

Alunite has interested industrial chemists and metallurgists because of the possibilities of recovering potassium, aluminum, and sulfur, all marketable products. The first mining of alunite in the United States was for potash during World War I, when German imports were not available. Approximately 260,000 tons of alunite rock was produced from the Marysvale district, Utah, between 1915 and 1920. Production of alunite for potash ceased in 1920, but 5,000–10,000 tons was produced for fertilizer shortly after World War II. During World War II, alunite was investigated as a possible source of aluminum. A process for the recovery of alumina and potassium sulfate from alunite was developed (A. Fleischer, 1944). A joint program of exploration was conducted by the U.S. Geological Survey and the U.S. Bureau of Mines (Hild, 1946); an experimental plant was constructed at Salt Lake City, Utah, by the Defense Plant Corp., and about 37,000 tons of alunite was mined for testing purposes.

The principal alunite deposits in the United States are in Utah, Colorado, and Washington; small deposits occur in Nevada, California, and Arizona (Thoenen, 1941); and deposits that may be large and high grade have been discovered in Wyoming (Love and Blackmon, 1962). Measured, indicated, and inferred resources of alunite total 6,101,000 short tons (Bridge and others, 1947, p. 222). The largest district is at Marysvale, Utah, which is estimated to contain 3,740,000 tons of rock having an average alunite content of about 54 percent (approximately 20 percent  $\text{Al}_2\text{O}_3$ ). Resources of alunite at Sheep Rock, Beaver County, Utah, consist of approximately 2 million tons of rock that is 34 percent alunite (Thoenen, 1941, p. 38). The resources in the Calico Peak district, Dolores County, Colo., consist of about 6 million tons of rock that is 17.1 percent alunite (Thoenen, 1941, p. 38); and deposits in the Marble Mountain district, Rio Grande County, Colo., were estimated by members of the Geological Survey (L. S. Gardner, written commun., 1942) to amount to 5.7 million tons that is about 40 percent alunite. Deposits in the Enumclaw district, King and Pierce Counties, Wash., contain 588,000 tons of alunite (Valentine and Huntting, 1960, p. 5). The alunite in Wyoming was discovered in 1957 by E. R. Keller while he was observing cuttings from shallow holes drilled for oil and gas (Love and Blackmon, 1962). This alunite occurs on Aspen Mountain in southwestern Wyoming. The deposits, exposed in a bulldozed trench, consist of white claystone 8 feet thick, containing 60–90 percent alunite. Resources of alunite in these deposits have not been determined, but alunite is known to occur at two localities approximately 1 mile apart, and tonnages may be large. Additional information on alunite deposits in the United States can be obtained from references listed in an annotated bibliography by Nackowski, Brown, and Botbol (1962).

Alunite deposits mixed with quartz, pyrophyllite, kaolin, and sericite occur in the Cerro La Tiza area, Puerto Rico. The total alunite disseminated through this rock is inferred to be 288 million metric tons (Hildebrand and Smith, 1959, p. 66, table 5). The rock in which the alunite occurs is approximately 35 percent quartz and 45 percent pyrophyllite, sericite, and kaolin clays in roughly equal proportions.

Alunite is attractive as a potential source of alumina because of the possibilities for potassium and sulfur byproducts; however, no known alunite deposits in the United States are of the size required for more than an emergency source of alumina. The deposits in Puerto Rico may be large enough for industrial development, but the value of this alunite is reduced by its occurrence with a mixture of quartz, pyrophyllite, sericite, and kaolin.

**AUSTRALIA**

Alunite occurs in several places in Australia (Australia, Advisory Council Sci. and Industry, 1917, p. 9-12). Deposits in Lake Champion and vicinity, Western Australia, have been worked intermittently for a long time to recover alumina and potassium salts. Reserves of alunite in this area are described as significant (R. Lewis and G. E. Tucker, 1961, p. 912).

**CHINA (MAINLAND)**

Very large resources of alunite occur along the southeastern coast of mainland China. Deposits in the provinces of Chekiang and Anhwei were estimated to contain 210 million tons (Kleinbans, 1948, p. 3); according to a more recent estimate (Wilmot and others, 1959, p. 225), the alunite in these two provinces amounts to about 280 million tons containing 68 million tons of alumina. The deposits have been used on a small scale as a source of alum.

**JAPAN**

Alunite deposits occur in rhyolite, dacite, and andesite lavas and tuffs of Cretaceous and Tertiary age (Japan Geol. Survey, 1960, p. 215). At most places the alunite is associated with kaolin, pyrophyllite, and quartz. One type of alunite in Hiroshima Prefecture occurs in irregular masses in rhyolite and pyroclastic rock. A second type of deposit occurs as replacement of other rock and is ordinarily silicified in the upper part and is kaolinized in the lower part. This type of deposit occurs at Ugusu, Shizuoka Prefecture. Alunite reserves in Japan containing 15-29 percent  $\text{Al}_2\text{O}_3$  total 22.5 million tons (Japan Geol. Survey, 1960, p. 215). Small tonnages containing more than 30 percent  $\text{Al}_2\text{O}_3$  are present.

**U.S.S.R.**

Deposits of alunite occur at several places in the U.S.S.R. Those near Zaglik, south of the Caucasus Mountains, supply raw material for the alumina plant at Sumgait (Baer, 1959, p. 104; Shabad, 1958, p. 12). According to Sokoloff (1964, p. 769), 6.6 tons of alunite yields 1 ton of alumina, 0.5 tons of potassium sulfate, and 1.15 tons of sulfuric acid. Other large deposits on the southeastern slope of the Carpathian Mountains have been investigated (Petrovskii, 1947). One estimate of the alunite resources of the U.S.S.R., which are chiefly in the Caucasus region, is approximately 93 million tons (Collier, 1946, p. 83).

**OTHER COUNTRIES**

Principal foreign occurrences of alunite other than in Australia, the U.S.S.R., mainland China, and Japan are at La Talfa and Montioni, Italy; Musaz and Bereghszasz, Hungary; on the islands of

Milo, Argentiera, and Nevis, Greece; and Mont Dore, France (Australia, Advisory Council Sci. and Industry, 1917, p. 9). Alunite deposits also occur in Korea, and deposits near Puerto Camarones, Chile, are estimated to contain 26 million tons (Eng. Mining Jour., 1953, p. 188).

#### DAWSONITE

Dawsonite,  $\text{NaAl}(\text{OH})_2\text{CO}_3$ , consisting of 35 percent acid-extractable  $\text{Al}_2\text{O}_3$ , has been discovered recently in thick beds of oil shale in the Piceance basin of northwest Colorado. Studies by J. W. Smith of the U.S. Bureau of Mines, and Charles Milton of the U.S. Geological Survey and George Washington University (Smith, J. W., and Milton, Charles, 1966), and unpublished work by J. R. Dyni and R. J. Hite of the U.S. Geological Survey show that dawsonite is disseminated through shale which is interbedded with cyclic units of nahcolite,  $\text{NaHCO}_3$ , and other saline minerals. The oil shale and associated saline minerals are 900 feet thick where cored in one drill hole in the depositional center of the basin. In one select core, an oil-shale section is nearly 300 feet thick and contains 12.3 percent dawsonite; some thinner shale beds may be as much as 25 percent (by weight) dawsonite.

The information on dawsonite now available is inadequate to appraise its potential value as a source of aluminum. However, this mineral is known to be present in the Piceance basin, Colorado, through thick beds of shale averaging 25 gallons recoverable oil per ton, over hundreds of square miles (Smith, J. W., and Milton, 1966). It also may occur in oil shales in other basins in the Rocky Mountains region, and, therefore, the total alumina in dawsonite in the United States may be very large. The recovery of alumina from dawsonite and of soda ash from nahcolite as byproducts of the extraction of oil from shale are attractive possibilities.

#### HIGH-ALUMINA CLAY

##### UNITED STATES

High-alumina clay has been considered as a more likely source of alumina than any material other than bauxite. The chief reasons are that many clay deposits contain more alumina than do other nonbauxitic aluminous rocks, and large tonnages minable by stripping methods are common. The term "high-alumina clay" is used in several different ways. Because high-alumina content is essential, a minimum cutoff for  $\text{Al}_2\text{O}_3$  of 30 percent (Bridge and others, 1947, p. 221) is commonly applied. Though some large kaolin deposits are so pure that they contain appreciably more than 30 percent  $\text{Al}_2\text{O}_3$ , many large deposits, such as those in Latah County, Idaho,

which were tested in a pilot plant, contain less than 30 percent alumina. The term "high-alumina clay," therefore, must be applied, primarily in an economic sense, to any clay that can be considered as a source of alumina. Kaolinite,  $(OH)_8Si_4Al_4O_{10}$ , and to a lesser extent the other kaolin minerals—halloysite, dickite, and nacrite—which are similar to kaolinite in composition, are the dominant minerals in high-alumina clay; but other aluminous minerals, such as diaspore, boehmite, and alunite also occur in some deposits. The mineralogy of high-alumina and other types of clays is complex, and the reader is referred to a summary by Murray (1960) and to books by Grim (1953, 1962) for detailed information on this subject.

High-alumina clay deposits occur in many parts of the United States, and in several different types of rocks. Nearly all large deposits are in rocks of Pennsylvanian, Cretaceous, or Tertiary ages. Most deposits are in sedimentary rocks; many have been transported to their present location, others have formed in place from sedimentary, igneous, or metamorphic rocks, and a few were formed by hydrothermal processes and are associated with other hydrothermal minerals.

Resources of clay suitable for use as a source of alumina in the United States are difficult to appraise because few deposits have been investigated adequately. Though intensive investigations of all potential alumina sources were carried out by the U.S. Geological Survey, the U.S. Bureau of Mines, and several State geological surveys during World War II, and many deposits have been explored by companies since the war, complete exploration of several large districts has never been necessary because known deposits have been adequate to fulfill demands. Therefore, resource information discussed in the following pages is far from complete, and most tonnage figures listed are very conservative. Tonnage figures, where given, apply to total clay, and problems related to loss in mining and to overburden limitations on profitable mining, as well as many other economic factors, were not considered. Also, no consideration is given to high-grade clay deposits that are no longer available for the extraction of alumina because they are much in demand for use in refractories, paper coater and filler, filler for rubber and adhesives, and for other purposes. Nearly all these special uses require a clay that is very low in iron or has other valuable characteristics, and high-alumina clay that is high in iron or otherwise unsuitable for the special uses is bypassed in most districts where these clays are mined. Many important published reports on high-alumina clay are referred to in this bulletin, but others are listed in the bibliography in the report by Mark (1963).

## CLAY FORMED BY HYDROTHERMAL PROCESSES

Small deposits of high-alumina kaolinitic clay that formed by hydrothermal processes occur at several localities, but few are large enough to have possible value as a source of alumina. Large deposits of kaolin associated with alunite occur in the Marysvale district, Piute County, and at White Mountain, Beaver County, Utah. Some of these deposits are nearly pure kaolinite, and others are mixtures of kaolinite, alunite, and quartz. Though the recovery of alumina from alunite has been investigated, the possibilities of using the kaolins associated with the alunite have not been adequately appraised, and little is known of the size of the deposits. The kaolin minerals halloysite and dickite occur in deposits of probable hydrothermal origin in Montana and Utah; however, none of these are large enough to be possible sources of alumina.

## ALUMINOUS UNDERCLAY OF PENNSYLVANIAN AGE

High-alumina underclay deposits of Pennsylvanian age, occurring below or associated with coal beds, are very extensive in the Eastern and Central United States. They include several grades of clay that are now or have in the past been used for refractories, light-colored face brick, and other products in Pennsylvania, Maryland, West Virginia, Virginia, Ohio, Kentucky, Tennessee, Indiana, Illinois, Iowa, Missouri, Kansas, Oklahoma, and Texas. The underclays can be classified into three general types: (1) very high alumina clay, consisting of mixtures of kaolinite, diaspore, and boehmite, which contains more than 39.5 percent  $\text{Al}_2\text{O}_3$ , the amount present in pure kaolinite; (2) high-grade clay of nearly pure kaolinite, but ranging from 33 to nearly 39.5 percent  $\text{Al}_2\text{O}_3$  because of varying dilution by minerals other than kaolinite; (3) moderate- and low-grade underclay containing 20–33 percent  $\text{Al}_2\text{O}_3$ , which consists chiefly of kaolinite but contains variable quantities of other clay minerals including illite, montmorillonite, and mixed-layer clay minerals, as well as non-clay minerals. The very high alumina and high-grade kaolin underclay is much more abundant in rocks of Pottsville age than in younger Pennsylvanian rocks. The moderate- and low-quality underclay occurs in rocks of Pottsville age and is also abundant in younger Pennsylvanian rocks.

## VERY HIGH ALUMINA AND HIGH-GRADE KAOLIN UNDERCLAY

The most extensive deposits of high-grade underclay are the: (1) Mercer fire clay, Clearfield district, central Pennsylvania; (2) Sciotoville fire clay, southern Ohio; (3) Olive Hill Clay Bed of Crider (1913), eastern Kentucky; and (4) Cheltenham fire clay, east-central Missouri. These clays are not identical in age, but they all

occur within rocks of Pottsville age, and most are only a few feet above unconformities between rocks of Pottsville and Mississippian ages. Also, the clays in all four regions are associated with thin coals which are thick enough to be valuable at few localities. The origin of these and younger underclay deposits has been investigated by a number of geologists. Most agree that the association of coal and underclay indicates an origin related to a swampy environment. Plants once grew in the clay, and underclay differs from other argillaceous Pennsylvanian rocks in lacking bedding and being lighter in color. Opinions differ, however, whether the very high grade clay was altered from impure argillaceous sediments by leaching and recrystallization or was originally deposited with approximately its present mineral composition.

*Clearfield district, Pennsylvania.*—The largest and most valuable very high alumina and high-grade kaolin clay deposits are in the Clearfield district, Clearfield, Centre, and Clinton Counties, Pa. (Pennsylvania Geol. Survey, 1964). The clay occurs below the Mercer coal (middle Pennsylvanian) in the Pottsville formation (Bolger and Weitz, 1952). The Mercer fire clay ranges in thickness from a few inches to 20 feet. Nodular, blocky, flinty, and plastic types of clay occur in the deposits. Kaolinite is the principal mineral in the clay. Diaspore is the second most abundant mineral and occurs chiefly in aggregates of crystals resembling pisolitic structures or nodules. Boehmite is the third most abundant mineral and occurs as fine crystals in nodules, some of which are pure and some mixtures of boehmite and diaspore. Measured and indicated reserves of Mercer fire clay in two areas in Clearfield County were estimated by the U.S. Geological Survey and the Pennsylvania Geological Survey during World War II to be 73 million tons (Conley and others, 1947, p. 11). Of this tonnage 14–20 million tons was high-iron flint clay containing 35–39 percent  $\text{Al}_2\text{O}_3$  and 3–25 percent  $\text{Fe}_2\text{O}_3$ ; the very high alumina, high-iron nodular clay, ranging from 40 to 70 percent  $\text{Al}_2\text{O}_3$  and 5 to 25 percent  $\text{Fe}_2\text{O}_3$ , was believed to total 5–6 million tons. The clay in one small area in Clinton County was estimated to be 4 million tons (K. M. Waagé, written commun., 1945). Though clays have been mined extensively in the Clearfield district since these estimates were made, large tonnages of high-iron clay unsuitable for refractories remain in the district.

*Deposits in districts other than Clearfield in the Appalachian region.*—High-grade kaolin underclay of Pottsville age occurs in several places in the Appalachian region other than in the Clearfield district. High-grade flint and semiflint clay has been mined for several decades at scattered localities in Somerset County, Pa. (Leighton, 1941, p.

206-222), and neighboring counties. Several beds have been mined for more than a hundred years in the panhandle of Maryland (Waagé, 1950); however, the high-grade deposits that occurred under conditions permitting cheap mining are now virtually exhausted. Scattered deposits of high-grade kaolin clay of Pottsville age occur in West Virginia (Tallon and Hunter, 1959, p. 16-17).

*Deposits in southern Ohio.*—The Sciotoville fire clay deposits are scattered throughout much of Scioto, Jackson, and Vinton Counties in southern Ohio (Stout and others, 1923, p. 109-147). The deposits are lenticular and form a discontinuous bed from a few inches to nearly 15 feet thick; they are 3-6 feet thick at most places where mined. Flint, semiflint, plastic, and a ferruginous plastic clay that is locally called "pink eye" occur in these deposits. The flint clay and the better grades of semiflint clay are chiefly kaolinite, and most of them contain more than 35 percent  $\text{Al}_2\text{O}_3$ . The Sciotoville fire clay has been mined since 1861. The remaining high-grade low-iron clay is much in demand by the refractory industry, but appreciable tonnages of high-iron clay remain. The resources of clay at depth, located eastward from the belt of outcrops, are also presumably large.

*Deposits in eastern Kentucky.*—Extensive deposits of high-grade clay occur in the discontinuous Olive Hill Clay Bed of Crider (1913) in a belt more than 60 miles long and 5-10 miles wide extending southwestward from a point on the Ohio River near Portsmouth, Ohio. Thicknesses of the bed range from a few inches to as much as 25 feet, and the thickness of most deposits mined is 3-6 feet. Flint, semiflint, and plastic clay occur in the bed. The flint clay contains the most alumina and is nearly pure kaolinite. The plastic clay is the lowest in alumina, and though it consists chiefly of kaolinite, it contains appreciable amounts of illite, and mixed-layer-clay minerals. Resource estimates of the clay in eastern Kentucky have been attempted only in the Haldeman and Wrigley 7½-minute quadrangles (S. H. Patterson and J. W. Hosterman, 1962, p. 78). The total clay of all grades in these two quadrangles is estimated to be 275 million tons, but the high-grade refractory clay containing 35-38 percent  $\text{Al}_2\text{O}_3$  is only about 30 million tons. No limits were placed on overburden in making these estimates, and only small deposits could be stripped. Inasmuch as the two quadrangles for which clay has been estimated are only a small fraction of the eastern Kentucky belt, the total resources of high-grade clay must be more than 100 million tons, and the total of all grades possible as much as 1 billion tons. Though reserves of high-grade clay having low iron content that are under thin overburden have been exhausted or are much in demand by the refractory industry, large tonnages of clay containing more than 3 percent iron remain under thin overburden.

*Deposits in Missouri.*—Deposits of very high alumina and high-grade clay of Early Pennsylvanian age are scattered throughout a large area in the north-central Ozark district (Keller and others, 1954), and high-alumina clays occur in east-central Missouri (McQueen, 1943). The deposits, known as the Cheltenham fire clay, are preserved in sinkholes and depressions in Mississippian limestone and are only locally associated with coal. Blocky, nodular, flint, and plastic clays occur in the deposits. The very high alumina clay is chiefly nodular clay consisting of kaolinite, diaspore, and boehmite, and the high-grade clay is chiefly kaolinite. The Missouri deposits are largely depleted or are now owned by refractory companies; however, high-iron clay deposits of considerable size may have been bypassed in mining refractory clay.

#### MODERATE- AND LOW-GRADE UNDERCLAY

Moderate- and low-grade underclay is widespread in the Eastern and Central United States. Underclay containing 20 percent  $Al_2O_3$  or more is common in many places where coal beds of Pennsylvanian age occur in the Appalachian Plateaus and Central Lowland provinces, and probably one-fourth of these underclay deposits contain as much as 30 percent  $Al_2O_3$ . Though moderate- and low-grade underclay is mined extensively in several States and has been investigated by many geologists, very few dimensional and grade data on which to appraise deposits have been published. Probably the best summary of the mineralogy of this clay in many areas and at several different stratigraphic positions was published by L. G. Schultz (1958), and many of the other numerous reports on them are listed in the bibliography accompanying a map by Mark (1963). The total resources of these clays in the United States undoubtedly amount to many billions of tons, but the size and locations of deposits that are most favorable for mining have not been determined. The conclusion that resources of low- and moderate-grade aluminous underclays in the United States are extremely large is supported by Cross and Schemel (1956, p. 48, 49), who estimated that in two counties in the panhandle of West Virginia alone, clay resources under less than 500 feet of overburden, below the Clarion coal, are at least half a billion tons, and those below the Lower Kittanning coal are about a billion tons.

#### HIGH-ALUMINA CLAY OF CRETACEOUS AGE

*Colorado.*—The largest and best grade high-alumina kaolinitic clay in Colorado occurs in Fremont, Pueblo, Custer, Huerfano, and Las Animas Counties. The deposits are in the Glencairn Shale Member of the Purgatoire Formation and in the Dakota Sandstone of Early Cretaceous age. Deposits occur as discontinuous beds and tabular

lenses, ranging in thickness from 3 to 30 feet. Plastic, semiplastic, and flint types of clay are present. The flint clay is the richest in alumina and consists chiefly of kaolinite. Quartz sand is the principal impurity, and muscovite, nontronite, and organic matter occur in minor quantities. The measured and indicated reserves of flint clay, containing an approximate average of 35 percent  $\text{Al}_2\text{O}_3$  in the Turkey Creek district, Pueblo County, were estimated to be 2.5 million tons, and those in the Canon City district, Fremont County, 1.2 million tons (Waagé, 1953, p. 70). Total reserves of the flint, semiplastic, and plastic clay have not been estimated. Though the total is probably many times the tonnage estimated by Waagé, all three types of clay are now much in demand by refractory and other ceramic industries, and large tonnages may not be available for the extraction of alumina.

*Plains States.*—Very large deposits of aluminous clay in the Dakota Formation of Early Cretaceous age occur in north-central Kansas, and similar clays may occur in an extensive belt of Cretaceous rocks in east-central Nebraska. The Kansas clay includes materials investigated as potential sources of alumina by the Kansas Geological Survey (Kinney, 1952). Presumably it contains much of the 125 billion tons of clay in Kansas that is reported to be 20–30 percent alumina and minable by stripping methods (Jewett and others, 1942, p. 101, 133). Investigation by the U.S. Bureau of Mines (McMillan and Wilson, 1948), however, failed to find extensive deposits that are exceptionally rich in alumina. The average contents of the most abundant oxides in three large deposits are as follows:  $\text{Al}_2\text{O}_3$ , 18.12–21.96 percent;  $\text{SiO}_2$ , 61.78–65.46 percent,  $\text{Fe}_2\text{O}_3$ , 2.65–5.13 percent, and  $\text{TiO}_2$ , 1.14–2.11 percent; the loss on ignition is 8.52–10.21 percent.

*Northwestern Alabama.*—Kaolin deposits of Cretaceous age or older occur along the contact of rocks of the Tuscaloosa Group and the underlying beds of Pennsylvanian age in several areas in Marion and Franklin Counties, Ala. (O. M. Clarke, 1964, p. 503–504). Some of this clay is nearly pure kaolin, and part of it contains appreciable quantities of quartz sand. Resources of clay in this area have not been appraised, but they may be of sufficient size to be considered as possible sources of aluminum.

*Central Georgia.*—Extensive high-grade kaolin deposits occur discontinuously throughout much of the belt between Macon and Augusta, Ga., where the Coastal Plain sedimentary rocks of Cretaceous and Tertiary ages overlap older crystalline rocks. The kaolin occurs as irregular lenses in the Tuscaloosa Formation of Late Cretaceous age (Kesler, 1963, p. 7–8), and deposits are known to occur as much as 175 feet below the top of the formation. The kaolin

lenses range in thickness from a few inches to about 60 feet, and the average deposit mined is about 20 feet thick. The clay is chiefly white kaolinite. The best grade deposits are nearly pure, but some contain so much quartz sand and mica that they are of little value, and trace amounts of these impurities are present in even the purest deposits. Other impurities in the kaolin include titanium and iron-bearing minerals and small quantities of montmorillonite. Lenses of gibbsitic bauxite occur locally in the kaolin. Few of these lenses are more than 5 feet thick, and none are extensive enough to be of value. A few deposits contain thin beds of lignite. Most of the kaolin is 35–40 percent  $\text{Al}_2\text{O}_3$ , 44–48 percent  $\text{SiO}_2$ , 0.3–1.7 percent  $\text{Fe}_2\text{O}_3$ , and 1.30–3.40 percent  $\text{TiO}_2$ , and the loss on ignition is 13–14 percent (Kesler, 1963, p. 8).

Tentative unpublished estimates by the U.S. Geological Survey during World War II placed the measured, indicated, and inferred reserves of kaolin (mostly containing more than 37 percent  $\text{Al}_2\text{O}_3$ ) in the Macon-Sandersville district, Georgia, at 145 million tons; this figure includes deposits near Irwinton, which reportedly contain 60–75 million tons (W. B. Lang and others, 1965, p. 11). Though very large tonnages of kaolin have been mined each year since these estimates were made, much prospecting has been done by several companies, and discoveries have probably much more than kept pace with depletion. Also, large deposits not included in these estimates occur northeast of Sandersville. Several geologists familiar with company exploration programs have conservatively estimated that 1 billion tons of kaolin of all grades is present in this region.

*South Carolina.*—Large deposits of transported kaolin similar to those in central Georgia occur in a belt 22 miles long and 10 miles wide, extending northeast and southwest from the city of Aiken. The deposits are irregular lenses interlayered with sandstone of the Tuscaloosa Formation of Late Cretaceous age (W. B. Lange, 1940). Much of the kaolin is nearly pure, but parts contain appreciable sand and muscovite.

Reserves of kaolin containing an average of 35 percent  $\text{Al}_2\text{O}_3$  in one area of the Aiken district explored by the U.S. Bureau of Mines in 1942 were estimated to be 10 million tons, and the total of all grades 19.5 million tons (Smith, K. M. 1949, p. 2). Total inferred reserves of high-grade kaolin in the entire district were estimated by the U.S. Geological Survey during World War II (J. J. Page, written commun., Sept. 1954) to be 100 million tons, and total tonnage of lower grade sandy kaolin was approximately the same. Much mining has been done by several companies since these estimates were made; nevertheless, the remaining reserves of high-grade kaolin are large, and large tonnages could be recovered by removing the sand impurities.

## HIGH-ALUMINA CLAY OF TERTIARY AGE

*Eastern Washington and northern Idaho.*—Extensive clay resources in eastern Washington and northern Idaho include deposits of (1) residual clay or saprolite that has weathered from intrusive igneous and metamorphic rocks, (2) residual clay weathered from basalt, and (3) transported clay in the Latah Formation of Miocene age. The parent intrusive rocks are part of the Idaho batholith fringe of Late Jurassic or Cretaceous age. They consist chiefly of granodiorite, but monzonite, tonalite, granite, and syenite occur locally. The metamorphic rocks are chiefly gneisses and schists of the Precambrian Belt Series. The extrusive rocks that have weathered to clay are massive basalt flows, pillow lavas, and breccias occurring in the older parts of the Columbia River Group and are probably of Miocene age. The residual clays formed in an area of low relief during Miocene time when the climate was warm and humid (Scheid, 1947). The transported clays are composed of material that was eroded from intrusive igneous and metamorphic rocks and deposited in local basins formed where basalt flows dammed streams. These clays are in lenses and discontinuous beds that are associated with silt, sand, and pebble beds, and minor amounts of lignite.

The clay formed on granodiorite consists chiefly of kaolinite and halloysite, but it includes much quartz and muscovite and small amounts of resistant accessory minerals. In the most thoroughly weathered parts of deposits, all the feldspar of the parent rock has been altered to clay, but feldspar is abundant in some of the less weathered parts. Glass sand and scrap mica are possible byproducts recoverable by washing this clay (Carter and others, 1962, p. 20).

Most of the clay formed from basalt is halloysite. Blue-black ilmenite is typically uniformly distributed throughout the clay, preserving the relict basaltic texture. The ilmenite is so abundant that the average  $\text{TiO}_2$  content of the clay is 6.4 percent (Hosterman and others, 1960, table 4), and might be recovered as a byproduct by washing the clay.

The transported clay in the Latah Formation consists chiefly of kaolinite. Quartz sand and silt and muscovite flakes are the principal impurities, and resistant accessory minerals from the igneous rocks and carbonaceous matter occur in minor quantities. Local zones within the clay are very sandy, and in a few places sand and pebble beds are interlayered with the clay.

The clays in Latah, Kootenai, and Idaho Counties, Idaho, and Spokane County, Wash., were investigated during World War II by the U.S. Geological Survey and the U.S. Bureau of Mines (Hosterman and others, 1960). Most of the tonnage and grade information

obtained during this work was published in a pamphlet by the Idaho Bureau of Mines and Geology (Hubbard, 1956, table 1, pl. 2). Areas in Latah County, Idaho, totaling about 20 square miles contain 183.9 million tons of measured and indicated clay resources that are 21.7 percent  $\text{Al}_2\text{O}_3$  and 277 million tons of inferred clay that is 20 percent  $\text{Al}_2\text{O}_3$  (Hubbard, 1956, table 1). Kootenai County, Idaho, has 1.6 million tons, and Spokane County, Wash., has 12.5 million tons of measured, indicated, and inferred resources of clay (Scheid, 1945, table 2). The total clay containing more than 20 percent  $\text{Al}_2\text{O}_3$  inferred to be present in the areas investigated is approximately 475 million tons. Areas not investigated that are geologically favorable for clay in Idaho include several thousand square miles extending from Kootenai County in the north to the northern part of Idaho County in the south (Sohn, 1952). In Latah County alone an area of as much as 280 square miles is favorable for the discovery of clay (Hubbard, 1956, p. 4). In parts of Spokane and Whitman Counties, Wash., large areas are favorable for discovery of clay. If the density of clay deposits in all these favorable areas is only half that found in the areas investigated, the total resources of clay in eastern Washington and northern Idaho is several times the 475 million tons inferred to be present where estimates have been made.

*Western Washington and Oregon.*—Six small clay deposits occur in King County, Wash., about 20 miles southeast of Seattle and 30 miles northeast of Tacoma. The clay is of sedimentary origin and occurs in the Cowlitz(?) Formation of late Eocene age. It is light gray to black and flinty and is associated with coal. The bed ranges in thickness from 3.5 to 33 feet, and average thickness is approximately 12 feet. The clay is composed of kaolinite and boehmite and minor amounts of diaspore, gibbsite, and possibly alumina gel. Sideriate is the most abundant nonclay impurity and occurs as concretions and veins. Other nonclay minerals present are limonite, pyrite, muscovite, feldspar, and quartz. Approximately 3.7 million tons of measured and inferred clay having an average  $\text{Al}_2\text{O}_3$  content of 33 percent was found in the King County deposits during World War II (R. L. Nichols, 1945, table 12). An additional 20 million tons of approximately the same grade clay was indicated in geologically favorable areas surrounding the deposits investigated. The tonnage mined since World War II and the size of the deposits found since then are unknown.

High-alumina clay deposits occur 7 miles northeast of Castle Rock, Cowlitz County, Wash. The deposits are in the upper Oligocene, part of the Toutle Formation. They consist of carbonaceous white to gray clay that is chiefly kaolinite but also contains miner

amounts of gibbsite and montmorillonite (Popoff, 1955, p. 15). In its massive dry state, the clay is a semiflint variety. The chief impurities are sand- and pebble-size sideriate nodules and tuff breccia (Roberts, 1958, p. 56). An unnamed lignite occurs in the upper part or above the clay at most places. Clay deposits covering 247 acres and containing 17.8 million tons having an average  $\text{Al}_2\text{O}_3$  content of 29 percent were explored during World War II (R. L. Nichols, 1943, table A). Some of this reserve has been mined since the war, but appreciable tonnages still remain, and an additional 10–20 million tons of similar grade clay is indicated in the geologically favorable areas surrounding the deposits explored.

The Molalla high-alumina clay deposits are 3 miles southeast of Molalla, which is 30 miles south of Portland, Oreg. Part of the kaolinitic materials in these clays has been transported and part has formed in place of weathering of breccias, silt, sand, and gravel (R. L. Nichols, 1944). The deposits occur in the Molalla Formation of Baldwin (1950) of Tertiary age. The deposits consist chiefly of kaolinite but contain minor quantities of halloysite, gibbsite, and montmorillonite. Deposits in four areas investigated by the U.S. Geological Survey and the U.S. Bureau of Mines in 1942–43 contain 49 million tons of measured and indicated resources of clay, and inferred resources are approximately 50 million tons (R. L. Nichols, 1944, pp. 16–23). This clay contains an average of 26.38 percent  $\text{Al}_2\text{O}_3$ , and part of it contains more than 30 percent  $\text{Al}_2\text{O}_3$ . Presumably very large tonnages of clay are present in other parts of the Molalla region, and the total resources probably are much larger than the estimates indicate.

The Hobart Butte high-alumina clay deposits are approximately 16 miles south of Cottage Grove, Lane County, Oreg. The aluminous material consists mainly of clay, clay-fragment breccia, clay-pellet shale, sandstone, and conglomerate (V. T. Allen and others, 1951). The deposits probably were derived from a land surface to the east and were deposited in water with other sediments that form the Calapocoya Formation of late Eocene and Oligocene age. Both semiflint and plastic types of clays occur in the deposits. The clays were invaded by hydrothermal solutions in late Miocene time and now contain both sedimentary kaolinite and hydrothermally formed dickite kaolin minerals. They also contain minor amounts of realgar, stibnite, pyrite, sideriate, scorodite, mansfieldite, and other minerals (V. T. Allen and others, 1951, p. 1). Three areas on Hobart Butte investigated by the U.S. Geological Survey and the U.S. Bureau of Mines in 1942 contain nearly 15 million tons of measured and indicated clay resources that are 29 percent  $\text{Al}_2\text{O}_3$  and 3 percent  $\text{Fe}_2\text{O}_3$  (Loofbourow, 1943, p. 12–14). An additional 14 million

tons of lower grade clay is present (Wimmler and others, 1944, p. 7). Several areas on Hobart Butte not investigated also contain high-alumina clay, and clays similar to those on Hobart Butte occur as far north as the Putman deposits near Cottage Grove. The total resources of high-alumina clays in the Hobart Butte region are, therefore, much larger than the available estimates indicate.

*California.*—The largest deposits of high-alumina clay in California are in the Ione Formation of Eocene age, which crops out in a discontinuous belt bordering the western foothills of the Sierra Nevada Range. This belt extends approximately from the Feather River on the north to the San Joaquin River on the south. The clay deposits are as much as 30 feet thick, and the average thickness is about 15 feet. They are enclosed by beds that are chiefly sand but contain minor amounts of sand-clay mixtures, clay, shale, gravel, and lignite. Most of the Ione clays are sedimentary in origin, and presumably they are part of the weathered products of the crystalline rocks in the Sierra Nevada Range that were transported to lagoonal basins. Minor residual clays formed on Jurassic metamorphic rocks occur adjacent to the Ione deposits. The Ione clays are chiefly kaolinite, but minor quantities of anauxite, a silica-rich kaolin mineral, are also reported to be present. Most of the Ione clays that have been mined are near Ione, Amador County, but appreciable tonnages have been mined near Lincoln, Placer County. In recent years deposits have been mined at Valley Springs, Calaveras County; Knights Ferry, Stanislaus County; Michigan Bar and Folsom, Sacramento County; and near Coopers-town, Tuolumne County (Cleveland, 1957b, p. 136). No appraisals of the clay resources in the Ione Formation have been made; however, one area near Ione explored during World War II contained 53,800,000 tons of clay whose average composition was 23.6 percent  $\text{Al}_2\text{O}_3$  and 2.4 percent  $\text{Fe}_2\text{O}_3$  (Cleveland, 1957a, p. 30). Though much of this clay may have been mined, the total resources of Ione clays remaining, including much low-grade sandy clay, are probably several times this figure. The large resources of sandy clay are potential sources of both clay and silica sand.

Probably the second most valuable high-alumina clay deposit in California occurs in parts of the Santa Ana Mountains in western Riverside and eastern Orange Counties. The Alberhill area in this region contains the largest known reserves of fire clay in the southern part of the State. Both residual and sedimentary clay occur in this area (Cleveland, 1957b, pp. 136–138). The residual clay apparently formed by weathering of Mesozoic crystalline rocks in Paleocene time. The sedimentary clays are part of the Silverado Formation of Paleocene age, and they probably were transported

from the weathered crystalline rocks. The sedimentary clay has an average thickness of about 80 feet, and the residual clay is as much as 130 feet thick. No realistic estimates of the amount of kaolin in the Santa Ana Mountains region have been published. The total probably amounts to several millions of tons, but the best grade and the cheaply mined clay is being consumed by refractory and brick-making industries, and large quantities may not be available for alumina extraction.

High-alumina clay deposits other than those in the Ione Formation and the Santa Ana Mountains occur at several places in California, including the Tesla area, Alameda County; Castle Mountains and other localities in San Bernardino County; and scattered localities in Mono and Mojave Counties (Cleveland, 1957b, fig. 10). None of these deposits are known to be of sufficient size to form valuable resources of alumina.

*Northern Great Plains.*—Clays of Tertiary age have been investigated in several places in western North Dakota (F. F. Clarke, 1948; Hansen, 1959) and eastern Montana (Great Northern Railway Co., 1958). Probably the best grade clays are in the Golden Valley Formation, inasmuch as some of these clays are rich in kaolinite (Freas, 1962). Though very large tonnages of clay are present in this and other formations, only a few deposits contain as much as 22 percent  $\text{Al}_2\text{O}_3$ , and the existence of large tonnages of clay that is of sufficiently high grade to permit profitable extraction of alumina is yet to be demonstrated.

*Texas.*—A belt of lower Eocene rocks containing scattered kaolin deposits extends across Texas from the corner of the State near Texarkana, Ark., to a region on the Rio Grande River northwest of Laredo. Most of the clays in this belt are extremely sandy (Pence, 1954; Hoeman and others, 1945), but in several places they are sufficiently pure for use in making fire brick (Stenzel, 1950; King, 1940). Most of these clays contain less than 25 percent  $\text{Al}_2\text{O}_3$ , and the prospects for the recovery of alumina from them are, therefore, less favorable than from kaolins in other States.

*Arkansas.*—The principal high-alumina clay deposits in Arkansas are associated with the bauxite deposits that fringe the buried nepheline syenite hills in Pulaski and Saline Counties (Gordon and others, 1958, p. 255). The bauxite bodies grade both laterally and vertically through bauxite clay into the enclosing large masses of kaolin clay. This clay and bauxite is a facies of the Berger Formation, the lower formation of the Wilcox Group of early Eocene age. The bauxite kaolin zone attains a maximum thickness of 80 feet, but in most places does not exceed 60 feet. The typical kaolin zone in these deposits contains more than 35 percent  $\text{Al}_2\text{O}_3$ , less than 45

percent  $\text{SiO}_2$ , and less than 5 percent  $\text{Fe}_2\text{O}_3$ . The clay is chiefly kaolinite, and the principal impurities are siderite, limonite, ilmenite, and carbonaceous matter; biotite is common locally. According to a conservative estimate, the Arkansas bauxite region contains at least 100 million tons of kaolin that is covered by no more than 50 feet of overburden (Tracey, 1944), and presumably additional larger resources exist under greater thicknesses of overburden.

Numerous kaolin deposits also occur in a broad belt of Wilcox Group rocks extending southwest of the Arkansas bauxite region in parts of Grant, Hot Springs, Dallas, Ouachita, and Miller Counties (N. F. Williams and N. V. Plummer, 1951). The clay in this belt is in lenses ranging in thickness from 6 inches to 30 feet and in areal extent from a few square feet to 40 acres or more. The clay lenses are enclosed by beds of chiefly unconsolidated sandstone, which contain appreciable quantities of lignite. Part of the clay is pure, and part is contaminated with silt, sand, and lignite. One sample examined by Dr. R. E. Grim, who used X-ray and differential thermal analysis methods (N. F. Williams and N. V. Plummer, 1951, p. 6), consisted chiefly of kaolinite but also contained montmorillonite and quartz. No estimates of the clay resources in this broad belt have been made, but the total is probably very large. Much of this clay is probably nearly as high in alumina as the deposits in the bauxite region.

*Western Kentucky and Tennessee.*—Kaolin deposits are scattered throughout a belt in Kentucky and Tennessee lying west of the Tennessee River (Gildersleeve, 1950; Whitlatch, 1940). The best grade deposits, which are nearly pure kaolins, are in the Claiborne Group of middle Eocene age. These deposits occur as lenses in a formation that is chiefly unconsolidated sandstone. Thin beds of lignite commonly occur interlayered with and overlying the clay. Carbonaceous matter, quartz sand, and iron-bearing minerals are the principal impurities in the clay. The deposits are now mined for ball, slip, refractory, and other types of clay. Though resources of high-quality kaolin in this region may be large, the clay is much in demand, and deposits of the size required to supply an alumina plant may not be available.

*Mississippi.*—High-alumina clay deposits are scattered along an arcuate belt extending from Tippah County in the northeastern part of Mississippi to a point in eastern Lauderdale County in the east-central part of the State. This belt extends 185 miles from the Tennessee to the Alabama boundaries. The deposits in Tippah and Benton Counties occur in a transition zone of sand, sandy kaolin, kaolin, and bauxite that occurs between the marine Porters Creek Clay of Paleocene age and the Wilcox Formation of early Eocene

age. Farther south the clay is associated with bauxite and lignite deposits that occur within the Wilcox Formation. Most of the clay deposits are 10 feet thick or more and occur as pockets, lenses, and channel-fill deposits.

A total of more than 7.5 million tons of kaolin and bauxite clay, containing 30–40 percent  $\text{Al}_2\text{O}_3$ , was found by the U.S. Geological Survey and U.S. Bureau of Mines during World War II (Coulter, 1948; Reed, 1948, 1952; Conant, 1965, p. B68; Tourtelot, 1964, p. C31). These deposits are in the Tippah-Benton district, Fowler and Pinedale areas, and the Winston-Noxubee Kemper district. The areas investigated include the most favorable ones in Mississippi for the occurrence of high-alumina clays; however, scattered areas not investigated may contain clay, and the total in the State may considerably exceed 7.5 million tons.

*Alabama.*—High-alumina clays occur in a number of places in Alabama. Most deposits contain only a few hundred thousand tons of kaolin. The largest deposits are in the Eufaula district, Barbour and Henry Counties. These deposits commonly enclose lenses of bauxitic clay and bauxite. They occur in the nonmarine facies of the Nanafalia Formation of early Eocene age (Warren and Clark, 1965, p. E18). The bauxite, bauxitic clay, and kaolin in the Eufaula district appraised by the U.S. Bureau of Mines during World War II amounted to 6.5 million tons (S. A. Allen, 1949, p. 17), and 5–6 million tons of kaolin have been bypassed in bauxite mining and prospecting (Pigott and Tyrrell, 1959, p. 1).

*Florida.*—Kaolin occurs in a large area in east-central Florida and in a smaller area west of the Apalachicola River in western Florida (Calver, 1949). The central Florida deposits extend in a belt as much as 25 miles wide from southern Clay County to southern Polk County, a distance of 150 miles. Deposits in the western part of the State are in a narrow belt extending from Round Lake, Jackson County, to the Escambia River, Santa Rosa County. Florida kaolins are mixtures of quartz sand and kaolinite and ordinarily contain less than 2 percent mica, iron minerals, and other heavy minerals. The kaolin content of the sands ranges from 5 to 45 percent, and the average is about 18 percent. Though no estimates of the resources of kaolin in the State have been made, very large tonnages of sandy kaolin are known to be present. High-quality kaolin and silica sand are recovered by dredging and washing.

*West-central Georgia.*—Very large deposits of high-alumina kaolin are associated with bauxitic clay and small bauxite deposits in the Springvale district, Randolph and Quitman Counties; and the Andersonville district, Sumter, Macon, and Schley Counties, Ga. The deposits are in the nonmarine facies of the Nanafalia Forma-

tion of early Eocene age, which unconformably overlies strata of the Clayton Formation of Midway age. The kaolin occurs as irregular lenses and locally encloses smaller pods and lenses of bauxitic clay and bauxite. The kaolin is chiefly kaolinite, and the bauxitic clay is a mixture of kaolinite and gibbsite. Both types of clay contain small amounts of montmorillonite and iron-bearing minerals.

The deposits in both districts were investigated by the U.S. Geological Survey and the U.S. Bureau of Mines during World War II as part of a country-wide search for bauxite. Kaolin reserves in the Springvale district were not calculated, but bodies more than 50 feet thick and more than 700 feet in diameter were found (Clark, 1965, p. 8). Total resources of kaolin in several deposits shown on maps and drill-hole logs published by the U.S. Bureau of Mines (Beck, 1949) and in other deposits not investigated probably amount to several million tons. Deposits in the Andersonville district were investigated in much more detail than those in the Springvale district because both bauxite and kaolin deposits are larger and more abundant. Deposits of kaolin and bauxitic clays in the Andersonville district were estimated (Zapp, 1965, p. 20) as follows: (1) Under less than 50 feet of overburden, bauxitic clay (40–50 percent  $\text{Al}_2\text{O}_3$  and less than 43 percent  $\text{SiO}_2$ ) 5,990,000 long tons and kaolin (more than 37 percent  $\text{Al}_2\text{O}_3$  and less than 2 percent quartz sand) 83,000,000 tons; (2) under more than 50 feet of overburden, bauxitic clay 17,930,000 long tons and kaolin 162,500,000 long tons. The total resources of high-alumina clay, then, is 269,420,000 long tons. Some clay has been mined since these estimates were made, but most of the reserve remains, particularly in deposits under more than 50 feet of overburden.

*North Carolina.*—Numerous scattered deposits of residual kaolin occur in the Spruce Pine district, North Carolina. The deposits have formed by weathering of feldspathic rocks and contain high percentages of quartz and other resistant minerals. High-quality kaolin containing 37 percent or more of  $\text{Al}_2\text{O}_3$  and less than 1 percent  $\text{Fe}_2\text{O}_3$  is recovered by washing. Total crude kaolin resources in the district are estimated to be 51 million tons (C. E. Hunter, 1940, p. 102). The amount of recoverable kaolin, however, is only 9–15 percent of the crude, and the total kaolin that could be refined is estimated to be only 3–7 million tons (J. M. Parker, 1946, p. 42).

Deposits of high-alumina clay occur in several other places in North Carolina; however, none are of sufficient size and grade to be considered as possible sources of alumina.

*Vermont.*—A discontinuous belt of kaolin deposits west of the Green Mountains extends from Monkton to Pownal. Within this belt, kaolin crops out at Brandon (Forestdale), Rutland, North

Clarendon, South Wallingford, Tinmouth, North Dorset, Shaftsbury, and Bennington (Burt, 1929). These deposits are associated with small deposits of iron, manganese, and lignite. Pollen in the lignite is of probable Oligocene age (Traverse, 1955), and presumably the clay formed at about the same time as the lignite. Most of the Vermont kaolins are residual, having formed from feldspar in gneisses and aluminous minerals in argillaceous quartzites of Precambrian age. Deposits are known to occupy areas as much as 1,100 feet long and 600 feet wide and extend to depths of more than 150 feet. The crude kaolin contains 26.03–28.52 percent  $\text{Al}_2\text{O}_3$  and 53.96–58.92 percent  $\text{SiO}_2$  (Jacobs, 1940, p. 15). Much of the silica is in the form of quartz grains, and the kaolin can be upgraded considerably by washing. On one property deposits of 6 million tons of kaolin have been proved by core drilling (Jacobs, 1940, p. 14), and presumably the State's total kaolin resources exceed this figure many times.

#### OTHER COUNTRIES

Large quantities of high-alumina clay occur in several countries, but very little information is available on size and grade of the deposits. A plant to extract alumina from bauxitic clays was reportedly built recently in Poland (Wilmot and others, 1960, p. 237); thus, large clay deposits may exist there. A similar inference can be made for deposits in Argentina, where a plant to utilize high-grade clays was considered (Eng. Mining Jour., 1954a). Deposits of high-alumina clay also occur in England, France, Italy, Germany, the U.S.S.R., India, China (mainland), Japan, Brazil, British Guiana, Surinam, several countries in Africa, and other countries.

#### IGNEOUS ROCKS

##### UNITED STATES

Anorthosite, a rock consisting chiefly of feldspar, is richer in  $\text{Al}_2\text{O}_3$  than most other igneous rocks and has, therefore, been considered as a source of aluminum. The possibility of recovering aluminum from this rock has been investigated thoroughly by the U.S. Bureau of Mines. The deposits investigated are in the Laramie Range, Wyo. (St. Clair and others, 1959), and the San Gabriel Mountains, Los Angeles County, Calif. (Lundquist and Oakeshott, 1963).

The Laramie Range and the San Gabriel Mountains anorthosite masses are both very large. The Laramie Range masses cover more than 200 square miles (Hagner, 1951, p. 1; Newhouse and Hagner, 1957). The total resources of anorthosite in these masses that are at depths of less than 100 feet below the average ground level are

TABLE 10.—*Chemical analyses (in percent) of aluminous igneous rocks*

	1	2	3	4	5	6
SiO <sub>2</sub> .....	51.91	53.50	55.23	50.68	47.06	53.56
Al <sub>2</sub> O <sub>3</sub> .....	25.87	28.92	27.32	30.67	32.61	24.43
Fe <sub>2</sub> O <sub>3</sub> .....	.78	.62	.12	.21	.18	2.19
FeO.....	2.80	.14	-----	.29	.65	1.22
MgO.....	.72	.07	tr	.42	.28	.31
CaO.....	9.18	10.78	9.58	13.79	16.03	1.24
Na <sub>2</sub> O.....	4.51	4.54	5.64	3.40	1.97	6.48
K <sub>2</sub> O.....	.78	.62	.39	.09	.29	9.50
H <sub>2</sub> O+	.94	.39	.55	.50	1.00	-----
H <sub>2</sub> O-	.04	.01	-----	.03	.07	-----
TiO <sub>2</sub> .....	1.20	.14	.04	.07	.05	.93
P <sub>2</sub> O <sub>5</sub> .....	.07	.04	-----	.16	.03	-----
CO <sub>2</sub> .....	.82	.02	-----	.03	.00	-----
MnO.....	.05	.03	-----	.01	.01	.10
BaO.....	.04	.03	-----	-----	-----	-----
Total.....	99.80	99.85	-----	100.35	100.23	99.96

1. Anorthosite, Iron Mountain, Laramie Range, Wyo. (Hagner, 1951, p. 12).

2. Anorthosite, Shanton deposit, Laramie Range, Wyo. (Hagner, 1951, p. 12).

3. Anorthosite, Los Angeles County, Calif. (Cleveland, 1957a, p. 29).

4. Anorthosite, Split Rock quarry, sec. 5, T. 54 N., E. 3 W., Minn. (Grout and Swartz, 1939, p. 55).

5. Anorthosite, Boehls Butte, Idaho (Hietanen, 1963, table 11, sample 949).

6. Nepheline syenite, Beemerville, N.J. (Iddings, 1898, p. 211).

estimated to be 30.2 billion tons (St. Clair and others, 1959, p. 59). The total anorthosite present is many times this figure, because the rock is known to extend to depths of more than 750 feet. Most of this rock contains 25–30 percent Al<sub>2</sub>O<sub>3</sub>, and it is also rich in calcium and sodium (table 10). The anorthosite deposits in the San Gabriel Mountains, Calif., cover 52 square miles (Lundquist and Oakeshott, 1963, p. 9). They crop out at altitudes of from 1,700 to 6,500 feet, and therefore enormous tonnages must be present. The average Al<sub>2</sub>O<sub>3</sub> content in eight samples that have been analyzed is 27.18 percent.

Anorthosite masses occupy 1,200 square miles in the eastern Adirondacks, N.Y. (Krieger, 1937, p. 38–57), and 22 square miles in Nelson and Amherst Counties, Va. (Ross, 1941, p. 2). Anorthosite also crops out in many areas along the northern shore of Lake Superior in Lake County, Minn. (Grout and Swartz, 1939); scattered areas in the Wichita Mountains, Okla. (Hamilton, 1956); Shoshone and Clearwater Counties, Idaho (Hietanen, 1963); southwestern Montana (Jones and others, 1960); and Chester County, Pa. (Bascom and Stose, 1938). The only tonnage estimates of these deposits available are for those in Oklahoma, which, according to Dott (1946), contain more than 1 billion tons. The total anorthosite in the United States probably amounts to several hundred billion tons.

Certain igneous rocks other than anorthosite also are rich in alumina and may eventually be considered as a source of metal. These include leucite-bearing rocks and nepheline syenite. Large masses of leucite-bearing rocks occur in the Leucite Hills, Sweet-

water County, Wyo. The total leucite rock there is estimated to be nearly 2 billion tons containing 197 million tons of  $\text{Al}_2\text{O}_3$  and 197 million tons of  $\text{K}_2\text{O}$  (A. R. Schultz and W. Cross, 1912, p. 35). Other large masses of leucite-bearing rocks occur in the Highwood Mountains, Mont. (Pirsson, 1905). Large masses of nepheline syenite that are rich in  $\text{Al}_2\text{O}_3$  occur in the Arkansas bauxite district (Gordon and others, 1958); Magnet Cove district, Arkansas (Erickson and Blade, 1956); and Beemerville, N.J. (Wilkersen, 1946). A small stock occurs in the Bearpaw Mountains, Mont. (Pecora, 1942).

#### CANADA

Nepheline syenite occurs at many places in southern Ontario (Hewitt, 1961). High-grade deposits at Blue Mountain contain the only commercially productive nepheline in the Western Hemisphere. The mineral is used chiefly in the making of glass and other ceramic products. The syenite mass forms a ridge 200–350 feet above the surrounding lowland. It is 3 miles long and  $1\frac{1}{2}$  miles wide. The rock is approximately 23 percent  $\text{Al}_2\text{O}_3$ , 60 percent  $\text{SiO}_2$ , and 4 percent  $\text{K}_2\text{O}$  (Bates, 1960, p. 231).

#### ITALY

Very large deposits of leucite occur in a belt of lavas 185 miles long that extends north from Naples. The amount of leucite present is estimated at about 100 billion tons. From this amount, 11 billion tons of alumina could be extracted (Collier, 1946, p. 102). The leucite is 17–18 percent  $\text{Al}_2\text{O}_3$  and 7–12 percent  $\text{K}_2\text{O}$ . The alumina content can be upgraded to 21–23 percent by magnetic separation (Barrand and Gadeau, 1964, p. 129). Processes were developed and a plant constructed at Aurelia to recover alumina and potash salts from this rock (Collier, 1946, p. 102); however, the attempt was not commercially successful.

#### NORWAY

Alumina was extracted from labradorite feldspar in Norway during World War II (Bracewell, 1962, p. 43). The rock used presumably came from the classic anorthosite localities in southern Norway, and the resources are probably large.

#### U.S.S.R.

Nepheline syenite is reportedly used as a source of alumina on a large scale in the U.S.S.R. Very large deposits occur near Kirovsk on the Kola Peninsula, and in the Lake Baikal region of Siberia. Some of the nepheline,  $\text{Na}(\text{AlSiO}_4)$ , in eastern Siberia is in a peculiar calcite-bearing rock called "tuvinite," which is described as being 96 percent nepheline (Eng. Mining Jour., 1958, p. 201). Re-

sources of nepheline syenite in the U.S.S.R. are regarded as virtually inexhaustible (Harris and Trought, 1955, p. 48; Nalivkin, 1960, p. 16). "Nephelinite" in the Goryachegorsh deposit in Siberia is described as being on the "order of 100 billion tons" (Shabad, 1958, p. 17).

Nepheline syenite on the Kola Peninsula that is used for alumina contains approximately 30 percent  $\text{Al}_2\text{O}_3$ , 20 percent  $\text{K}_2\text{O}$  and  $\text{Na}_2\text{O}$ , 43 percent  $\text{SiO}_2$ , and 7 percent other oxides (Baer, 1959, p. 103). Presumably the syenite of this composition has already been processed to recover apatite (Shabad, 1958, p. 15-16). In the process used for extracting alumina, limestone is added to the syenite, and the mixture is treated to yield an anhydrous alumina, soda ash, potash, and cement (Baer, 1959, p. 103). The nepheline that is mined at Goryachegorsh, 35 miles west of the town of Uzhur in Siberia, is processed in a plant at Achkisk (Shabad, 1958, p. 16-18). This rock is reported to be 22 percent  $\text{Al}_2\text{O}_3$ , 44 percent  $\text{SiO}_2$ , about 10 percent  $\text{Fe}_2\text{O}_3$ , and about 10 percent alkali oxides.

#### METAMORPHIC ROCKS

Some metamorphic rocks, other than those composed chiefly of sillimanite-group minerals (p. 152), rank with the high-alumina nonbauxite rocks. A chloritoid phyllite near Liberty, Md., contains 32.3 percent  $\text{Al}_2\text{O}_3$  (Clarke, 1924, p. 625). Phyllites from four localities in Albemarle and Fluvanna Counties, Va., consist chiefly of muscovite and chlorite and contain 28.7-31.3 percent  $\text{Al}_2\text{O}_3$  (Greenberg, 1964, p. 7). Probably metamorphic rocks containing 25-30 percent  $\text{Al}_2\text{O}_3$  occur at several localities in the United States. However, no review of all possible localities was made, because the possibilities for the extraction of alumina from metamorphic rocks have not been evaluated. The alumina in most metamorphic rocks is tightly bonded in silicate minerals, and its extraction would probably be more costly than from other nonbauxite materials.

#### SAPROLITE

##### UNITED STATES

Aluminous saprolite is a weathered rock in which nearly all original minerals have been replaced by secondary minerals but most original textures and structures have been preserved. It has accumulated in large amounts at several places in the United States. The most extensive saprolite deposits are in the Piedmont province and other parts of the Southeastern States. Other saprolite deposits are associated with the bauxite deposits in Arkansas, with low-grade ferruginous bauxite resources in Oregon, Washington, and Hawaii, and with weathered anorthosite in Oklahoma.

Saprolite in the Piedmont province was investigated intensively by major aluminum companies in 1957. Two subsidiary companies, Piedmont Properties, Inc., and Palmetto Lands Co., were formed to lease and prospect large acreages between Spartanburg, S.C., and Rutherfordton, N.C. (Chem. Week, 1957). Most of this area is in an extensive belt of sillimanite and biotite schists and other metamorphic rocks (W. C. Overstreet and W. R. Griffiths, 1955). These rocks have been weathered to saprolite to considerable depths, and their weathered parts are now rich in iron- and alumina-bearing minerals but also contain varying quantities of residual quartz.

The information gathered by the companies that investigated the Carolina saprolite has not been released, and two reconnaissance-type investigations provide the only basis for appraising the deposits. In a brief report on one of these studies, Council and Llewellyn (1959) summarized the results of chemical analyses of 99 samples of saprolite, mostly from a large area in South Carolina lying south and east of the one investigated by the aluminum companies. These samples are from saprolite that formed various types of mica schist, rocks of the volcanic slate belt, granite, pegmatite, sillimanite schist, and hornblende-bearing rocks. The analyses indicated 2-16 percent free alumina, 2-11 percent iron oxide, and 8-26 percent total alumina. The second reconnaissance was by the author, who collected 12 samples of saprolite in the vicinity of Shelby, N.C., and northwest of Gaffney, S.C.; both areas are in the belt investigated by the companies. These samples were analysed by X-ray fluorescence methods in the U.S. Geological Survey laboratory at Beltsville, Md. They contain 25-36 percent  $Al_2O_3$ , but the comparative standards used may not have been reliable, and the results obtained from alumina may have been excessively high. However, some of these samples contain more gibbsite, as identified by X-ray diffraction methods, than required to account for the small percentage of free alumina reported by Council and Llewellyn. In addition to gibbsite, the saprolite consists of halloysite, altered mica, quartz, and iron-bearing minerals. Most of the gibbsite is very fine grained and intimately associated with clay minerals and would be extremely difficult to concentrate; therefore, all the rock would have to be processed in order to extract alumina. The saprolite in the region where these samples were collected also contains minor quantities of monazite, zircon, ilmenite, sillimanite, and garnet (W. C. Overstreet and others, 1963). Some of these minerals might be recovered by byproducts if alumina is extracted from this rock. No information on the total size of the deposits is available, but they are known to extend irregularly over many tens of square miles; and if the average thickness is considered to be only 10 feet, they contain aluminous rock amounting to many

hundred million tons. The range in total alumina content of this rock is probably more than the 8–26 percent reported by Councill and Llewellyn (1959) but less than the 25–36 percent found by the author.

In addition to the saprolite in the Piedmont province in North and South Carolina, large accumulations occur at several other localities in the Southeastern States. Saprolite in the Piedmont province in Alabama contains appreciable quantities of gibbsite (Bryant and Dixon, 1964) but has not been evaluated as a potential aluminum resource. Extensive titaniferous aluminous saprolite occurs in weathered parts of the Roseland Anorthosite in Nelson and Amherst Counties, Va. Rutile and ilmenite have been recovered from these deposits, which may have real potential as sources of both alumina and titania. The inferred reserves of saprolite containing 7 percent  $\text{TiO}_2$  in only a fraction of the area occupied by saprolite exceed 20 million tons (Fish, 1962, p. 38). No information on the alumina content of this rock has been published, but parts of it have been described as kaolin, and the rock may therefore be rich in alumina.

The saprolite associated with the bauxite in Arkansas has not been adequately investigated, and little is known of its extent or quality. That large deposits are present is obvious from statements and illustrations by Gordon, Tracey, and Ellis (1958, p. 140, fig. 38), who described a widespread and complete gradation from nepheline syenite to kaolin and much material between residual bauxite and fresh syenite as white kaolinitic clay in which syenite textures are preserved. No estimates of the saprolite deposits in Arkansas have been made, but they probably are adequate to supply a large alumina plant, and interest in them will probably increase as the bauxite deposits approach exhaustion. Two samples of this saprolite for which analyses are available (Gordon and others, 1958, table 11, samples 15, 16) contain 37.2–39.6 percent  $\text{Al}_2\text{O}_3$  and 42.9–44 percent  $\text{SiO}_2$ , and the loss on ignition is 13.5–14.4 percent.

The saprolite in Oklahoma occurs in weathered anorthosite and other igneous rocks forming an extension of the Wichita Mountains in Kiowa County. Much of these weathered rocks is saprolite, as is evident from the following description by Knox (1948, p. 4): "Most of the clay encountered in the drilling was formed by decomposition of the anorthosite and gabbros in place, and even the poorly defined, near-surface bedding of the clays showed very little sorting action. All the material contains the accessory minerals and most of the decomposition products of the original rock." Large deposits of both saprolite and clay occur in Kiowa County, Okla.; however, analysis of a composite sample of saprolite by the U.S. Bureau of

Mines (Knox, 1948, p. 17) showed only 21.89 percent  $\text{Al}_2\text{O}_3$ , and analysis of a clay sample above the saprolite showed 26.34 percent  $\text{Al}_2\text{O}_3$ . The low alumina content of these rocks reduces their potential as a source of alumina.

Deposits of aluminous saprolite weathered from basalt are associated with the ferruginous bauxite deposits in Oregon and Washington. The saprolite consists of rock that is more than 10 percent  $\text{SiO}_2$ , an arbitrary maximum for the material that is classified as bauxite. The saprolite underlies the bauxite and varies considerably in thickness. According to plotted analyses of samples from one drill hole in Oregon (V. T. Allen, 1952, fig. 2), weathered basalt nearly 150 feet thick underlies bauxite approximately 30 feet thick. Valentine and Huntting (1960, p. 16) reported that bauxite in Washington is as much as 20 feet thick and is underlain by 20 feet or more of weathered basalt. Investigations of this saprolite are inadequate to permit an appraisal, but according to analyses of samples from depth (V. T. Allen, 1952, fig. 2; Corcoran and Libbey, 1956, table 6), much of it contains 25–30 percent  $\text{Al}_2\text{O}_3$ , 25–35 percent  $\text{Fe}_2\text{O}_3$ , and 5–7 percent  $\text{TiO}_2$ . This saprolite consists chiefly of halloysite and iron oxide minerals and contains minor quantities of gibbsite, ilmenite, and titaniferous magnetite.

Large deposits of aluminous saprolite are associated with low-grade bauxite on the islands of Kauai and Maui, Hawaii. The saprolite occurs below the bauxite as well as in many areas where bauxite is not present. This saprolite consists chiefly of fine-grained mixtures of halloysite, gibbsite, and iron- and titanium-bearing minerals. The deposits on Kauai have weathered from olivine basalt and feldspathoid-rich rocks, those on east Maui from olivine basalt, and those on west Maui from andesite and soda trachytes. Estimates of the saprolite in Hawaii and its approximate partial composition (S. H. Patterson, 1962, p. 4) are as follows:

	Type of rock	Dry tons (millions)	Approximate average partial chemical composition (percent)			
			$\text{SiO}_2$	$\text{Al}_2\text{O}_3$	$\text{Fe}_2\text{O}_3$	$\text{TiO}_2$
Kauai.....	Ferruginous, gibbsitic saprolite.....	500	20	27	27	5
West Maui....	Surficial bauxitic deposits and ferruginous gibbsitic saprolite.	200	20	33	22	4
East Maui....	Ferruginous, gibbsitic saprolite.....	200	15	31	27	6

#### OTHER COUNTRIES

Very extensive deposits of aluminous saprolite underlie most of the major bauxite deposits of the world except those that have been transported or are associated with limestone. Extensive deposits

occur in nonbauxitic weathered rocks in many tropical areas, and many deposits underlie ferruginous laterites (Sivarajasingham and others, 1962, p. 24-39). No information is available to indicate that any of these saprolite deposits have seriously been considered as possible sources of aluminum, and apparently no economic appraisals have been made. The world's total aluminous saprolite deposits are probably many times larger than the total bauxite deposits.

#### SILLIMANITE GROUP MINERALS

The sillimanite group<sup>1</sup> minerals, kyanite, sillimanite, and andalusite (each having the same chemical composition,  $\text{Al}_2\text{SiO}_5$ , and containing 63.2 percent  $\text{Al}_2\text{O}_3$ ) as well as topaz and dumortierite (both similar to the  $\text{Al}_2\text{SiO}_5$  minerals in chemical composition) can be used in the manufacture of high-alumina refractories and ceramics and are possible sources of aluminum. Small quantities of alumina were recovered from andalusite in Sweden during World War II (Bracewell, 1962, p. 43). Probably the only other serious consideration of the minerals in this group as a source of alumina has been in the U.S.S.R., where both kyanite and sillimanite in the Lake Baikal region of Siberia have been investigated (Galaburda, 1958). Deposits of these minerals are presumably very large, and kyanite in the Mansko-Chyisk area in this region extends over 9,000 square miles.

The sillimanite group minerals occur chiefly in metamorphosed schists and quartzose rocks, but they also occur in quartzitic veins and pegmatites, and they are locally abundant in placer deposits. Kyanite is more common in minable deposits than the other minerals of this group, and, therefore, it has been used to a greater extent. Most kyanite in the United States occurs in fine grains disseminated through other rocks, and most of it that is produced is concentrated by a flotation process.

The sillimanite group minerals occur in many areas in the United States. Kyanite-bearing rocks are located in Virginia, North Carolina, South Carolina, Georgia, California, New Mexico, and elsewhere. Andalusite deposits occur in California, Idaho, Nevada, North Carolina, and Washington. Probably the largest dumortierite deposits are in Nevada. The measured and indicated reserves of rock that is 10-30 percent kyanite in the Southeastern States are estimated to total 100 million tons, and the inferred reserves of such rock are more than 50 million tons (Espenshade and Potter, 1960, p. 35). Reserves and resources of sillimanite group minerals in several other regions of the United States have been estimated (Espenshade, 1961;

<sup>1</sup> The term "sillimanite group" is used in an industrial sense and is not intended to conform with accepted mineralogical nomenclature.

Foster, 1960), but according to information now available, none of these deposits are of the same order of magnitude as the deposits in the Southeastern States. Additional information on most deposits of sillimanite group minerals in the United States can be found in references listed in a bibliography by Grametbauer (1959). The reports by Espenshade (1961) and Foster (1960) contain some information on these minerals in other countries.

Though the reserves of the sillimanite group minerals are large and their alumina contents are high, no attempts have been made to use them as a source of alumina in the United States. Probably the chief reasons are that they are costly to mine and require concentration, which makes them considerably more costly than bauxite. Also, the minerals in this group are all hard and tend to resist chemical action of several types. These characteristics would probably cause difficulties in extracting alumina from them.

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