THE UNIVERSITY OF TEXAS AT AUSTIN
Bureau of Economic Geology
March 19, 1942
Typeset from original stencil, April 1980

MINERAL RESOURCE CIRCULAR
No. 18

BAUXITE AND ALUMINUM
by Robert C. Redfield

Aluminum is the third element in abundance in the rocks of the earth's crust, being exceeded only by oxygen and silicon, but it is never found in the elemental state. The element occurs naturally in chemical combination as the oxide, hydrous oxide, fluoride, phosphate, sulphate, silicate, and others, and is such a common constituent of minerals that it is impracticable to list all minerals containing aluminum. The common aluminum silicate, clay, which is more or less impure kaolin or mixtures of kindred mineral species, is the most abundant product of rock decay, and its deposits are widespread and are usually found at or near the surface of the ground.

The percentage of alumina (aluminum oxide) in various minerals, calculated on the basis of a chemically pure substance, is given in the following table, the data in large part being taken from TEXTBOOK OF MINERALOGY, by Dana and Ford, 1932.

Mineral	*Per cent of Alumina*	*Formula*
Corundum	100	Al_2O_3
Diaspore	85	$Al_2O_3.H_2O$
Chrysoberyl	80.2	$BeO.Al_2O_3$
Bauxite	73.9	$Al_2O_3.2H_2O$
Spinel	71.8	$MgO.Al_2O_3$
Gibbsite	65.4	$Al_2O_3.3H_2O$
Andalusite	63.2	$Al_2O_3.SiO_2$
Sillimanite	63.2	$Al_2O_3.SiO_2$
Kyanite	63.2	$Al_2O_3.SiO_2$
Staurolite	55.9	$H_2O.2FeO.5Al_2O_3.4SiO_2$
Gahnite	55.7	$ZnO.Al_2O_3$
Topaz	55.4	$(Al(Fe, OH))_2SiO_4$
Margarite	51.3	$H_2CaAl_4Si_2O_{12}$
Chloritoid	40.5	$H_2(Fe, Mg)Al_2SiO_7$
Kaolin	39.5	$Al_2O_3.2SiO_2,2H_2O$
Sericite	38.5	$K_2O.3Al_2O_3.6SiO_2.2H_2O$
Muscovite	38.5	$2H_2O.K_2O.3Al_2O_3.6SiO_2$
Wavellite	38.0	$4AlPO_4.2Al(OH)_3.9H_2O$
Alunite	37.0	$K_2Al_6(OH)_{12}(SO_4)_4$
Anorthite	36.7	$CaO.Al_2O_3.2SiO_2$
Zoisite	33.7	$4CaO.3Al_2O_3.6SiO_2.H_2O$
Nephelite	32.0	$NaAlSiO_4$ or $Na_8K_2Al_8Si_9O_{34}$
Sodalite	31.6	$3NaAlSiO_4.NaCl$
Cancrinite	29.3	$3H_2O.4Na_2O.CaO.4Al_2O_3.9SiO_2.2CO_2$
Spodumene	27.4	$Li_2O.Al_2O_3.4SiO_2$
Hauynite	27.2	$3NaAlSiO_4.CaSO_4$
Natrolite	26.8	$Na_2O.Al_2O_3.3SiO_2.2H_2O$
Scolecite	26.0	$CaO.Al_2O_3.3SiO_2.3H_2O$
Pyrope	25.4	$3MgO.Al_2O_3.3SiO_2$
Epidote	24.13	$H_2O.4CaO.3(Al, Fe)_2.O_3.6SiO_2$
Leucite	23.5	$K_2O.Al_2O_3.4SiO_2$
Analcite	23.2	$Na_2O.Al_2O_3.4SiO_2.2H_2O$
Grossularite	22.7	$3CaO.Al_2O_3.3SiO_2$
Spessartite	20.6	$3MnO.Al_2O_3.3SiO_2$
Albite	19.5	$Na_2O.Al_2O_3.6SiO_2$
Beryl	19.0	$3BeO.Al_2O_3.6SiO_2$
Orthoclase and Microcline	18.4	$K_2O.Al_2O_3.6SiO_2$
Clinochlore	18.4	$4H_2O.5MgO.Al_2O_3.3SiO_2$
Heulendite	16.8	$(Ca, Na_2)O.Al_2O_3.6SiO_2.5H_2O$

Cryolite, Na_3AlF_6, contains 12.8% aluminum.

Ores of Aluminum

Aluminum is present in all clays and shales, other sedimentary rocks, and in a great many igneous and metamorphic rocks. However, its high degree of chemical affinity for other elements and radicals, particularly oxygen and the silicate radical, prevents the occurrence of aluminum in the elemental state. The abundance of aluminum would make it the cheapest of all metals if it were not for its great chemical activity and the difficulty of extracting it from the ores. The process of breaking down aluminum silicates into the component constituents to yield alumina (Al_2O_3) of the required purity for industrial uses is lengthy, and a costly one. Large quantities of electrical energy are required, in addition, to sever the tenacious bond between aluminum and oxygen to produce metallic aluminum.

Bauxite, an industrial mineral raw material consisting of the alumina monohydrates boehmite and kayserite and the trihydrates gibbsite and hydrargillite, is the most important source of alumina from which aluminum is produced. It is sufficiently abundant, and its properties lend themselves to the economical extraction of alumina. Physical and chemical properties of another alumina monohydrate, diaspore, do not permit its use for the extraction of alumina in the aluminum industry. Ordinary clays, ubiquitous and easily mined rock material, may contain up to approximately 40 per cent alumina, but heretofore their use as a source of alumina has not been economically feasible because of the cost of large quantities of chemicals and electric power required to isolate the alumina. However, recent technologic development has progressed to a state that such clay deposits are being seriously considered as sources of alumina. Methods of treating clays in large quantities to yield aluminum have been reported recently and at a cost that may compete with metal produced from bauxite. The Tennessee Valley Authority is reported to be planning the immediate erection of a plant to start production of aluminum from clay. Alunite, leucite, nephelite, andalusite, and labradorite have been subjected to much consideration and experimentation as substitutes for bauxite, and commercial utilization of some of them is being attempted currently in certain portions of the world. Experimental attempts have also been made to use phonolite, alum shales, phosphatic alum, slates, aluminiferous schists, baked shales, leachings from lignite ashes, and blast furnace slags and other industrial waste products.

Bauxite

Bauxite is the commercial name of a mineral raw material whose varied uses include the following: the ore from which aluminum is obtained; raw material for the manufacture of many aluminum salts in the chemical industry; the crude material for the production of artificial aluminous abrasives; a refractory; a filtrant and bleaching agent; insulating material; and a constituent of special cements. But there is no universally accepted scientific definition of bauxite.

The word "bauxite" was first used to denote rock of high alumina content discovered by the French chemist Berthier, in 1821, near the village of Baux, Bouches du Rhone, in southern France. Later, the name has been applied by various investigators to each of three alumina hydrates having different chemical formulae. Mineralogical names have already been assigned to two of these substances, and the third has never been identified by chemical, spectrographic, or X-ray investigations; hence the anomaly arises that bauxite does not exist in the strict mineralogical sense. The monohydrate ($Al_2O_3.H_2O$) is called diaspore, and two varieties have been identified, namely, boehmite and kayserite. A colloidal form has been called sporogelite or diasporogelite, alumogel, and cliachite. The trihydrate ($Al_2O_3.3H_2O$) is called gibbsite and the crystallized form is known as hydrargillite. The third hydrate of alumina to which the term bauxite has been applied, the dihydrate, has not been identified. An amorphous quadrihydrate ($Al_2O_3.4H_2O$) has been found in Russia and called shanyavskite.

Crude bauxite of commerce consists predominately of alumina (Al_2O_3) chemically combined with water as the monohydrate and trihydrate. A mixing of the two hydrates may approximate a theoretical dihydrate in the raw material. The bauxites of the United States and those of tropical Africa, Asia, and South America are mainly composed of the trihydrates, gibbsite and hydrargillite. Bauxites of Continental Europe consist essentially of the monohydrate boehmite. A second monohydrate, diaspore, possesses the same chemical formula, but different chemical and mineralogical properties prevent its profitable substitution for bauxite in the extraction of alumina.

The physical properties of bauxite are highly variable. The color may be white, light gray, cream, ocher-yellow, buff, brown, pink, brownish red, or mottled, and the color of the streak varies. The material may be amorphous, or possess a granitic texture, but commonly there is a pisolitic, oolitic, or pebbly structure with rounded, concretionary grains embedded in an amorphous or claylike groundmass. The color of the oolites usually differs somewhat from that of the matrix — generally, but not always, being darker. The material may be porous and spongy or hard, dense, and blocky; some may be soft and chalky, or even plastic. The luster is dull to earthy, the fracture is conchoidal to uneven, and there is usually an argillaceous odor. American and South American bauxites range from buff to pink and cream, whereas that of Europe is characteristically red in color.

The alumina content of commercial bauxite usually falls between 52 and 65 per cent. Silica is invariably present, in the form of free silica sand or veinlets, or as one or more hydrated aluminum silicate clay minerals, and varies from 1 to 15 per cent. Iron oxide content may be as great as 25 per cent and may in part be an impurity such as the ferric or ferrous oxide, the carbonate, or sulfide and in part replace the aluminum. Titanium oxide is usually present in the form of rutile, titanite, ilmenite, and possibly as the titanate, and the allowable per cent may be as high as 10. Chemically combined water ranges from 12 to 32 per cent. The amount of free water in an ore depends upon the attendant geologic conditions of the deposit. Other impurities may be lime, magnesia, potash, soda, manganese, fluorine, phosphorus, and sulfur.

The relative proportions of the impurities often determine the marketability of a bauxite; hence it should not be concluded that a buyer could be found for any substance that fell within the chemical limits indicated above. All purchasers require a maximum of the most desired and valuable component, aluminum oxide. Some users place a premium on low silica content, others on low iron content, while other consumers demand a certain relationship between silica, iron, and titanium percentages. Occasionally minor quantities of other impurities have commercial significance. Physical properties as well determine marketability of bauxite and give rise to problems of preparation for market. A particular bauxite may have the requisite chemical analysis demanded by a consumer, yet be unsuitable because of its hardness, softness, or porosity.

Mode of occurrence. — Residual blanket deposits of bauxite occur at or near the land surface in horizontal, undulating, and tilted sheet-like or lens-like masses. A soil cover of varying thickness may be present, or the mineral material may be exposed at the surface, in which case the upper portion is usually indurated by secondary or concomitant cementation, and this land surface is capable of supporting only a sparse growth of vegetation. Lateritic accumulations of this type are more commonly found in tropical or semitropical regions and may occur at low altitudes or may cap extensive elevated plateaus and flat-topped hills representing erosional remnants of elevated former base-levels. Blanket deposits may reach a thickness of 75 feet, but the average thickness is generally much less, often averaging not more than 25 feet and usually somewhat less; the blanket may be localized or may cover extensive areas. Some occurrences of this nature are fairly uniform in composition, but many others are quite irregular. The lower bounding surface is usually rather abrupt, but localized variations and irregularities occur.

Bed and lens-like bauxite deposits occur at definite stratigraphic horizons and may represent ancient residual blanket deposits formed on land surfaces of the geologic past. These occurrences may rest on either sedimentary or igneous rocks and may be covered by later sediments of sandstone, shale, or limestone. The bauxite is usually more compact and more indurated, but otherwise its characteristics are the same as those of the blanket deposits. Such deposits suffer the capricious vicissitudes of geologic change such as faulting, folding, metamorphism, and erosion during the interim.

Irregularly shaped pockets of bauxite may be found in grouped or scattered crevices, caverns, or depressions in limestone or other containing rock in a manner unrelated to layers and lenses of bauxite unless the latter have been removed by erosion. Other pockets of bauxite are associated with interlayered and blanket deposits and represent accumulations within depressions in the rock surface on which the bauxite was formed or deposited. Contact between bauxite and enclosing rock in such types of deposits is usually abrupt, although in some cases the contact is gradational or foreign interlayered material may be present at the contact.

Interlayered, stream placer, and other occurrences may be detrital material derived from the erosion of pre-existing bauxite deposits.

Origin. — Various hypotheses have been offered to explain the origin of bauxite, but the most common and generally accepted one is that it represents the end product in the chemical decay (decomposition weathering) of aluminous silicate minerals composing rocks. Acceptance of this explanation would make bauxite an aluminous-rich laterite, and all gradations between bauxite and laterite might be expected; such gradations are found. Conditions most favorable for the formation of a surficial residuum of the nature of aluminous-rich laterite might be as follows: a parent rock containing relatively unstable aluminous silicates such as feldspar, nephelite; a warm and humid climate, perhaps of the tropical or semitropical rain forest type, to promote profound chemical weathering, broken by seasons of dryness to permit reprecipitation of mineral solutes near the soil surface; a topographic surface very nearly flat, sloping, or hilly on which there is no marked or very active erosion; ground water to permit thorough leaching and promote deeper bedrock decay; a continuation of an optimum bauxite-forming environment prevailing for a sufficient duration of time.

Bauxite Mining and Beneficiation

Bauxite is commonly associated with clay and limestone and with certain types of alumina-bearing igneous rocks that made up ancient land surfaces now represented by unconformities in rock series or by more recent, undisturbed peneplain surfaces. Deposits are often found at relatively shallow depths and are usually discovered from float material and outcrops. When located, deposits should be thoroughly tested and extent of the body delineated. Testing may consist of pitting, core drilling, and augering if the deposit is accessible, or by shafts or drifts if the material is more deeply buried; measuring thicknesses and observing texture and variations; and collecting labeled samples for chemical analyses to determine the total content of alumina, silica, iron oxide, titanium oxide, mechanically and chemically combined water, and perhaps other constituents.

Prior to development or expenditure of large funds, the marketability, demand, and average price should be determined for the particular raw material; means of transportation and cost of haulage to consumers should be considered; and the availability of labor, fuel, and water should be determined. Sound advice should be sought in selecting and adapting mining methods to obtain maximum recovery and anticipate difficulties that might arise in carrying out such operations. Processing plants should be wisely constructed and conveniently located and the production cost calculated in advance.

Mining methods employed in the recovery of bauxite differ with regions and types of deposits. Surficial blanket deposits and those covered with unconsolidated overburden not too great in thickness may be strip mined by hand or mechanical means. Economic limit of overburden that may be removed depends on the thickness and value of the ore to be mined, thickness and degree of consolidation of the overlying strata, and the kind of mechanical equipment available, because ore mined fifteen years ago by underground methods might now be mined by stripping, due to the evolution and advance of the earth-moving capacity of machinery. A working face averaging 11 feet in height of ore and approximately 1 mile in length was maintained in a strip mine in Arkansas.

Because of the limited extent of pocket deposits of bauxite in limestone and dolomite, simple hand methods are resorted to in recovering the ore. Such methods are used in southeastern United States and southern Europe.

Standard underground mining methods are used where the overburden becomes excessively thick, the ore is interbedded with solid rock, or the accompanying geologic structure causes the deposits to reach considerable depths. Drifts and crosscuts are used in advancing mining operations, and almost complete extraction is made by caving in retreating. Stripping methods were practiced exclusively in Arkansas until about 1924 when underground and combination methods were adopted. More than half of the present domestic production is mined underground. Ore bodies mined by underground methods have been reported to vary up to about 60 feet maximum thickness in the United States.

Mining problems arise that are peculiar to the bauxite industry because of the uneven character of the upper and lower bounding surfaces of deposits; often poor roof conditions, inclination of deposits; variation of physical properties and chemical composition of ore bodies; and dilution from extraneous material, particularly silica.

The question of beneficiation depends on the cost of application, the relative improvement of the grade and consequently the value of the product, the per cent of material discarded and its relative value. The method of beneficiation and the degree of success of such treatment will be to a large extent determined by the texture of the raw material and the manner of occurrence of any impurities.

Bauxite is a low-priced commodity that usually requires beneficiation prior to shipment in order that freight costs may be reduced, and its accceptability and value to the consumer may be enhanced by eliminating impurities and concentrating the desired aluminum compounds. Frequent chemical analyses of the raw material must be prepared during mining operations to exclude low grade material from ore, and care must be taken to prevent dilution from the enclosing rock. Satisfactory grades are frequently produced by selective mining and blending of various grades. Crushing and drying of ore is commonly practiced to remove mechanically held moisture, and sometimes the ore is calcined to remove a portion of chemically combined water prior to shipment to afford a saving in transportation costs and facilitate fine grinding. Bauxite of suitable texture is thermally activated to increase adsorptive properties for the refining industries.

Siliceous fines are removed by passing crushed bauxite over screens and through rake classifiers. Concentrates are also obtained by removing clay in log washers. Magnetic methods are used in the treatment of certain types of ore to produce low-iron fractions. Experimental work in producing low-silica fractions of bauxite by flotation has been encouraging and may afford the means of exploiting low-grade bauxites of 45 to 50 per cent and even lower alumina content as the relatively higher grades of ore approach exhaustion. The problem of eliminating iron compounds by the same method appears to be more difficult. Gravity concentration and careful grinding followed by desliming may prove feasible. A combination of beneficiation methods with a flexible treating system will probably be necessary in milling bauxites of varying grade and mineralogical composition.

Ore is shipped by box car in bulk form to prevent its gathering moisture while in transit and is not insured because of its relatively low value.

Selective mining is practiced in Europe, but beneficiaction is virtually unknown. Distances between mines and consumers are short; hence ore is neither crushed nor dried before shipment.

Bauxite Production and Consumption

Domestic production of bauxite in 1941, although amounting to no more than 25 per cent of the annual United States consumption, was greater than for any year since 1923, when domestic producers supplied 75 per cent of the material consumed in the United States. In 1938 shipments of domestically produced ore amounted to 311,354 tons valued at $1,812,545, and shipments in 1940 amounted to 434,988 tons valued at $2,578,968, with Arkansas accounting for about 97 per cent of the total quantity. Apparent United States consumption during the latter year amounted to about 960,000 tons. For purposes of statistical comparison, quantities of bauxite are expressed in long tons converted to a dried basis of 1.5 per cent free moisture. Tonnages of calcined bauxite must be converted to equivalent dried basis in which about 1.5 tons of dried ore are equivalent to 1 ton of calcined or sintered bauxite. Bauxite is now subject to export license.

Average price of bauxite at mines and processing plants during 1940, according to the U.S. Bureau of Mines, was $3.44 per ton for crude ore; $5.51 for "crushed and dried" bauxite; $14.30 for calcined or sintered material; $36.97 for thermally activated bauxite.

Estimates of the United States Bureau of Mines indicate that world production of bauxite in 1940 was approximately 4,627,000 metric tons, an increase of about 7 per cent above production of the previous year.

Possible purchasers. — Following is a list of possible purchasers of bauxite:

Aluminum Ore Company, Gulf Building, Pittsburgh, Pennsylvania (subsidiary of Aluminum Company of America)
American Cyanamid & Chemical Corporation, 30 Rockefeller Plaza, New York, New York
Bauxite Mining Corporation, Federal Reserve Bank Building, Richmond, Virginia (subsidiary of Reynolds Metals Company)
Consolidated Chemical Industries, Inc., 811 Petroleum Building, Houston, Texas
E. I. du Pont de Nemours & Company, Inc., 1007 Market Street, Wilmington, Delaware
General Chemical Company, 40 Rector Street, New York, New York
Gulf Oil Corporation, Gulf Building, Pittsburgh, Pennsylvania
Hercules Powder Company, Wilmington, Delaware
Norton Company, Worcester, Massachusetts
Porocel Corporation, 260 South Broad Street, Philadelphia, Pennsylvania
Republic Mining and Manufacturing Company, 230 Park Avenue, New York, New York
The Carborundum Company, Niagara Falls, New York

Foreign Resources

Bauxite of Europe is dominantly the monchydrate, with a relatively large content of iron oxide. High grade ores are relatively common, the texture is homogeneous, the material is usually dense and consequently contains less free moisture, and the ores may be selectively mined with ease to produce special grades for particular uses.

The deposits of France were the first to be exploited, and the production has been very great for these deposits have been worked extensively and almost continuously since 1872. With the exception of a few individual years, France has always been the leading world producer, although within the past few years its dominant position has been contested by a second European producer, Hungary, and the Dutch colony of Surinam on the northern coast of South America.

Complete geologic analysis has proved enormous reserves of stratified deposits of French bauxite, mostly of the pisolitic, highly ferruginous variety. The occurrences in the vicinity of the original locality, Baux, were some 30 feet in thickness. Pit, underground, and combination mining methods are used. Domestic needs are suppled, and, in addition, France shipped large quantities to England, Germany, Norway, Switzerland, and smaller quantities to the United States prior to the present war. Three grades supplied to the market prior to the collapse of France were "red," "gray," and "white." The red variety, chiefly used in the production of aluminum, was low in silica but contained about 22 per cent iron oxide. The gray variety ccontained less iron oxide, but the silica content was from 6 to 12 per cent; its main use was in the manufacture of abrasives and aluminate cement. The white variety, of which both production and reserves were limited, contained a much lower percentage of iron and was used in the chemical industry and for refractory material.

The enormous reserves of Hungarian bauxite, estimated to be about 250,000,000 metric tons, have been largely developed by German capital and supply the major portion of the latter country's needs. Mining methods are by simple means in open pits, and operations are halted during the winter season. The Jugoslavian deposits are variable in alumina content, and the quantity of chemically combined water averages greater than other European ore, suggesting that it is a mixture of the monohydrate and trihydrate. Most of the production is shipped to Germany, although some has been exported to the United States for cement manufacture. Greek bauxite was widely used in cement prior to the present war because of low cost and low silica content, although the per cent of alumina was variable. The ore was exported by water to Germany, England, Norway, Japan, and the United States.

The bauxite deposits of the Italian peninsula, first brought into production in 1905, are widely scattered in thousands of small pits that are excavated by simple means. Most of the ore is consumed domestically, althogh some has been shipped sporadically to north European countries.

Russian bauxite production, consumption, and resources largely remain an enigma. The 1939 and 1940 plans were not fulfilled because of insufficient development of bauxite production and delay in completion of alumina plants. The discovry of large deposits of low grade ore in recent years has been reported. A marked shortage of aluminum has existed in the USSR, perhaps due to withholding the metal from domestic consumption to accumulate emergency stocks. No bauxite is exported from Russia.

Spain, Roumania, and County Antrim, Ireland, contribute small quantities of bauxite to the market from time to time.

Europe, the greatest producer and consumer of bauxite and aluminum, possesses abundant reserves of raw material. France is self-sufficient in raw material and industry, but England, Germany, Norway, Sweden, and Switzerland, where great aluminum industries are also developed, are dependent on imports of the raw material. England imported most of its bauxite from France but some now depend on ore from the enormous reserves in the tropical regions of the British Empire. Germany, the greatest producer and consumer of aluminum during the past few years, obtains less than 2 per cent of the necessary bauxite from domestic sources. Shipments of bauxite from Italy and southeastern Europe to Germany have been disrupted by congested railway traffic, but sufficient raw material is being furnished to Germany by France as a result of economic collaboration. Prior attempts by Germany to produce aluminum from clay with sulfurous acid, and phonolite, a lava corresponding in composition to nephelite or leucite-syenite, met with some measure of success. Norway, whose aluminum production is largely exported to Germany, and Sweden are cut off from Mediterranean imports and must turn to more siliceous substitutes for raw material. Extensive domestic deposits of labradorite (lime-soda feldspar) are being utilized in Norway, and in Sweden the use of andalusite derived from native sources is being attempted, and a method for producing aluminum from clay containing 20 per cent alumina has been patented but has not been perfected. Despite difficulties of obtaining raw material, the Swiss industry continued to operate in 1939, but less is known of operations since that time. Italy supplies most of her domestic needs, but despite having considerable bauxite reserves extensive experiments have been conducted to utilize leucite to produce alumina, with potassium salts for fertilizer as a by-product. Results are unknown of Russian experiments to use high alumina slag from blast furnaces, nephelite, and the leachings of lignite ashes which contain as much as 40 per cent alumina.

Bauxite was first produced in the Dutch East Indies, and exported to Germany, in 1935, but since the latter part of 1939, Japan has consumed the entire production. The material is the trihydrate variety, nodular and loosely consolidated, and is mined from open pits. The ore is screened and dried prior to shipment and has an alumina content of 53 to 55 per cent. Some bauxite is produced sporadically in Australia, British India, Indo-China, and the Unfederated Malay States. Production of aluminum from alunite, alum shale, aluminiferous schist, clay, phosphatic alum, and industrial wastes has been attempted and subsidized in Japan, but the aluminum industry of that country remains dependent on imported bauxite.

Bauxite production in British Guiana began in 1917, while the production of Surinam or Dutch Guiana was initiated about 1922. Most of the material produced in this South American district is used in the manufacture of aluminum, although some high grade "white" or chemical ore is produced. All Surinam ore is consumed by the United States, whereas ore from British Guiana is shipped to Canada and the United States. Development of extensive Brazilian deposits has been retarded by higher costs of mining and transportation, while those of Colombia remain undefined.

British Guiana bauxite occurs in beds and lenses from 15 to 25 feet thick with a mineable overburden of as much as 100 feet. The ore is a high grade trihydrate containing about 60 per cent alumina, a maximum iron content of about 3 per cent, but the silica ranges up to 4 per cent. The ore is in demand for the manufacture of aluminum and chemicals.

Two crushing and drying plants are operated in Surinam by a subsidiary of Aluminum Company of America at Moengo Hill and at Paranam. The production of the newer plant at Paranam is reported to be 150 tons of dried bauxite per hour and that of the older plant at Moengo Hill is reported to be 100 tons per hour. A Dutch East Indies company plans to develop its properties in Surinam. The bauxite is of the tropical lateritic variety and occurs as a surficial deposit forming slight ridges and hills in the coastal lowland. The ore is a high grade trihydrate containing 57 to 59 per cent alumina, a maximum of 7 per cent iron oxide, and the silica content is low.

Domestic Resources

A mineral material was found near Rome, Georgia, in 1883 that was called bauxite. Significant mineralogical and chemical differences from the French material existed but were not recognized. First American production of bauxite began in Georgia in 1889, and its first reported use was in the manufacture of aluminum salts. Similar material was discovered in northeastern Alabama a few years later, and production commenced in 1891. J. C. Branner identified bauxite from a locality near the present mining region of Arkansas in 1887, and production began in 1899. The material was later discovered in Tennessee, Virginia, and Mississippi, and recently in Missouri.

Arkansas bauxite is generally considered to be the best domestic material and has furnished about 90 per cent of all bauxite produced in the United States. The material is largely used in the manufacture of aluminum, and the State produces about 25 per cent of the current domestic consumption.

The bauxite deposits of Arkansas are in the central part of the State, near Little Rock, in Pulaski and Saline counties. The production and reserves of Saline County are much greater than those of Pulaski. Both bauxite areas are located from beneath

Tertiary strata of the comparatively flat Gulf Coastal Plain, a few miles southeast of a region of strongly folded Paleozoic rocks forming the east end of the Ouachita Mountains.

Cretaceous strata are present not far distant to the south and southwest, but Eocene sediments appear to overlap them and rest directly on Paleozoic and igneous rocks in the bauxite region. The oldest beds of the Cenozoic in this vicinity appear to be of Midway age, consisting of fossiliferous limestone grading upward into blue-gray clay or its weathered equivalent. The bauxite-kaolin zone overlies the Midway clay and, where the cover has not been removed by erosion, is overlain by Wilcox nonmarine strata composed of clay, sand, and lignite. The Wilcox sediments covered the bauxite and originally extended over the syenite hills.

Geological relations indicate that syenite intruded Paleozoic rocks in pre-Midway time, but the cover was in large part subsequently removed by erosion, exposing the syenite at the surface before encroachment of the Midway sea. The early Eocene sea did not cover the top of the syenite hills, but limestone and clay were deposited around them. Withdrawal of the Midway sea exposed the region to pronounced weathering and some erosion, and by the coincidence of favorable climatic conditions and topography persisting through a sufficient span of time, the alumina-rich syenite, detrital feldspar, and clay were subjected to intensive weathering, thus forming bauxite and kaolin as residual alteration products. The bauxite grades downward into clay and weathered syenite, and deposits underlain by syenite in places are saprolites that have retained the granitic texture of the parent rock.

Bauxite deposits of southeastern Alabama occur as pockets adjacent to the Midway-Wilcox unconformable contact. The occurrences are generally small, with a thickness varying from 1 foot to more than 50 feet, the average maximum thickness being about 15 feet. The bauxite is closely associated with bauxitic clay and clay, there being a complete transition among the three.

Bauxite deposits of Georgia and Tennessee occur as pockets in Paleozoic dolomite and limestone that have been subjected to deep weathering believed to have taken place in Eocene time, and in the form of beds and lenses interlayered in Eocene sediments, perhaps near the Midway-Wilcox contact. The chemical industry is the principal consumer of Georgia bauxite.

Enormous reserves of bauxite of commercial grade have been proved in various parts of Africa, particularly in French and British colonies. Undeveloped deposits are known in China and Australia. These reserves, and those of South America, Europe, the United States, and lesser deposits elsewhere, insure a supply that should dispel any fear of a world shortage of bauxite in the future. Industries in the United States could carry along indefinitely if foreign sources of raw material were cut off, but production costs would be greatly increased because of the necessity of relying on low-grade ores. However, in order that domestic resources may be conserved, greater quantities of bauxite are being imported each year.

Uses of Bauxite

Abrasives. — Natural emery, a granular form of the mineral corundum, was used as an abrasive for hundreds of years, but in 1896 a method was discovered to manufacture an artificial abrasive by fusing bauxite in an electric-arc furnace. Since the beginning of the present century the use of natural emery has been largely superseded by synthetic corundum and silicon carbide. The synthetic material is also used in making certain types of crucibles and as a refractory for electric furnaces.

Synthetic aluminous abrasives are prepared by fusing high grade bauxite, and also pure alumina, the resulting product being a very hard, crystalline, purple-black material with an adamantine luster. The crystalline material is crushed, sized, and a bonding substance added, and the material is then molded into abrasive stones and wheels. Finely ground, calcined, or sintered bauxite is used to prevent trouble with water vapor in the electric furnace. High alumina clays carrying 48 to 52 per cent aluminum oxide, largely in the form of diaspore, are also used. Commercial grades of artificial corundum usually contain not less than 90 per cent aluminum oxide; therefore, a bauxite high in alumina and low in content of impurities, mainly silica, is necesary. The cost of manufacture is increased if supplementary material must be added or certain impurities must be eliminated in the electric furnace in order to obtain the desired relationship between alumina and impurities in the finished product. The United States industry depends almost entirely on ore from Arkansas, the material suited for this purpose being sorted in mining.

Cement. — An aluminate cement that attains maximum hardness within about 24 hours as compared to several weeks for ordinary Portland cement, withstands higher temperatures, and is relatively resistant to acids and other chemicals, has been used in the United States since about 1924 and in Europe since 1908. The period of "setting" is about the same for both aluminate and Portland cements. Portland cement manufacturers have successfully competed with aluminate cements because of the lower cost of their product and by obtaining high early-strength properties by finer grinding and increasing the lime content.

Aluminate cements are used as a binder in refractories, for at elevated temperatures ceramic qualities are developed as the result of interaction of the cement and the finer particles of the refractory aggregate. Because of the high early-strength quality it is of military importance for gun emplacements. Aluminate cements are used in industries where chemically resistant cement is required.

Manufacture of aluminate cement requires a bauxite low in silica, other impurities being of minor importance except phosphorus, which forms injurious phosphides. Proper proportions of limestone and suitable bauxite are mixed and fused to a clinker in a kiln and then pulverized. Formerly, practically all of the bauxite used in making cement was imported from Greece at very low cost, but at present american manufacturers must obtain raw material elsewhere.

Chemical industry. — The chemical industry formerly manufactured aluminum salts from kaolin, aluminous clays and shales, and natural alums, but it now depends almost entirely on bauxite containing a large proportion of acid soluble alumina. The amount of available alumina is roughly indicated by the percentage of chemically combined water (loss on ignition), for the trihydrate, which contains about 30 per cent of water of crystallization, is much more soluble in commercial acids than the monohydrates. Acid soluble iron must be low, but silica acts only as a diluent. Alumina hydrate made by the Bayer process is used to make iron-free salts. The raw material is digested with acid to produce the salt.

Aluminum sulfate is used for treating water in municipal filtration plants and for sewage precipitation, and sodium aluminate is used to treat boiler-feed water and supplementary to aluminum sulfate in municipal systems. Aluminum chloride is used in refining certain petroleum products. Aluminum hydroxide is used as a mordant in dyeing by combining with dyes to form lakes. The fluoride is a component of the bath in the electrolysis of alumina for the production of aluminum. There are many other uses of aluminum compounds, one of which is in making pigments, an example being common laundry blueing.

Bauxite for the chemical industry is called "white," "alum," or "chemical" because of the relatively low iron content. The ore is shipped in the "crushed and dried" form and is obtained mainly from Arkansas, although Georgia, Alabama, Surinam, and British Guiana supply some.

Bleaching agent. — The selective adsorptive properties of specially treated bauxite are utilized in refining sugar, and by the petroleum industry to remove deleterious substances from kerosene and gasoline, and to bleach lubricating oils. Bauxite is crushed, dried, and partially calcined to remove a part of the chemically combined water and may be reactivated by repeated thermal treatment. Raw material suitable for this purpose must possess a high alumina content and must be relatively hard and dense and fracture into angular fragments to produce a more permeable filter bed.

Synthetic gems. — A synthetic gen is identical in chemical composition and all physical properties with the corresponding natural gem but has been prepared in the laboratory by artificial means. Presence of blebs, inclusions, structure lines, and tension cracks permits ready identification of artificial material in most instances except the small cut gems. Synthetic material is sold as gems and for bearing surfaces in watches and scientific instruments. Cut synthetic gems often exhibit greater brilliance and are usually cleaner than natural stones.

The manufacture of gem varieties of artificial corundum is an important European industry. Synthetic rubies, various colors of sapphire, spinel, and alexandrite are made by fusing aluminum oxide derived from bauxite in furnaces burning a mixture of hydrogen and oxygen. The desired dolors are obtained by the addition of various metallic oxides. Gems weighing as much as 250 carats are produced.

Miscellaneous. — Bauxite has been used in the steel industry to treat blast furnace slags. Other uses are as a light insulating material and as a refractory material in the form of bauxite brick and high-alumina brick, where iron compounds would be objectionable.

Alumina Industry

The alumina industry, which is essentially the aluminum industry, requires a relatively high grade bauxite with maximum aluminum oxide content and minimum content of silica, which is the most harmful and expensive impurity in processing ore by the Bayer method. The silica impurity combines with alumina of the bauxite and cuastic soda in the Bayer process to form sodium aluminum silicate, a waste product. The silica factor is purely one of relative cost, for expensive caustic soda and valuable alumina are lost when combined with the silica, although the quality of the alumina produced remains the same. Bauxite currently used in the United States for recovery of alumina contains 55 to 60 per cent aluminum oxide and up to 7 per cent silica. However, ore containing as much as 19 per cent silica has been successfully used. Maximum titanium content should be 3 per cent. The aluminum industry of the United States imports about 75 per cent of the annual consumption from Dutch Guiana or Surinam, the remaining 25 per cent being domestically produced and largely derived from Arkansas. The bauxite is crushed and dried prior to shipment. The production of aluminum consumes about 65 per cent of the annual world production of bauxite.

Bayer Process

A process for extracting aluminum hydrate from bauxite was patented by Karl Bayer in Germany in 1888. In 1894 United States patents were granted to him, and shortly thereafter a plant was established in this country. The Bayer, or wet, process has been modified and improved but has remained fundamentally unchanged and is still the most economical means of winning aluminum oxide of requisite purity from its ores.

The principal raw products used in producing alumina by the Bayer process, an intermediate step in the production of metallic aluminum, are bauxite, lime, and soda ash. Raw bauxite received from the mines is unloaded by bulk-handling methods, tramp iron is removed, and the ore is ground in hammer mills and screened.

Lump quicklime is ground in hammer mills, and individual charges of bauxite, soda ash, and lime are weighed for mixing, the relative amounts needed being based on laboratory analysis of the bauxite and the liquor of caustic soda with which it is to be mixed. A solution of caustic soda is produced by the reacction of soda ash and hydrated lime. Action of caustic soda is highly selective, dissolving only the alumina of the bauxite, forming a solution of sodium aluminate, while the impurities of iron, titanium and silicon oxides, remain in suspension in the slurry.

Bauxite, lime, and cuastic soda liquor are passed through mechanical mixers, and the mix is then transferred to digesters where an additional volume of pre-heated caustic soda liquor is added. The slurry is heated with injected steam and is held at an elevated temperature sufficiently long to permit completion of the chemical reaction. The reaction consists of solution of the alumina as sodium aluminate and precipitation of dissolved silica as sodium-aluminum silicate.

Upon completion of digestion the sodium aluminate solution and suspension of impurities ("red mud") are conducted to pressure reduction-cooling tanks and then pumped to filter presses where the red mud is removed and washed. The mud cake is then mixed with water, and the slurry is pumped to settling ponds as waste.

The sodium aluminate filtrate and the weak solution derived from the mud washing are conveyed to cooling tanks and subsequently to precipitation tanks. A seed charge of aluminum trihydrate is added to each tank-fill of sodium aluminate solution, and the solution is stirred for 30 to 60 hours. During the stirring process about one-half of the alumina content of the sodium aluminate is precipitated out on the particles of the aluminum trihydrate seed charge. Upon completion of this state of the process, the contents of the precipitation tanks are pumped to thickeners where the precipitated hydrate is separated from the remaining sodium aluminate solution. Additional soda ash is added to the clarified filtrate of sodium aluminate, and this mixture is recycled to extract more aluminum trihydrate.

The residue of hudrate from the above separation process is washed, and the clean slurry of hydrate is transferred to storage tanks. Subsequently the water of the slurry is removed by filters, and the hydrate is conducted to gas heated rotary kilns where free moisture and chemically combined water are driven off. Dehydrated alumina leaves the kiln at a temperature of about 1800 degrees Fahrenheit and passes to rotary coolers where a blast of air reduces the temperature. The alumina is screened to remove large lumps and then sacked or loaded in specially designed railroad cars and shipped to reduction plants.

Hall-Heroult Process

Charles Martin Hall, a young American chemist, and Paul Heroult, of France, discovered concurrently in 1886 a process for producing aluminum by electrolysis. The modern aluminum industry, jointly founded upon the Hall-Heroult process and the Bayer process for extracting alumina from bauxite, through technological development has placed aluminum in the category of common industrial metals. The reduction of alumina to metallic aluminum is accomplished electrolitically. The electric furnace used in the process is an iron vessel having a refractory lining over which a layer of carbon is placed. The anode consists of a number of very pure carbon rods, while the vessel of the furnace acts as the cathode. The vessel is approximately 1 foot deep, 5 feet long, and 2.5 to 3.5 feet wide. Electric currents of 8000 to 20,000 amperes are used, and voltages of 5.5 to 6.5 are required for each furnace. Often 40 to 50 furnaces are placed in series. Production of a pound of metal requires 10 to 12 kilowatt-hours of electric current.

Alumina of a high degree of purity is required in the Hall-Heroult process because impurities in the oxide would be largely reduced with the aluminum, thereby impairing its purity. The charge of alumina and cryolite, with or without other flourine compounds, is placed in the furnace. The electrodes are brought together, and then the anode is gradually raised to form an arc that heats the contents of the furnace to about 950 degrees Centigrade and fuses the cryolite. Alumina is dissolved by the fused cyolite, and the electrical energy disrupts the chemical bond of the aluminum and oxygen of the alumina to form oxygen and metallic aluminum. The oxygen thus formed combines with the carbon of the anode, producing gasses which gradually consume the electrodes. The metallic aluminum is produced in an environment far above its melting point (m.p. circa 659 degrees Centigrade), is therefore in the liquid state, and, being heavier than the electrolyte, sinks to the bottom of the bath where it conducts the electric current to the furnace lining. The operation is practically continuous for, as molten aluminum is tapped from the bottom of the furnace, quantities of alumina are added, and the carbon anodes are replenished.

The production of one ton of aluminum by electrolysis consumes about 0.5 ton of carbon and 0.1 ton of cryolite. Theory demands 1.88 tons of alumina to produce 1 ton of aluminum, and this quantity is but slightly exceeded.

Cryolite is a comparatively rare mineral, there being only three commonly known occurrences. The largest and only commercial deposit is at Ivigtut, on the shore of Arksuk Fjord, Greenland, where it is associated with pegmatite in an intrusive mass of prophyritic granite. The mine is owned by the Danish Government, and the raw output is divided between the Pennsylvania Salt Manufacturing Company, Philadelphia, and the Oresunds Chemiske Fabriker, Copenhagen, Denmark. The other two occurrences are in rocks of Pikes Peak, Colorado, and at Miask, in the Ural Mountains of Russia.

The mineral cryolite is a double fluoride of aluminum and sodium crystallizing in the monoclinic system, having a hardness of 2.5 and a specific gravity of 2.95 to 3.0. The pure substance is colorless to snow-white and almost insoluble in water. In the manufacture of aluminum the natural mineral is meeting commpetition in the form of artificial cryolite, made from sodium carbonate, bauxite and flourspar, or from their derivatives which supply sodium, aluminum, and flourine.

Aluminum

Aluminum is a bluish silver-white metal possessing a specific gravity of about 2.6 and a tensile strength of from 15,000 to 20,000 pounds per square inch, or about that of cast iron. A cubic foot of the metal weighs 159 to 169.5 pounds. The metal is very ductile and malleable but must be annealed frequently for it hardens while being worked. Thermal conductivity of aluminum is 38 (silver 100 and copper 73.6), and the electrical conductivity is 50 (silver 100 and copper 90), although when measured by weight the electrical conductivity of aluminum is greater than that of copper. A high power of reflecting light and radiant heat is possessed, and a polished surface is retained a long time because it resists oxidation. Common impurities ordinarily found in the metal are iron, silicon, manganese, and copper.

Aluminum of relatively high purity finds the most ready market, and the metal of commerce ranges above 98 per cent purity, although most commercial applications require aluminum in the form of alloys. Aluminum is sold in the form of plates, sheets, rods, wire, tubes, ingots, castings, powder, foil, in a large number of fabricated forms, and various alloys.

Zinc, copper, nickel, iron, manganese, magnesium, and silicon increase the tensile strength of aluminum, but the amount of alloying elements required to acquire optimum results seldom exceeds 10 per cent. Zinc is an exception to this rule. Cold working by rolling, forging, and drawing with repeated annealing further strengthen the alloys, and those containing magnesium silicide age-harden upon standing for a few days after quenching. The process of age-hardening may be accelerated with controlled elevated temperatures. Alloys of aluminum and silicon are highly resistant to sea-water corrosion and are lighter than pure aluminum, while aluminum-copper bronzes possess an ultimate stress of 38 tons per square inch.

In the electrical industry aluminum is used in field coils of heavy traction motors and is widely used for power transmission cables by winding about a central supporting steel wire. Manufacturing industries such as those making soap, sugar, foodstuffs, and varnish use large aluminum vessels and tanks. Aluminum powder is used for protective paint, because it resists sulfur vapors and sea-water corrosion, and as an undercoat, but it reduces radiant efficiency. The powder is also used in lithographing, thermit welding, incendiary bombs, cyanide precipitation, as a deoxidizer in making steel, and in the preparation of ammonal. The metal is employed in windows and other architectural features and for insulation in the form of foil. Aluminum is ideally suited for cooking utensils because when it is ingested the metal does not pass through the stomach wall and is never found in urine analyses but is completely rejected with the faeces.

The transportation industry is the major consumer of aluminum. In the automotive industry, particularly in heavy trucks and busses, aluminum is replacing other metals for special alloy bearings, pistons, engine heads, and structural parts. Railroads are utilizing aluminum alloys in developing lighter and faster trains, with resulting economies in fuel consumption, increased pay load, and decreased road-bed maintenance cost. Besides many varies military uses, aluminum is or prime importance in the construction of aircraft. Quantities of metals used in an average plane of 8300 pounds net weight are: aluminum 5120 pounds; iron and steelf 1680 pounds; copper 360 pounds; others (nickel, chromium, molybdenum, magnesium, tin) 60 to 70 pounds each; and small quantities of lead and zinc.[1]

---

[1] Bidwell, P. W., The battle of the metals: Mining and Metallurgy, vol. 21, no. 405, p. 417, 1940.

Production and consumption. — United States production of aluminum in 1940 increased 26 per cent above that of 1939, and imports of the metal increased the same amount while export decreased about 25 per cent. Aluminum Company of America and Reynolds Metals Company are expected to produce ingot aluminum at an annual rate of almost 1,000,000,000 pounds by the end of 1941, and by the end of 1942 production and fabrication facilities will be expanded in a two-year period that would normally have required almost 20 years to accomplish. The urgency of military needs has subordinated all civilian applications of the metal and is the sole impetus of the greatly accelerated program of expansion in the industry. Economics of mass production and technological development have enabled producers of primary aluminum to reduce the price of the metal from 20 cents to 17 cents per pound in large lots despite the general upward trend of prices of other rearmament materials. The price reduction combined with the physical properties of strength and lightness made aluminum more strongly competitive with other metals. Government agencies have been forced to stabilize the secondary aluminum market.

United States production of primary aluminum in 1940, according to the U.S. Bureau of Mines, was 206,280 short tons values at $75,292,000.

The United States Bureau of Mines estimates that world production of aluminum in 1940 increased about 20 per cent over that of 1939, primarily due to defense and war effort. World consumption of aluminum in 1940 is estimated to have been about 880,000 metric tons, and production of aluminum since 1931 is estimated to have risen some 300 per cent. Foreign trade in aluminum is now curtailed or controlled according to the political affiliations of the respective nations.

Bibliography and References

Adams, G. I., The formation of bauxite in sink-holes: Econ. Geol., vol. 18, 1923.

Allen, V. T., Mineral composition and origin of Missouri flint and diaspore clays: Missouri Geol. Survey and Water Resources, App. IV, 58th Bien. Rept., 1925.

Anderson, Robert J., German aluminum industry: Mining Mag., vol 62, nos. 4 and 5, 1940.

———, The aluminum industry of Italy: Mining Mag., vol. 61, no. 1, 1939.

———, Primary aluminum: Mining Mag., vol. 60, no. 4, 1939.

Behre, C. H., Jr., Origin of bauxite deposits: Econ. Geol., vol. 27, no. 7, 1932.

Bramlette, M. N., Geology of the Arkansas bauxite region: Arkansas Geol. Survey, Inf. Circ. 8, 1936.

Branner, J. C., The bauxite deposits of Arkansas: Arkansas Geol. Survey, Ann. Rept. for 1890, vol. 2, 1891.

Burchard, E. F., Bauxite in northeastern Mississippi: U.S. Geol. Survey Bull. 750-G, 1925.

Cash, F. F., and Von Bernewitz, M. X., Methods, cost, and safety in stripping mining coal, copper ore, iron ore, bauxite, and pebble phosphate: U.S. Bur. Mines. Bull. 298, 1929.

Clarke, Frank Wigglesworth, The date of geochemistry: U.S. Geol. Survey Bull. 770, 1924.

Clemmer, J. B., Clemmons, B. H., and Stacy, R. H., Preliminary report on the flotation of bauxite: U.S. Bur. Mines Rept. Inv. 3586, 1941.

Cole, G. A. J., and other, Interbasaltic rocks (iron ores and bauxites) of northeast Ireland: Mem. Geol. Survey Ireland, 1912.

Cooper, W. G. G., Bauxite deposits of the Gold Coast: Gold Coast Geol. Survey Bull. 7, 1936.

Dana, Edward Salisbury, revised by William E. Ford, A Textbook of Mineralogy, with an Extended Treatise on Crystallography and Physical Mineralogy, John Wiley & Sons, Inc., New York, 1932.

de Lapparent, J., Geological reasons for the formation of the three natural aluminum hydroxides: Int. Congress Mines, Met. and Applied Geol. Paris, October, 1935.

———, Les bauxites de la France Meridionale: Mem. de la Carte Geol. Detail, France Ministere a Travaux Publiques, 1930.

Dix, E. H., Jr., Aluminum and its alloys: Metal Progress, vol. 36, no. 4, 1939.

Eckel. E. C., Alumina cement in France: Eng. News-Record, August 30, 1023.

Fox, Cyril, The bauxite resources of India: Mining Mag., vol. 26, 1922.

Fox, C. S., Bauxite and aluminous laterite: Technical Press, London, 1932.

Gandrud, B. W., and DeVaney, Fred D., Bauxite-float-and-sink fractionation and flotation experiments: U.S. Bur. Mines Bull. 312, 1929.

Harder, E. C., Edwards, J. D., Frary, F. C., and Jefferies, Zay, The Aluminum Industry — Aluminum and its Production, McGraw-Hill book company, New York, 1930.

Harder, E. C., Origin of bauxite deposits: Econ. Geol., vol. 28, no. 4, 1933.

Hardy, F., and Follett-Smith, R. R., Studies in tropical soils: Jour. Agri. Sci., vol. 21, 1931.

Hayes, C. W., Geological relations of the southern Appalachian bauxite deposits: Trans., Amer. Inst. Min. Met. Eng., 1895.

———, The Arkansas bauxite deposits: U.S. Geol. Survey 21st Ann. Rept., pt. 3, 1901.

Knibbs, N. V. S., The Industrial Uses of Bauxite, Earnest Benn., Ltd., London, 1928.

Le Lande, W. A., Jr., Bauxite as a sugar-refining adsorbant: Ind. Eng. Chem. vol. 33, no. 1, 1941.

Lee. J. A., Making alumina at Mobile: Chem. and Met. Eng., vol. 47, no. 10, 1940.

Lindgren, Waldemar. Mineral Deposits, McGraw-Hill Book Company, Inc., New York, 1933.

Litchfield. Lawrence, Jr., Bauxite, part 1: Chem. Ind., vol. 48, February, 1941; part 2, vol. 48, March, 1941.

———, The bauxite industry of northern South America: Eng. and Min. Jour., August 17 and 31, September 21, 1929.

Morse, P. F., The bauxite deposits of Mississippi: Mississippi Geol. Survey, Bull. 19, 1923.

Nelson, W. A., Appalachian bauxite deposits: Bull. Geol. Soc. Amer., vol. 34, 1923.

Rettger, R. E., Bauxite deposits of southeastern Alabama: Econ. Geol., vol. 20, no. 7, 1925.

Singer, F., Methods of extracting alumina from clay: Brick and Clay Record, vol. 94, no. 6, June, 1939.

tone, Frank J., Abrasives, 1918-38: Chem. Ind., vol. 45, No. 2, pt. 1, 1939.

Watson, T. L., A preliminary report on the bauxite deposits of Georgia: Geol. Survey Georgia, Bull. 11, 1904.

Wilkes, Gordon B., Reflective insulation: Ind. Eng. Chem., vol. 31, no. 7, 1939.

Aluminum and bauxite, the mineral industry of the British Empire and foreign countries, War Period (1913-1919): Imp. Min. Res. Bureau, London, 1921.

Brookings Lectures, Mineral Economics, edited by F. G. Tryon and E. C. Eckel, McGraw-Hill Book Company, Inc., New York, 1932.

Industrial Minerals and Rocks, edited by the committee on the Industrial Minerals Volume, Amer. Inst. Min. Met. Eng., New York, 1937.

The Blue Book of Southern Progress, 1941, Manufacturers Record Publishing Company, Baltimore, Maryland (annual publication).

Minerals Yearbook, compiled under the supervision of H. Herbert Hughes and others, U.S. Bur. Mines (annual publication).

Mineral Trade Notes, vol. 9, no. 6, U.S. Bur. Mines, Dec. 30, 1939; vol. 10, no. 3, March, 1940.