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See page 622 for
discussion of titania.

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FORMATION OF BAUXITE FROM BASALTIC ROCKS OF OREGON.*

VICTOR T. ALLEN.

ABSTRACT.

In Oregon the plagioclase of basaltic rocks weathered to kaolinite or to halloysite; ferromagnesian minerals and the basaltic glass of the groundmass and of tuffaceous fragments weathered to nontronite. Then, by loss of silica, the clay minerals changed to gibbsite and to high-iron bauxite. Gibbsite and a trace of boehmite are the chief aluminous minerals in the bauxite which contains from 47 to 25 percent Al_2O_3 . Titaniferous magnetite, ilmenite, maghemite, goethite, hematite, limonite, and nontronite are the chief iron minerals in the bauxite which contains from 49 to 18 percent Fe_2O_3 . Development of pisolitic structure in the upper part of the bauxite obscured early structures. Bauxite, which is formed from tuffaceous fragments or from detrital materials containing some quartz and other minerals foreign to basaltic rocks, lacks relict shapes of minerals that are preserved in the bauxite formed from basaltic lavas. A transitional layer of clay, composed of kaolinite, halloysite, and nontronite, and locally 100 feet thick, separates the bauxite at the top of the deposit from the underlying parent basaltic rocks of Miocene age and indicates that bauxite in Oregon formed by a two-stage process of weathering.

INTRODUCTION.

SEVERAL recent papers emphasize that plagioclase and basic igneous rocks weather directly to gibbsite without the formation of intermediate products.

In discussing the soils of Netherlands East Indies, Mohr¹ states that the hydrolysis of calcium feldspar gives free aluminum hydroxide, that kaolin is very resistant to weathering, and that anorthite is not.

Goldman and Tracy² question that kaolinization of nepheline syenite in

* Published by permission of the Director, U. S. Geological Survey. Presented before the Geological Society of America, Ottawa Meeting, December, 1947.

¹ Mohr, E. C. J., The soils of equatorial regions with special references to the Netherlands East Indies, p. 78, Ann Arbor, Mich., J. W. Edwards Co., 1944.

² Goldman, M. I., and Tracy, Joshua I., Relations of bauxite and kaolin in the Arkansas bauxite deposits: ECON. GEOL., vol. 41, pp. 573-575, 1946.

Arkansas is an intermediate step in its weathering to bauxite. Also, they make the general statement that "much evidence is accumulating to support the belief that at least under certain conditions gibbsite precedes kaolin in the weathering of all but the most silicic igneous rocks."

Harrison³ considered that laterites were developed from basic igneous rocks and clay from granitic rocks. In a later paper⁴ he reaffirmed that gibbsite was formed directly by the weathering of basic igneous rocks. Lateritization was recognized as being succeeded by resilication of aluminum hydroxide, resulting in the formation of clay, but clay was considered unlikely as an intermediate stage in the formation of bauxite. However, he believed that under tropical conditions pot clays can undergo desilication and can be changed to bauxite.

Clarke's⁵ opinion may be summarized as follows: kaolinite is an insoluble hydrated silicate, and further change ends with its formation; possibly halloysite, which has the composition of kaolinite plus water and is decomposed by acids, is the intermediate compound formed in the transformation of basalts to bauxite by atmospheric or thermal waters.

Other examples can be cited but these are sufficient to indicate that a difference of opinion exists and that further study is needed before a solution to this interesting problem can be reached.

This petrographic study is part of a cooperative project of the U. S. Geological Survey, the Oregon Department of Geology and Mineral Industries, the U. S. Bureau of Mines, the Alcoa Mining Company, and the St. Louis University Institute of Geophysical Technology. It is based upon specimens collected by the writer from 1944 to 1947 during several visits to the bauxite areas, upon samples furnished by the Oregon Department of Geology and Mineral Industries, and core samples contributed by the Alcoa Mining Company along with the chemical analyses plotted as Figure 1.

The location and the geology of the deposits have been adequately described in reports of the U. S. Geological Survey⁶ and the Oregon Department of Geology and Mineral Industries.⁷ The principal deposits are located in Washington, Columbia and Multnomah Counties, 25 to 50 miles northwest of Portland and in Polk and Marion Counties, within a few miles of Salem, Ore.

CHEMICAL DATA FROM DRILL HOLES.

In Oregon ferruginous bauxite is exposed to a depth of several feet at a number of places, but a complete sequence down to the parent rock is lacking

³ Harrison, J. B., The residual earths of British Guiana commonly called "laterite": *Geol. Mag. London*, dec. II, vol. 7, p. 560, 1910.

⁴ Harrison, J. B., *Katamorphism of igneous rocks under humid tropical conditions*: *Imp. Bur. Soil Sci.*, Harpenden, England, pp. 1-79, 1933.

⁵ Clarke, F. W., *The data of geochemistry*, 5th edit.: U. S. Geol. Survey Bull. 770, p. 503, 1924.

⁶ Bell, G. L., *Laterite deposits and occurrence in the Portland region*. Strategic minerals investigations, open file report: U. S. Geol. Survey, Washington, D. C., 1945.

⁷ Libbey, F. W., Lowry, W. D., and Mason, R. S., *High alumina iron ores in Washington County, Oregon*: G. M. I. Short paper No. 12, Oregon Dept. Geol. and Min. Ind., 1944; *Ferruginous bauxite deposits in northwestern Oregon*: Oregon Dept. Geol. and Min. Ind. Bull. No. 29, pp. 1-99, 1945.

at any one vertical exposure. Basaltic rocks in varying degrees of alteration occur near some of the bauxite, but their exact position and relation to the nearest bauxite outcrops are open to question. A continuous series of samples from a hole drilled by the Alcoa Mining Company into one ferruginous bauxite deposit in Oregon is valuable, because it is free from doubt concerning the vertical sequence of the samples. The 84 chemical analyses supplied by that company have been plotted by the writer as Figure 1 and show the variation in chemical composition with depth at each 2-foot interval. At this drill-

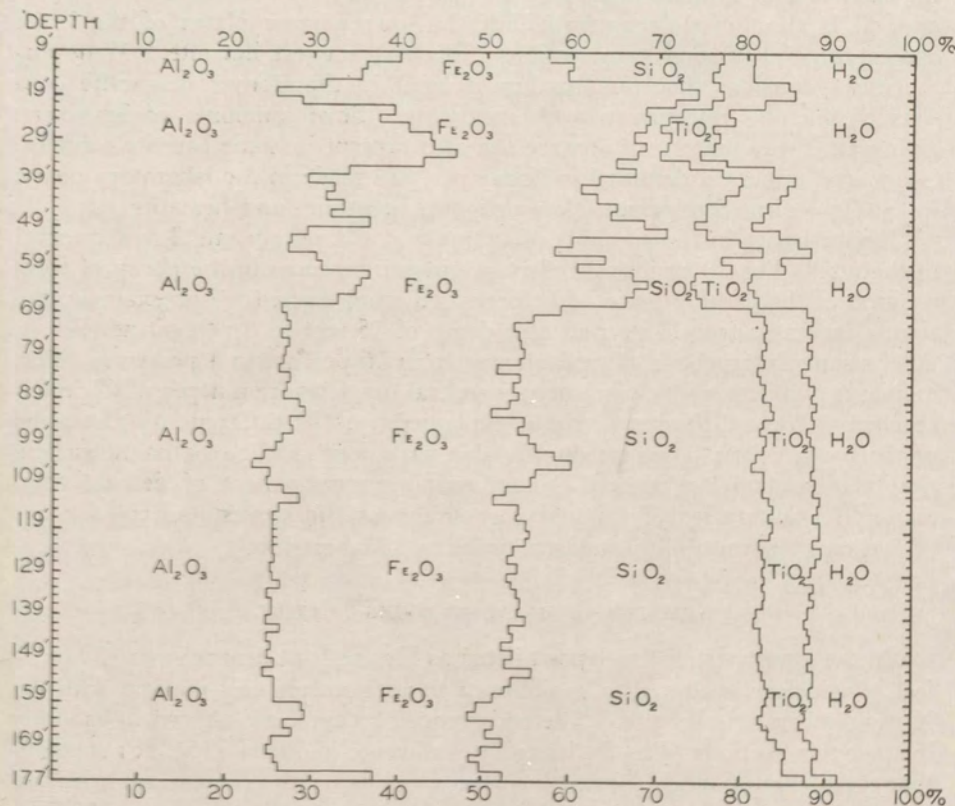


FIG. 1. Diagram showing variation in chemical composition with depth in a ferruginous bauxite deposit in Oregon. Analyses at 2-foot intervals by Alcoa Mining Company.

hole locality weathering penetrated downward more than 175 feet; alumina, ferric oxide, titania, and water increased progressively but not regularly at the expense of silica. At this deposit the sample with the highest alumina, 47 percent, occurs at a depth of 31 feet. Its high water content and low silica suggested the presence of the alumina trihydrate, gibbsite, which has been confirmed by petrographic and X-ray methods. In some samples traces of boehmite in addition to gibbsite are represented in the X-ray patterns. The sample with highest ferric oxide content, 49 percent, came from a depth of 19

feet, and like the sample with highest alumina occurs in a zone with a low silica content of about 2 per cent. Below a depth of 69 feet the silica is combined with iron, aluminum, and water to form the hydrous aluminum silicates, kaolinite or halloysite and the hydrous iron-aluminum silicate, nontronite. These clay minerals form a transitional layer over 100 feet thick that separates the bauxite at the top of the profile of weathering from the underlying parent basaltic rocks of Miocene age.

The titania content varies between 3 and 8 percent. X-ray patterns of the black opaque mineral present in all samples indicate that the chief titanium mineral is titaniferous magnetite, but the long narrow plates of the black opaque mineral in some thin sections (Fig. 3a) suggest ilmenite. Many authorities⁸ consider that the titanium present in titaniferous magnetite consists of ilmenite intergrown with magnetite. Small amounts of leucoxene giving an X-ray pattern of anatase are also present in some bauxite samples. Other iron minerals identified in X-ray patterns made in the laboratory of the U. S. Geological Survey include maghemite, goethite, and hematite.

Irregularities in the amounts of titania and silica from one 2-foot interval to the next (Fig. 1) probably reflect original differences in the chemical composition of the basaltic material before weathering started. For example, the titania increases from 4 percent at a depth of 15 feet to 8 percent at 17 feet. At the same interval the silica decreases from 16 percent to 4 percent. Silica increases and decreases conspicuously several times before a depth of 67 feet is reached. These differences may be explained by: (1) differentiation of some of the basaltic lava flows causing notable variations in the original silica and titania of certain horizons; (2) mechanical rearrangement of detrital fragments; (3) alteration of the glassy groundmass and vesicles provided zones of increased permeability and susceptibility to alteration.

CHANGE OF BASALTIC ROCKS TO CLAY.

In the lower part of the deposit listed as Figure 1, at depths from 179 to 68 feet, plagioclase is altered to kaolinite or to an isotropic clay mineral with the X-ray pattern of halloysite. The occurrence of plagioclase altered to kaolinite in some thin sections (Fig. 2a, b) and to halloysite in others (Fig. 2c) suggests that these clay minerals formed in Oregon under nearly similar conditions of weathering. Possibly slightly different pH and other conditions within the chemical system determined whether kaolinite or halloysite crystallized.

Locally nontronite replaces some plagioclase (Fig. 2a). Under conditions of poor drainage and in the presence of magnesium and ferrous iron, nontronite is formed from augite (Fig. 2b), from iddingsite (Fig. 2c), from the glassy groundmass (Fig. 2c), from vesicles (Fig. 2a, d), from tuffaceous fragments and from palagonite.⁹ Under conditions of thorough drainage and under neutral or slightly acid conditions, nontronite migrates into cracks and openings, and plagioclase is weathered to kaolinite or halloysite. In the

⁸ Dana, J. D. and Dana, E. S., *The System of Mineralogy*, 7th ed., vol. I, p. 702, 1944.

⁹ Allen, Victor T. and Scheid, Vernon C., Nontronite in the Columbia River region: *Am. Mineralogist*, vol. 31, pp. 294, 312, 1946.

lower part of this deposit nontronite fills vesicles in the altered lava (Fig. 2a, d). These features are characteristic not only of the lower part of this bauxite deposit, but also of all the specimens of weathered Columbia River lava studied by the writer in connection with other investigations.^{9, 10} At several localities the evidence indicates that nontronite formed early from basaltic glass and ferromagnesian minerals under conditions of poor drainage and remained in place as long as the stagnant alkaline conditions persisted. In the upper part of the profile of weathering, kaolinization of plagioclase feldspars started as soon as good drainage conditions were established and when the chemical system changed from alkaline to neutral or slightly acid. Migration or movement of clay minerals was favored by conditions of good drainage and the presence of dispersing agents.¹¹

FORMATION OF OREGON BAUXITE.

At a depth of 67 feet plagioclase laths are altered to gibbsite at the edges, but some halloysite remains near the center (Fig. 3a). This suggests that plagioclase was altered first to halloysite and by loss of silica the halloysite changed to gibbsite. Another locality, the Yankton Railroad cut (sec. 1, T. 4, N., R. 2 W.) in the St. Helens quadrangle, Ore., also shows the change of clay minerals to gibbsite below the ferruginous bauxite layer. Here the clay mineral is kaolinite, which occurs as plates having gray interference colors and other characteristic optical properties. Grains and patches of gibbsite are present in the center and along the edges of the kaolinite (Fig. 5a), and the relation indicates an invasion and replacement of kaolinite by gibbsite. This specimen was obtained by digging below the lowest part of the abandoned railroad grade. In the overlying ferruginous bauxite the replacement of plagioclase by gibbsite is complete (Fig. 5b), and the other thin sections of the bauxite from the Yankton cut show all the replacement features described here for the drill-core samples.

At depths from 65 to 20 feet in the Alcoa drill core (Fig. 1) the shapes of plagioclase laths (Fig. 3b) and other minerals, as well as the structure of the original basaltic rocks, were preserved as the change to gibbsite took place. The edges of vesicles afforded permeable channels for solutions and were altered to gibbsite which penetrated inward and replaced nontronite that formerly filled the interiors of the vesicles (Fig. 3b).

The replacement of nontronite by gibbsite took place along veins and embayed areas where gibbsite invaded the nontronite (Fig. 3c, d). The utilization of alumina present in the nontronite and its fixation as gibbsite liberated the iron from nontronite as the oxides. Some of these oxides formed pisolites of goethite, hematite, or maghemite, which were added to the titaniferous magnetite liberated by weathering of the basaltic lavas. Some of the iron stained the finely divided clay minerals and gibbsite grains, increased their indices of

¹⁰ Allen, Victor T. and Nichols, Robert L., Weathered gravels and sands of Oregon and Washington: *Jour. Sedimentary Petrology*, vol. 16, pp. 52-62, 1946.

¹¹ Allen, Victor T., Effect of migration of clay minerals and hydrous aluminum oxides on the complexity of clay: *Am. Ceramic Soc. Jour.*, vol. 28, pp. 265-275, 1945.

refraction, and made their determination difficult by optical methods. The term limonite is used in this paper to denote the indefinite mixture of iron oxides of brown color that stains much of the ferruginous bauxite. Hematite, which has been verified in X-ray patterns, accounts for the red colors.

The development of gibbsite and ferruginous bauxite in the deposits of Oregon was accomplished by a continuation of the same process of weathering and thorough leaching as that which formed the kaolin minerals. Laboratory experiments¹² demonstrate the effectiveness of carbonic acid solutions in removing silica from clay minerals, and emphasize that removal of silica is facilitated by circulation of solutions. Good drainage conditions are essential in the leaching of silica in order to renew the supply of carbon dioxide and to remove the solutions that become partly or wholly saturated with silica. The optimum pH for silica removal from each of the clay minerals is unknown, but the range of pH of carbon dioxide in water varies from slightly below 7 to 3.85 at saturation. This final stage of weathering, in which silica was removed from the clay minerals, is present at only a few localities in the Columbia River region. It has been observed by the writer near Molalla, Clackamas County, Ore., and near Castle Rock, Cowlitz County, Wash.,¹³ but at these localities the concentration of gibbsite falls considerably below the requirements for bauxite ore.

Although nontronite formed early because of the instability of basaltic glass and ferromagnesian minerals under conditions of poor drainage, some migration of nontronite took place after the formation of gibbsite. Veins of nontronite cut areas of gibbsite (Fig. 4a), but the general relation is veins of gibbsite cutting nontronite. The end product of the replacement of nontronite and kaolin minerals by gibbsite or of its downward migration is the formation of nodules of nearly pure gibbsite. These nodules range from a few inches to about 3 feet in their longest diameters and have a granular texture not unlike some limestones. Their Al_2O_3 content varies from 50 to 60 percent,¹⁴ compared to the theoretical composition of gibbsite of 65 percent Al_2O_3 and 35 percent water. One of these nodules, collected by the writer from a road cut on U. S. Highway 99E, 8 miles south of Salem, Ore., shows the preservation of the outlines of the plagioclase laths which have been changed to gibbsite (Fig. 5c). Another consists of interlocking grains of gibbsite without a suggestion of the textures of basaltic rocks (Fig. 5d). It probably represents secondary gibbsite that has been concentrated by migration and recrystallization. A similar sample was analyzed in the laboratory of the Defense Plant Corporation at Salem, and contains 60.05% Al_2O_3 , 2.55% SiO_2 , 1.68% Fe_2O_3 , 1.77% TiO_2 , and ignition loss 31.35 percent. No silica mineral could be found in it by microscopic examination, and the X-ray pattern was reported to show only gibbsite. A differential heating curve made by S. S. Goldich

¹² Allen, Victor T., Mineral composition and origin of Missouri flint and diasporic clays: Missouri Geol. Survey, 58 Biennial Report, app. IV, pp. 22-24, 1935.

¹³ Allen, Victor T., Sedimentary and volcanic processes in the formation of high alumina clay: ECON. GEOL., vol. 41, pp. 126-129, 1946.

¹⁴ Libbey, F. W., Lowry, W. D., and Mason, R. S., Ferruginous bauxite deposits in Northwestern Oregon: ECON. GEOL., vol. 41, no. 3, p. 261, 1946.

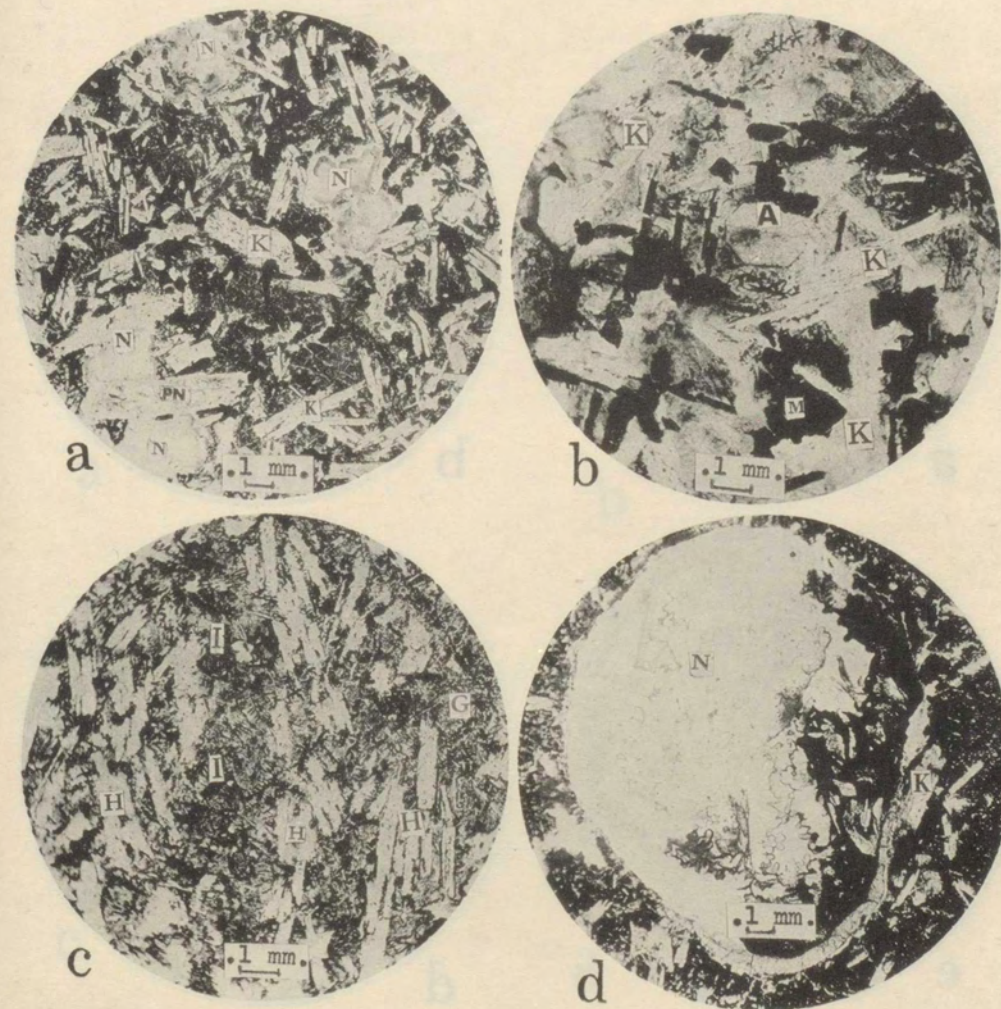


FIG. 2. Change of basaltic rocks to clay minerals.

- Plagioclase laths altered to kaolinite (K), or to nontronite (PN); vesicles are filled with nontronite (N).
 Al_2O_3 , 26%; Fe_2O_3 , 23%; SiO_2 , 35%. Depth: 173 feet.
- Augite (A) is altered to nontronite; plagioclase is altered to kaolinite (K). Magnetite (M, black).
 Al_2O_3 , 29%; Fe_2O_3 , 22%; SiO_2 , 33%. Depth: 92 feet.
- Iddingsite (I) is altered to nontronite; plagioclase to halloysite (H); glassy matrix (G) to nontronite.
 Al_2O_3 , 26%; Fe_2O_3 , 25%; SiO_2 , 31%. Depth: 82 feet.
- Large vesicle is altered to nontronite (N). Plagioclase is altered to kaolinite (K).
 Al_2O_3 , 27%; Fe_2O_3 , 32%; SiO_2 , 22%. Depth: 68 feet.

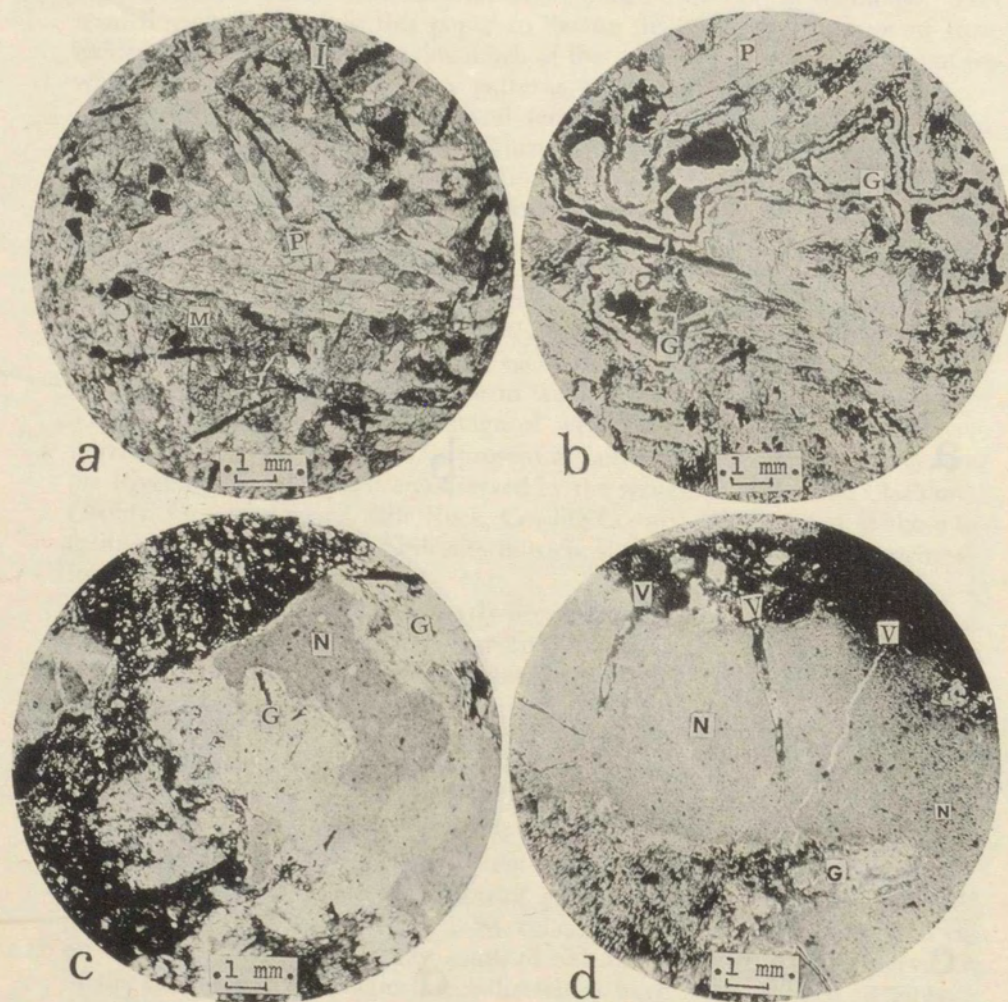


FIG. 3. Changes of clay minerals to gibbsite.

- a. Plagioclase (P) altered to gibbsite at edges; some halloysite remains near center. Glassy matrix (M) is altered to nontronite. Ilmenite (I).
Al₂O₃, 33%; Fe₂O₃, 33%; SiO₂, 8%. Depth: 67 feet.
- b. Gibbsite (G) replaces plagioclase (P) and nontronite that once filled vesicles.
Al₂O₃, 43%; Fe₂O₃, 25%; SiO₂, 2%. Depth: 31 feet.
- c. Gibbsite (G) replaces nontronite (N).
Al₂O₃, 43%; Fe₂O₃, 25%; SiO₂, 2%. Depth: 29 feet.
- d. Veins of gibbsite (V) cut large area of nontronite (N).
Al₂O₃, 43%; Fe₂O₃, 25%; SiO₂, 2%. Depth: 30 feet.

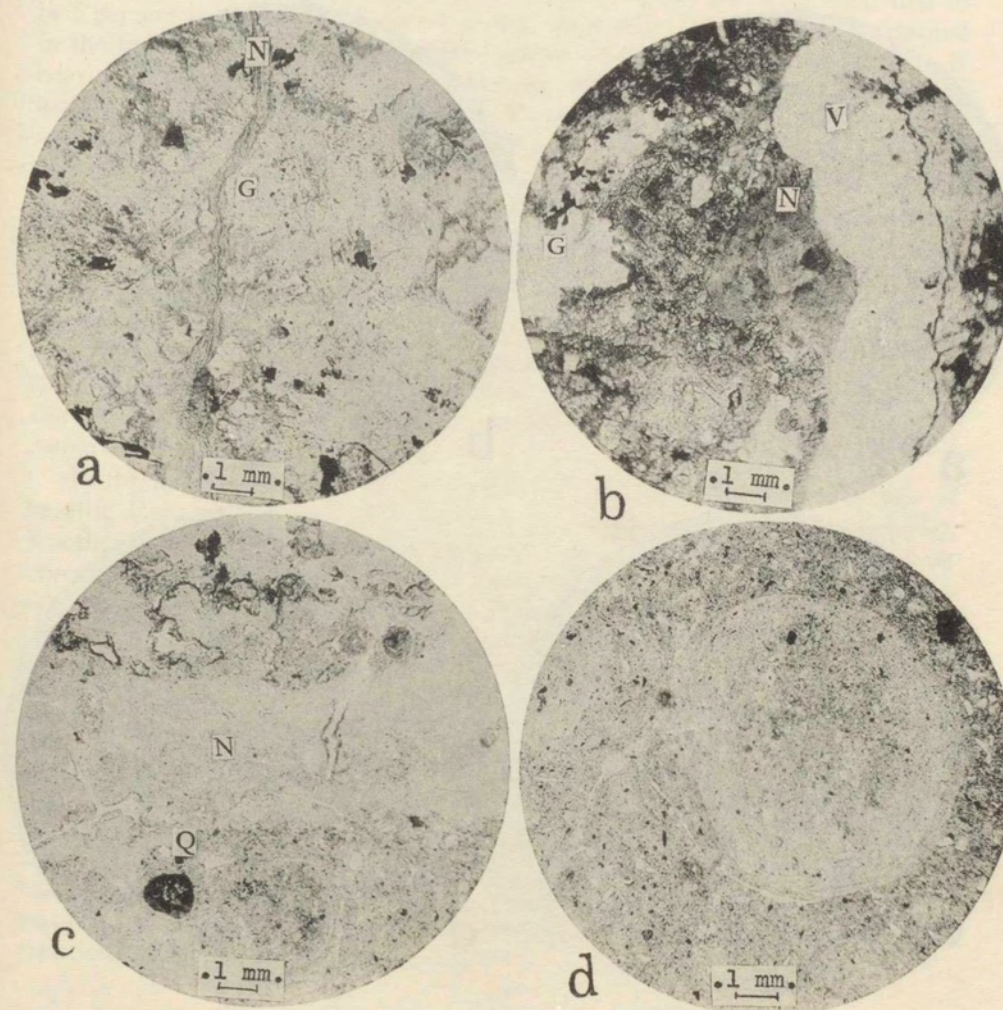


FIG. 4. Changes in bauxite in Oregon.

- a. Vein of nontronite (N) cuts gibbsite (G).
Al₂O₃, 37%; Fe₂O₃, 30%; SiO₂, 9%. Depth: 60 feet.
- b. Vein of gibbsite (V) cuts nontronite (N). Gibbsite (G).
Al₂O₃, 36%; Fe₂O₃, 31%; SiO₂, 6%. Depth: 48 feet.
- c. Nontronite (N) in center.
Pisolites are composed of gibbsite, iron oxide and quartz (Q).
Al₂O₃, 36%; Fe₂O₃, 24%; SiO₂, 16%. Depth: 14 feet.
- d. A large pisolite composed of gibbsite, nontronite, iron oxides, and quartz.
Al₂O₃, 36%; Fe₂O₃, 24%; SiO₂, 17%. Depth: 12 feet.

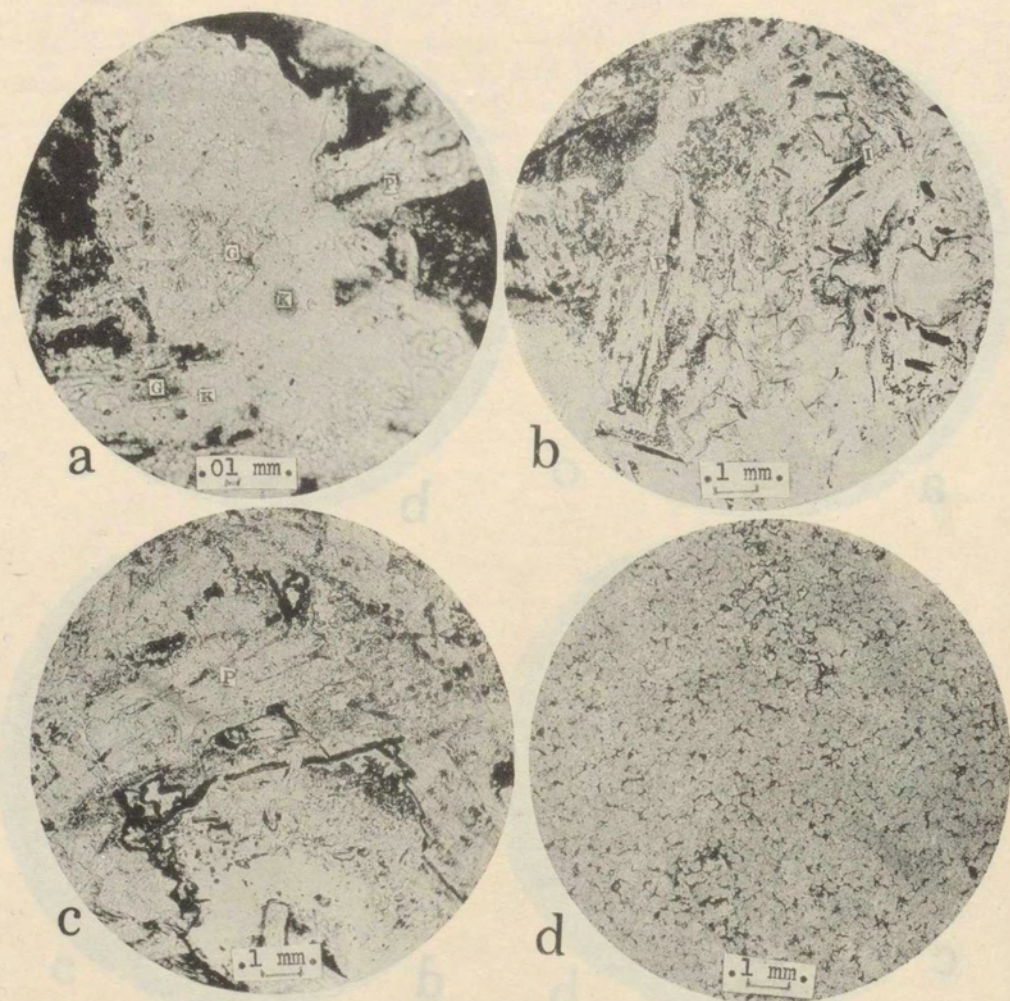


FIG. 5. Formation of gibbsite near St. Helens and Salem, Oreg.

- a. Gibbsite (G) replaces kaolinite (K). Small patches of gibbsite are scattered through kaolinite, indicating that alteration to gibbsite started at many centers. Plagioclase (P) is altered to gibbsite. At lower left a plagioclase lath is partly changed to kaolinite (K) and to gibbsite (G). Yankton cut, near St. Helens, Oreg.
- b. Plagioclase (P) altered to gibbsite; vein of gibbsite (V) cuts across section. Gibbsite (G) fills a vesicle formerly filled by nontronite. Ilmenite (I). Specimen overlies that shown in 5a, at Yankton cut near St. Helens, Oreg.
- c. Nodule of gibbsite in which shape of plagioclase (P) is retained. Near Salem, Oreg.
- d. Nodule of secondary gibbsite consisting of plates of gibbsite with no relict structure. Dark areas at lower center are iron oxide stains. Near Salem, Oreg.

showed a pronounced gibbsite peak and a smaller peak which he estimated to be 5 percent kaolinite. This indicates that some relict kaolinite can be retained in the impermeable part of a sample even when the replacement by gibbsite is nearly complete. It is also of interest because it offers an explanation for the inability to substantiate by optical or X-ray methods the presence of kaolin minerals in the high-silica zones above 59 feet in the Alcoa drill hole (Fig. 1). Some of the silica is combined as nontronite, but the possibility remains that some relict kaolinite or halloysite is present as finely divided grains in the highly colored material.* X-ray patterns on samples from 15 to 55 feet with a silica content from 2 to 23 percent were reported to show gibbsite, a trace of boehmite and titaniferous magnetite. X-ray patterns of samples from 69 feet to 173 feet, with a silica content from 27 to 36 percent, were reported to contain halloysite and titaniferous magnetite but no gibbsite. The X-ray data substantiate the conclusion based on this petrographic study that gibbsite is confined to the upper 68 feet of the Alcoa drill hole and that clay minerals comprise the lower part.

In the upper 18 feet of the Alcoa drill hole the structures characteristic of basaltic lavas are absent. Part of this may represent tuffaceous material. Another part consists of pisolites of gibbsite, nontronite and iron oxides, which obscured early structures (Fig. 4d). However, the presence of angular grains of quartz (Fig. 4c) and other minerals foreign to basaltic rocks indicates mechanical rearrangement and transportation of detrital fragments. The relatively high silica content of this zone is related to silica present as detrital quartz and combined as nontronite. Nine feet of silt overburden overlies the ferruginous bauxite and came from the same source as the detrital quartz now mixed with the nontronite, gibbsite, and other minerals forming the top of the bauxite deposits. The alteration of the silt is less intense than that of the ferruginous bauxite. Thus, the formation of the ferruginous bauxite was completed before the deposition of the overlying silt. The age of this silt has been assigned to the Pliocene.¹⁵ On this basis the period of bauxite formation in Oregon was confined to the interval between the Miocene basaltic eruptions and the Pliocene epoch.

CONCLUSION.

This petrographic study indicates the formation of bauxite from clay minerals derived by the weathering of basaltic rocks in Oregon. Gibbsite formed in the upper 60 feet of the deposit shown in Figure 1 as silica was leached from kaolinite, halloysite, and nontronite. A transitional zone of clay, locally 100 feet thick, underlying the ferruginous bauxite, affords proof of this two-stage process in the formation of bauxite from parent basaltic rocks of Miocene age in Oregon.

* Since the preparation of this manuscript, the presence of halloysite in an Alcoa drill hole sample (depth 53 to 55 ft. in Fig. 1) with 23 percent silica has been confirmed by a differential thermal curve made by Dr. George T. Faust and by an X-ray pattern made by Mr. Joseph M. Axelrod in the laboratory of the U. S. Geological Survey.

¹⁵ Libbey, F. W., Lowry, W. D., and Mason, R. S., *op. cit.*, p. 246, 1946.

ACKNOWLEDGMENTS.

The writer expresses his appreciation to the officials of the Alcoa Mining Company for the drill cores and chemical analyses contributed to this investigation. Also, the writer thanks Norman Davidson and J. M. Axelrod for X-ray patterns; G. T. Faust and S. S. Goldich for differential thermal curves; and Michael Fleischer, S. S. Goldich, and R. E. Van Alstine for critically reading the manuscript.

DEPARTMENT OF GEOLOGY,
SAINT LOUIS UNIVERSITY,
SAINT LOUIS, MISSOURI,
June 1, 1948.

THE ORE DEPOSITION TEMPERATURE AND PRESSURE AT
THE MCINTYRE MINE, ONTARIO.

F. GORDON SMITH.

ABSTRACT.

The temperature and pressure during vein deposition at the McIntyre Mine were determined using electrical measurements of pyrite and the decrepitation temperature of quartz, pyrite, ankerite, and calcite. It was concluded that there were two separate stages of mineralization, the first extending over the range of 630° to 400° C at a depth of 10 kilometers, and the second at 150° C and at a much shallower depth. Variations of temperature of deposition of pyrite were found to be unrelated to depth in the mine and to individual veins, but were found to be related to the distance from the contact of the porphyry and the wall rock. A gradient of the mean temperature of deposition was found to be 14° C per 100 feet, from 500 feet within the porphyry to 500 feet outside the porphyry. The mineralization and the porphyry intrusives are closely related in space, time of emplacement and probably also in origin.

FOR somewhat over a year in this laboratory we have been developing techniques for determining the temperature and pressure of deposition of hydrothermal minerals, using data obtained from liquid inclusions and electrical measurements of pyrite. H. S. Scott¹ has recently described the decrepitation technique and the pyrite measurement method was outlined in 1947.² The determinations are so readily carried out that most of the graduate students in this department studying hydrothermal ore problems have calculated the temperature and depth of deposition of some vein minerals.

Recently, an excellent suite of ore specimens from the McIntyre Mine was made available for laboratory study through the efforts of the chief geologist, H. S. Robinson. The results of the tests are of considerable interest and illustrate the type of problems which can be solved using the new methods.

The McIntyre Mine is operated by the McIntyre Porcupine Mines Limited, and is situated near the town of Schumacher, Ontario. The geology of the mine has been described, in 1922, by the staff of the mine,³ in 1923 by H. S. Robinson,⁴ and in 1938 by G. B. Langford.⁵ In brief, the country rock consists of altered intermediate lavas intruded by quartz porphyry stocks and later by diabase dikes. The veins are composed principally of either quartz with a

¹ Scott, H. S., The decrepitation method applied to minerals with fluid inclusions: *ECON. GEOL.*, vol. 43, no. 8, pp. 637-654, 1948.

² Smith, F. G., The pyrite geo-thermometer: *ECON. GEOL.*, vol. 42, pp. 515-523, 1947.

³ Anon., Mining operations at the McIntyre Porcupine Mines, Limited: *Trans. Can. Inst. Min. Met.*, vol. 25, pp. 1-28, 1922.

⁴ Robinson, H. S., Geology of the Pearl Lake area, Porcupine district, Ontario: *ECON. GEOL.*, vol. 18, pp. 753-771, 1923.

⁵ Langford, G. B., Geology of the McIntyre Mine: *Amer. Inst. Min. Met. Eng.*, no. 903, pp. 1-19, 1938.