Investigations of Ferruginous Bauxite and Other Mineral Resources on Kauai and a Reconnaissance of Ferruginous Bauxite Deposits on Maui, Hawaii

GEOLOGICAL SURVEY PROFESSIONAL PAPER 656

Prepared in cooperation with the
State of Hawaii Department of
Land and Natural Resources Division
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U.S. DEPARTMENT OF THE INTERIOR
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Geology and origin of low-grade ferruginous
bauxite deposits on Kauai and Maui and of
construction materials and potential mineral
resources on Kauai

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INVESTIGATIONS OF FERRUGINOUS BAUXITE AND OTHER MINERAL RESOURCES ON KAUAI AND A RECONNAISSANCE OF FERRUGINOUS BAUXITE DEPOSITS ON MAUI, HAWAII

By SAM H. PATTERSON

ABSTRACT

Low-grade ferruginous bauxite deposits occur in the eastern part of Kauai. The bauxite has formed by weathering of basalt of the Koloa Volcanic Series. The deposits underlie old lava flow surfaces in interstream uplands. The bauxite consists chiefly of gibbsite, goethite, hematite, and titaniferous magnetite and contains minor halloysite-metahalloysite. Resources of ferruginous bauxite on Kauai are estimated to be 110 million tons containing an average of 25.9 percent Al_2O_3, 4.7 percent SiO_2, 39.4 percent Fe_2O_3, and 6.7 percent TiO_2. Washing out the -35-mesh material will upgrade the bauxite to 35–40 percent Al_2O_3, but the total recoverable bauxite would be reduced to about 30 million tons.

Large potential resources of aluminous saprolite, containing more than 10 percent SiO_2, are associated with the bauxite. This saprolite is similar to the bauxite in mineral content, except that halloysite is abundant. Potential resources of aluminous saprolite are about 500 million tons, containing an average of 27 percent Al_2O_3, 20 percent SiO_2, 27 percent Fe_2O_3, and 5 percent TiO_2.

Bauxite and saprolite formed by weathering of basalts chiefly by leaching by downward-percolating water. Water in weathered rocks ranges in pH from 4.0 to 5.9 and contains very little dissolved material. Water in fresh rock is higher in pH and contains significant quantities of dissolved silica, alkalies, and alkaline earths.

Ferruginous bauxite deposits in West Maui have formed on the Honolua Volcanic Series, and those in East Maui, on the Kula Volcanic Series. Deposits in East Maui contain an estimated 22 million tons averaging 33.4 percent Al_2O_3, 6.6 percent SiO_2, 31.4 percent Fe_2O_3, and 6.7 percent TiO_2. Deposits in West Maui may contain about 9 million tons of bauxite that is nearly 5 percent higher in Al_2O_3 and somewhat lower in Fe_2O_3 and TiO_2 than the bauxite in East Maui. Large deposits of aluminous saprolite occur in both East and West Maui.

Crushed basalt, volcanic cinder, beach sand, river sand and gravel, coral, and limestone for construction and road-building materials are the only local mineral resources used on Kauai. Small quantities of salt have been produced by evaporation of sea water. Plastic clay sufficiently low in iron to fire white or light gray occurs on the island but has not been used commercially. Small deposits of peat and gypsum probably are not in sufficient quantities and purity to be of much value. If the bauxite is ever mined, titanium and iron are potential coproducts of alumina.

INTRODUCTION

Detailed investigations of large deposits of low-grade ferruginous bauxite in the eastern part of Kauai and a reconnaissance of deposits on Maui, Hawaii (fig. 1), were made by the U.S. Geological Survey in cooperation with the State of Hawaii, Department of Land and Natural Resources, Division of Water and Land Development. The investigations were made in accordance with recommendations by J. B. Cathcart (1958) of the U.S. Geological Survey, who, with W. A. Calhoun (1958) of the U.S. Bureau of Mines, made a preliminary appraisal of Hawaiian bauxite resources and metallurgical problems. All work done by the U.S. Geological Survey and U.S. Bureau of Mines on Hawaiian bauxite, including a study of beneficiation problems and metallurgical testing (Calhoun and Hill, 1961, 1962, 1967), are parts of a program of research on Hawaiian bauxite initiated by Mr. Frank W. Hustace, former Commissioner of Public Lands, Territory of Hawaii. Support of the program was continued by Mr. C. Eric Reppun, who became commissioner shortly after Hawaii became a State in 1959; by Mr. E. H. Cook, Director, Hawaii Department of Land and Natural Resources; and by Mr. Robert T. Chuck, Manager-Engineer of the Hawaii Division of Water and Land Development.

Although this investigation was primarily an evaluation of the bauxite deposits, other possible mineral resources on Kauai were also considered; they include construction materials (the island's only min-

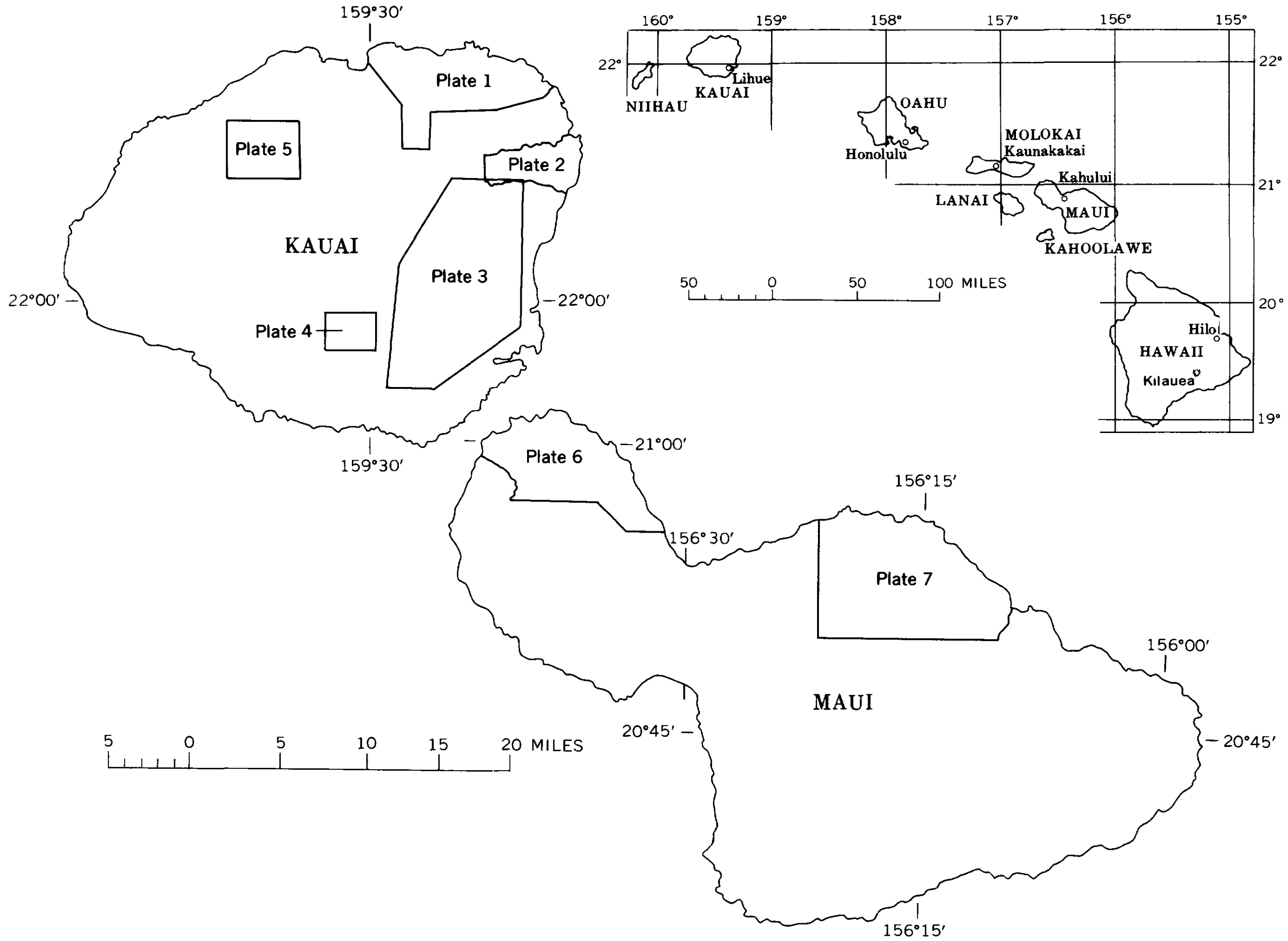


FIGURE 1.—Areas investigated on Kauai and Maui, Hawaii.

eral resources that are currently being used), iron, peat, plastic clay, salt, and titanium.

PREVIOUS WORK

The history of geologic investigations on Kauai, beginning with a visit by James D. Dana in 1840 and extending through the geologic mapping phase by the U.S. Geological Survey in cooperation with the Hawaii Division of Hydrography and the Hawaiian Sugar Planters Association, is outlined by Macdonald, Davis, and Cox (1960, p. 9–12). Their report includes earlier work by H. T. Stearns, who also is one of the authors of the geologic map in that report. Stearns (1946, 1966) also included discussions of the geology of Kauai in his reports on the entire State.

The high Al_2O_3 content of certain soils and weathered rocks of Kauai has been known since Maxwell (1898, p. 47) noted that "alumina is separating as masses having a remarkable degree of purity, exceeding that of bauxites of France and Ireland." Hinds (1929, p. 315) pointed out that some of the soils are similar to ferruginous bauxite in composition, and Sherman (1949, p. 314) concluded that "bauxite laterite" would be the end product of weathering in Hawaii. The first known positive identification of the bauxite mineral, gibbsite, on Kauai, was made by Tsuneo Tamura during research for a thesis at the University of Wisconsin; the first published information on gibbsite was given by Tamura, Jackson, and Sherman (1953). Publication of the information on gibbsite was followed by a period of intensive investigation by aluminum companies, which is described by Abbott (1958, p. 844) as follows:

> After a preliminary examination late in 1955 Reynolds Mining Corporation started an extensive exploration program on Kauai early in 1956. Shortly thereafter, Kaiser Aluminum and Chemical Corporation, Oregon Bauxite Company, and Olin Mathieson Company entered into exploration activities in the Islands. The exploration work continued until the end of 1957.

Other reports dealing with bauxite on Kauai include papers by Sherman (1954, 1958); Cathcart (1958); Calhoun (1958); Holmes, Takahashi, and Sherman (1960); Calhoun and Hill (1961, 1962, 1967); preliminary reports of the present investigation (Patterson, 1962, 1963); and a discussion by Allen and Sherman (1965).

Information related to the bauxite deposits is contained in the extensive literature on soils, soil formation, and weathering processes. This literature includes articles by Hough and Byers (1937); Hough, Gile, and Foster (1941); Sherman (1949, 1950, 1952, 1957); Sherman, Cady, Ikawa, and Blomberg (1967); a detailed report including soil maps of Kauai and Maui by Cline and others (1955); and a discussion of weathered rock and associated ground water by Patterson and Roberson (1961).

A brief description of the plastic clay in one bog on Kauai was given by Wentworth, Wells, and Allen (1940, p. 11–13), whose investigations were concerned chiefly with the Koolau clay on Oahu. The Kauai clays were described in more detail by Patterson (1962, p. 42–56; 1964).

A gravity survey of Kauai was made by Krivoy, Baker, and Moe (1965) of the U.S. Geological Survey. The littoral sedimentary processes on the island were investigated by Inman, Gayman, and Cox (1963).

Investigations of the weathering of volcanic rocks in other regions are helpful in understanding the geology of bauxite in Hawaii. A comparison of Hawaii and Oregon bauxites has been drawn by Allen and Sherman (1966); and Kear, Waterhouse, and Swindale (1961) have pointed out several similarities in characteristics between Hawaii and New Zealand bauxites. Bauxite in Ireland (Eyles and others, 1952) formed from basalts of a composition similar to that of the parent rocks of bauxite in Hawaii, and the two types of deposits are similar in several respects. The weathering of rocks in Hawaii involves changes similar to those taking place in rocks of volcanic origin on Guam (Carroll and Hathaway, 1963); in Japan (Aomine and Wada, 1962); on Norfolk Island (Hutton and Stephens, 1956); and in New South Wales, Australia (Nicolls and Tucker, 1956; Carroll and Woof, 1951; Craig and Loughnan, 1964). The alteration of andesitic rocks in northeastern California during weathering (Hendricks and others, 1966, 1967; and Hendricks and Whittig, 1968a, b) is also similar to that taking place in Hawaii.

METHODS OF INVESTIGATION

Field investigations in Hawaii, from July 1, 1959, to July 1, 1961, were confined to Kauai, except for reconnaissance on Maui in June and July 1960. Field work consisted principally of drilling with a jeep-mounted 4-inch-diameter power auger, but a few holes were drilled by hand. A total of 495 power-augered holes and 44 hand-augured holes, aggregating 17,639 feet, were augered on Kauai. During reconnaissance on Maui, 42 holes, the total depth of which was 1,208 feet, were augered. Logs of all holes are given by Patterson (1962). Locations of the holes on Kauai are shown on plates 1–5; those on Maui are shown on plates 6 and 7.

Chemical analyses of the samples collected were done by rapid methods described by Shapiro and Brannock (1956); partial analyses were done by X-ray fluorescence; and determinations of the minor elements in 28 samples were made by semiquantitative spectrographic analyses. This analytic work was done in laboratories of the Geological Survey at Washington, D.C., and Beltsville, Md.

Mineralogic studies included (1) identification of the minerals in about 500 samples, by the author and his assistants, using X-ray diffraction methods; (2) investigation of the minerals in eight samples by J. C. Hathaway and in two samples by E. J. Dvornik, using the electron microscope; (3) examination of 30 thin sections, using the petrographic microscope; (4) mineral identification in 300 samples, using laboratory differential thermal analysis; and (5) mineral identification in about 2,500 samples, using portable differential thermal analysis techniques similar to those described by Parker, Hathaway, and Blackmon (1956). The portable differential thermal analysis work (Patterson, 1962) was done in the field laboratory near Lihue, Hawaii, and the results were used in determining the extent of the bauxite and clay deposits (pls. 1–7).

Remanent magnetism of basalt core samples was determined with a magnetometer, a technique described by Doell and Cox (1965). Oriented samples for these measurements were taken by drilling 1-inch-diameter core with a small portable diamond drill.

Several techniques were used in preparing the maps of the ferruginous bauxite and clay deposits (pls. 1–7). Aerial photographs were particularly useful in plotting bauxite deposits and auger-hole locations in the field, because interstream uplands, field roads, and other features are discernible in stereoscopic image. At the time the fieldwork was done, the only topographic map available for Kauai, the 1911 edition by the U.S. Geological Survey, was an inadequate base on which to plot the information from the aerial photographs. Maps locating the principal bauxite deposits were therefore prepared for the preliminary report from orthophoto mosaics (Patterson, 1962, pls. 1, 3). Maps of a small bauxite area and two plastic clay districts were prepared from aerial photographs by means of a Kelsh plotter. Advanced copies of 7½-minute quadrangle topographic maps by the U.S. Geological Survey became available after the preliminary report was released, and these maps were used as bases for plates 1–5. The maps for Maui (pls. 6, 7) were compiled from published 7½-minute quadrangle maps.

Fieldwork was conducted with the assistance of Melvin Nakamura, from August 1959 to January 1960, and Raymond S. Fajardo, from January 1960 to June 1961. Thomas A. Hahn and Robert M. Bromery assisted in preparation of the maps and in calculating the resources. John W. Hosterman identified the mineral constituents of about 100 samples; J. H. Jolly and William M. Turner assisted the author in some of the other mineralogic and analytic work. All the personnel mentioned above did the work while employed by the U.S. Geological Survey.

DEFINITIONS OF TERMS

Saprolite.—Saprolite is soft, decomposed rock in which nearly all the original minerals have been replaced by secondary minerals, but in which most of the original textures and structures have been preserved.

Ferruginous bauxite.—Ferruginous bauxite includes soil and saprolite rich in Fe_2O_3 and Al_2O_3 and containing 10 percent SiO_2 or less. This usage is a modification of the term "bauxite" as commonly used. However, Corcoran and Libby (1956, p. 4) have previously applied the term "ferruginous bauxite" to similar grade rock, and they cite Eyles, Bannister, Brindley, and Goodyear (1952) for a precedent in the usage of this term. Weathered basalt in New Zealand, which is similar to the deposits in Hawaii, in both grade and mineral composition, has also been referred to as bauxite (Kear and others, 1961).

Resources and potential resources.—The term "resources" is used for deposits that are classed as submarginal, and "potential resources" are those which are low grade and must await new improvements in technologies before they can be mined and processed profitably. Ferruginous bauxite is considered a submarginal resource, because alumina can be extracted by modification of presently used processes, and the time when material of this grade can be processed profitably may be approaching. The plastic clay is also considered a resource, because it too could be used, though not competitively with similar material from other sources. Aluminous saprolite, iron, and titanium are classed as potential resources, because their exploitation would require major changes in the current methods of extracting these metals.

Planeze.—This term applies herein to erosional remnants of original constructional surfaces of volcanic cones or shields, as it is used in New Zealand (Kear and others, 1961, p. 21, 32–34, fig. 10) and in the European literature. Planezes in Hawaii are gently sloping flat-topped uplands, commonly separated by deeply incised valleys.

Many lava flows that form planezes on Kauai and Maui can be traced upslope to their sources. However, some planezes on both islands are so dissected or remote from vents that their sources cannot be identified.

ACKNOWLEDGMENTS

Considerable time and effort were saved because information on the geology and metallurgy of the Kauai deposits was supplied by Mr. Malcom G. Bennett, Chief Geologist, Olin Mathieson Chemical Corp. Dr. G. Donald Sherman of the University of Hawaii contributed many ideas and much information that aided the field studies; he also generously permitted the use of field laboratory space on Kauai assigned to his department. Dr. Thomas F. Bates of Pennsylvania State University and Dr. Robert M. Grogan of Wilmington, Del., gave advice concerning geologic problems. Dr. John D. Cady of the U.S. Department of Agriculture and F. R. Fosberg, Dan A. Davis, and Richard R. Doell of the U.S. Geological Survey visited the author in the field, and each contributed many helpful suggestions regarding the geology and problems related to weathering of rocks on Kauai. Dr. Gordon A. Macdonald of the University of Hawaii, who was the senior author of the most thorough report on the geology of Kauai (Macdonald and others, 1960), aided in several ways, including advice in preparing this report. Dr. Delvin S. Fanning of the University of Maryland discussed problems related to weathering with the author on several occasions, which led to improvements in this report. Mr. Robert T. Chuck (written commun., Jan. 9, 1968) of the Hawaii Department of Land and Natural Resources supplied information on the sources of construction materials that were developed after the fieldwork was completed.

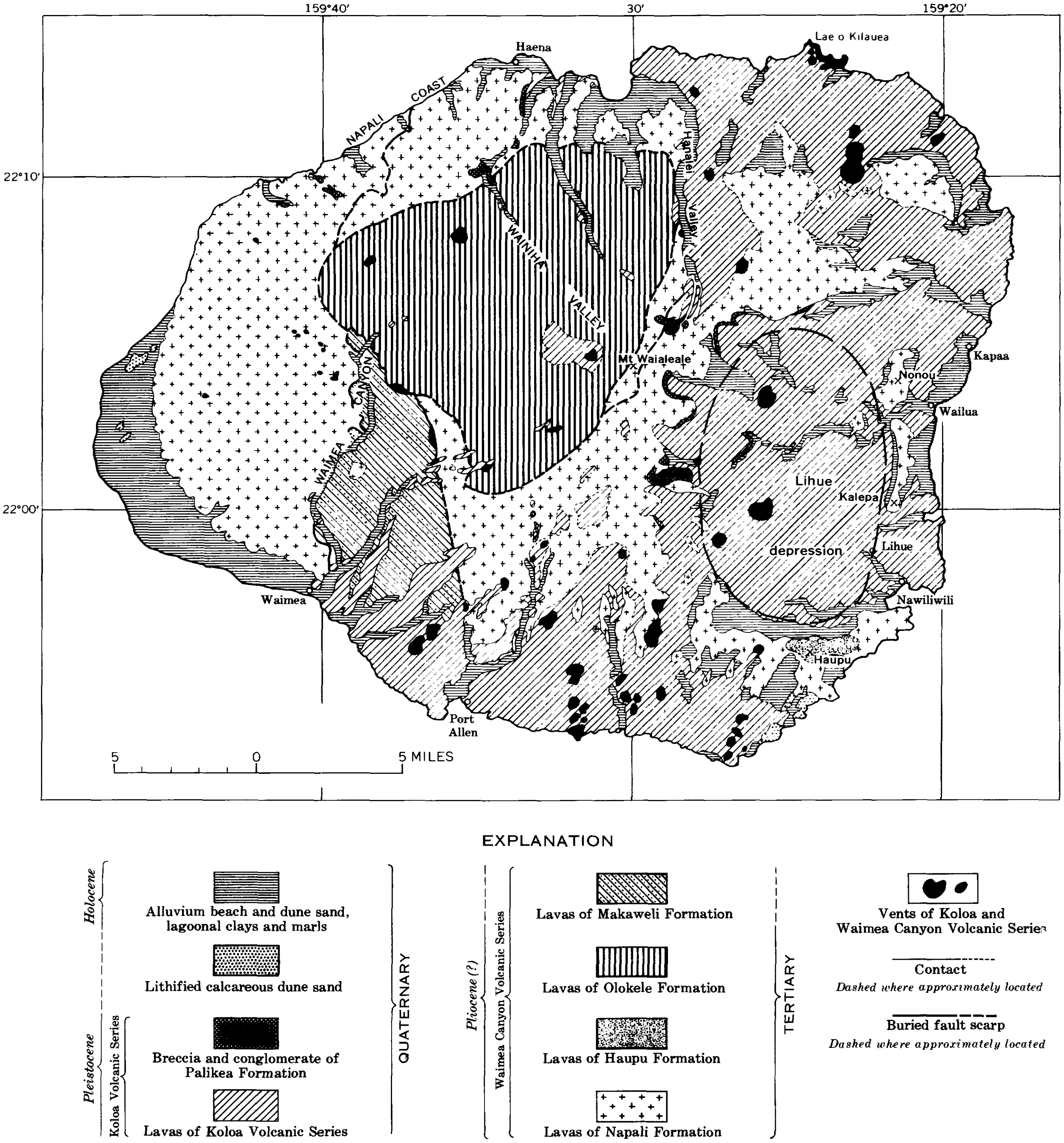


FIGURE 2.—Generalized geologic map of Kauai, Hawaii. Modified from Macdonald, Davis, and Cox (1960, p. 18).

Landowners and representatives of the plantations on Kauai were very cooperative. Mr. Keith B. Tester, Mr. David Silver, and Mr. Henry Wedemeyer of Lihue Plantation Co., Ltd.; Mr. John B. Humme of Hawaiian Canneries Co., Ltd.; Mr. Dorsey Edwards of Hawaiian Fruit Packers Co., Ltd.; Mr. William M. Moragne of Grove Farm Co., Ltd.; Mr. Wayne Gregg of Kauai Pineapple Co., Ltd.; Mr. Arthur H. Shaw of Kilauea Sugar Co., Ltd.; Mr. Frank C. Churchill of McBryde Sugar Co., Ltd.; Mr. Lester B.

Robinson, Mr. Valdemar Knudsen, Mr. J. H. Betencourt, and several owners of small farms gave permission to auger on their properties on Kauai. Access for augering on Maui was granted by Mr. William W. Girton of Libby, McNeill & Libby Co.; Messrs. Robert Bruce and Richard Taylor of the East Maui Irrigation Co., Ltd.; Messrs. Richard Cox, Bruce L. Fleming, and David A. Fleming of Baldwin Packers Co., Ltd.; and several farmowners.

FERRUGINOUS BAUXITE AND OTHER MINERAL RESOURCES ON KAUAI

LOCATION AND TOPOGRAPHY OF KAUAI

Kauai (lat 21°52′ N. to 22°41′ N.; long 159°17′ W. to 159°48′ W.) lies within the tropic zone, 1°13′ south of the Tropic of Cancer; it is the northwesternmost of the five major islands of the Hawaiian Archipelago. The island is nearly circular, and has a

TABLE 1.—*Stratigraphic units on the island of Kauai*

[Modified from Macdonald, Davis, and Cox (1960, table p. 20–21)]

Age	Major geologic unit	Rock assemblage		Thickness (feet)	General character
Holocene	Sedimentary deposits	Beach sand		5±	Loose sand, composed chiefly of fragments of calcareous algae, corals, mollusk shells, and skeletons of foraminifers.
		Unconsolidated calcareous dunes		10–100	Loose cream-colored crossbedded sand blown inland from the beaches and composed of the same materials.
		Younger alluvium		5–200	Unconsolidated earthy deposits consisting of loose, poorly to moderately well sorted stream-laid gravel, sand, and silt.
		Local erosional unconformity			
Pleistocene	Sedimentary deposits	Noncalcareous sediments	Lagoon deposits of Mana plain	----------	Poorly consolidated earthy and marly sediments accumulated in a lagoon between the volcanic rocks and the beach ridge.
			Older alluvium	100±	Poorly consolidated to well-consolidated earthy deposits consisting of stream-laid gravel, sand, and silt.
		Consolidated calcareous dune sand		10–100	Moderately cemented to well-cemented crossbedded calcareous sand blown inland from beaches during former lower stands of sea level.
		Local erosional unconformity			
	Volcanic rocks and associated sedimentary rocks	Koloa Volcanic Series	Tuff cone at Kilauea Bay	350±	Moderately indurated to well-durated palagonite tuff containing fragments of basaltic rocks and calcareous reef rock.
			Ash and tuffaceous soil beds	1–10	Fresh to highly decomposed ash and cinder intercalated with lava flows of the Koloa Volcanic Series.
			Cinder cones	25–250	Heaps of fresh to highly decomposed cinders at vents of lava flows of the Koloa Volcanic Series.
			Palikea Formation	2–700	Masses of poorly sorted breccia and beds of poorly to moderately well sorted conglomerate at the base of, or intercalated with, rocks of the Koloa Volcanic Series.
			Lava flows	1,000±	Aa and pahoehoe lava flows of nepheline basalt, melilite-nepheline basalt, picrite basalt, olivine basalt, and basanite.
?			MAJOR EROSIONAL UNCONFORMITY		
Pliocene(?)	Volcanic rocks and associated sedimentary rocks	Waimea Canyon Volcanic Series	Makaweli Formation, including Mokuone Member	1,500+ (Makaweli Formation proper); 0–1,000 (Mokuone Member.)	Aa and pahoehoe lava flows of olivine basalt, basalt, and picrite basalt accumulated in a graben on the southwest side of the major Kauai shield volcano. Mokuone Member, masses of poorly sorted breccia along the contact of lavas of the Makaweli Formation with the older rocks, and beds of moderately well sorted conglomerate intercalated with lavas of the Makewali Formation.
			Haupu Formation	1,850+	Massive flows of olivine basalt and picrite basalt accumulated in a small caldera on the southeast slope of the major Kauai shield volcano.
			Olokele Formation	2,600+	Thick, massive flows of olivine basalt, basalt, and picrite basalt accumulated in a broad caldera at the summit of the Kauai shield volcano.
			Napali Formation	2,700+	Thin flows of olivine basalt, basalt, and picrite basalt accumulated on the flanks of the Kauai shield volcano.

maximum length of 33 miles, a width of 25 miles, and an area of 555 square miles. Kawaikini Peak (alt 5,170 ft) in the central mountains is the highest point on Kauai, and Mount Waialeale, 1 mile to the north, rises to an altitude of 5,080 feet. The central mountains are surrounded by a belt of lowlands on all but the Napali Coast on the northwest side of the island. Of the total area, 198 square miles is below an altitude of 500 feet, and 305 square miles, or more than half of the island, is below 1,000 feet altitude (Macdonald and others, 1960, p. 5). The mountains are cut by deep canyons, the best known of which is the 2,600-foot-deep Waimea Canyon. A summit plateau between the heads of canyons on the northwest slope of the central mountains is an area of dense vegetation containing scattered patches of open marshland; this plateau area is called the Alakai Swamp.

GENERAL GEOLOGY

The geology of Kauai has been investigated by Stearns (1946) and Macdonald, Davis, and Cox (1954, 1960), and the following very generalized discussion is based on their reports. Kauai, one of the oldest and most geologically complicated of the Hawaiian Islands, is the top of a large volcanic shield built up of thousands of thin flows of basaltic lavas that now extend nearly 20,000 feet above the ocean floor; the entire shield contains about 1,000 cubic miles of volcanic rock. The Waimea Canyon Volcanic Series (fig. 2) forms the core and major part of the shield that is above sea level. Accumulation of the flows that form this series was followed by a long period of erosion—during which streams cut canyons as much as 3,000 feet deep, and thick mantles of soil and saprolite formed on the uplands. When volcanism was renewed, a group of flows called the Koloa Volcanic Series, which is as much as 2,100 feet thick (Stearns, 1966, p. 202), originated from minor vents scattered throughout the eastern two-thirds of Kauai. Koloa flows filled valleys, depressions, and lowlands to a considerable depth, but rocks of the Waimea Canyon Volcanic Series in rugged highlands—such as Nonou Mountain and Kalepa, Aahoaka, and Haupu Ridges in the eastern part of Kauai—were not blanketed by these younger flows. The accumulation of flows of the Koloa Volcanic Series took a very long time, and periods of volcanism were interrupted by periods of quiescence that were sufficiently long for streams to reexcavate some of the canyons filled by earlier flows and for weathering to form soils later buried by younger flows. The stratigraphic relation of the two volcanic series and younger rocks on Kauai are shown in table 1.

A very large caldera and a smaller one in the Waimea Canyon Volcanic Series have been recognized (Stearns, 1966, p. 190–191); the Koloa Volcanic Series erupted from many vents (Macdonald and others, 1960, fig. 16). The large caldera, about 12 miles long and 10 miles wide, occupies the main mountain mass of Kauai. This caldera is filled by horizontally bedded lavas of the Olokele Formation (fig. 2); their maximum exposed thickness is 2,600 feet. The smaller caldera is exposed in Haupu Ridge and is filled by the Haupu Formation (fig. 2). This caldera is about 2.6 miles long and 1 mile wide and is at a much lower altitude than the main caldera. Macdonald, Davis, and Cox (1960, fig. 16) identified 45 vents of the Koloa Volcanic Series (most of which are shown in fig. 2) and indicated the hypothetical location of eight more vents which they thought must have existed. Two additional vents were found during the present investigation; one is located 5.6 miles due west of the Lihue, and the other is 1.5 miles east of the upper reaches of the Hanalei River (fig. 2). This second vent is in an area where Macdonald, Davis, and Cox had hypothesized one should be located.

Age determinations by magnetism and potassium-argon techniques agree in a general way with the Pleistocene age assigned to the Koloa Volcanic Series and Pliocene age assigned to the Waimea Canyon Volcanic Series by Macdonald, Davis, and Cox (1960, p. 18, 29–31). During fieldwork for the present report, reconnaissance studies of the magnetism of rocks in both series were conducted by R. R. Doell of the U.S. Geological Survey, and investigations of the magnetism of hard basalt associated with the ferruginous bauxite were made by the author. The magnetism of rocks in the Napali Formation, the oldest formation of the Waimea Canyon Volcanic Series, was found to be normal and that of the Makaweli Formation, the youngest formation of the same series, is reversed with respect to the polarity of the earth's present field. Rocks in the lower (older) part of the Koloa Volcanic Series are magnetically reversed, and those in the upper (younger) part of the same series are normal (R. R. Doell, written commun., Apr. 30, 1962). Inasmuch as the last reversal of the earth's magnetic field has been dated by Cox, Doell, and Dalrymple (1964, p. 1542) and Doell and Dalrymple (1966, p. 1061) as occurring 0.7 m.y. (million years) ago (estimated to be within 0.05 m.y. accuracy limits), the lower part of the Koloa Series is older than this date, and the upper part is younger. The conclusion that the lower part of the Koloa Series is older than 0.7 m.y. is confirmed by McDougall (1964, p. 112), who, using the potassium-argon technique, found that one sample from this series is 1.41–1.43 m.y. old. More than one interpretation can be made for the ages of the magnetically reversed Makaweli Formation and the magnetically normal Napali Formation of the Waimea Canyon Volcanic Series. However, one probable period of reversal of the earth's magnetism, from about 3.4 to about 4 m.y. ago (Cox and others, 1964, fig. 3), may have been the period during which the Makaweli Formation accumulated. This age conforms with the 3.53– to 4.05-m.y. age range obtained by McDougall for samples from this formation. McDougall's (1964) potassium-argon ages of the Napali Formation range from 4.47 to 5.72 m.y., and his results imply that the erosional interval resulting in the unconformity between the Koloa and the Waimea Canyon Volcanic Series possibly lasted for as long at 2 m.y.

The Lihue depression (fig. 2), the principal structural feature in the area investigated, is a subcircular basin about 11 miles in longest dimension. It is filled by flows of the Koloa Volcanic Series and surrounded by a discontinuous rim of rocks of the Waimea Canyon Volcanic Series. This depression is bounded on the south by Haupu Ridge, on the east by Kalepa Ridge and Nonou Mountain (pl. 3), on the north by the Makaleka Mountains, and on the west by the central mountains. Three vents of the Koloa Series—Kilohana Crater, Hanahanapuni cinder cone, and an unnamed vent west of Lihue—occur within the depression.

The origin of the Lihue depression has been the subject of much discussion among geologists. Hinds (1930, p. 79) advocated caldera collapse for its origin, chiefly on the basis of its circular outline. Stearns (1946, p. 89) expressed the idea that stream erosion could have excavated the basin. Macdonald, Davis, and Cox (1960, p. 95) pointed out the north-south trend of Kalepa Ridge and Nonou Mountain is at right angles to the trend of ridges formed by stream erosion, and they favor the caldera collapse theory with some modification by stream erosion. Krivoy, Baker, and Moe's (1965) reconnaissance gravity survey indicates the presence of a dense intrusive body below most of the depression. The position of this dense body seems to favor the caldera collapse idea. At present, the weight of opinion is on the side of the caldera collapse idea, but the origin of the Lihue depression is far from being fully understood.

Most rocks in the Waimea Canyon and the Koloa Volcanic Series are similar petrographically, but they have significant structural and textural differences. The Waimea Canyon Series is almost entirely olivine basalt, but it contains minor amounts of basalt poor in olivine, picrite basalt rich in olivine, and basaltic andesite. These rocks consist chiefly of plagioclase, pyroxene, olivine, and magnetite. Most of the Koloa Series is olivine basalt and picrite basalt of the mimosite type, and the mineral composition of these rocks is similar to that of the Waimea Canyon Series. Koloa rocks in several areas, however, are undersaturated with silica, and melilite and nepheline occur in place of plagioclase. Olivine phenocrysts are generally much smaller and darker in the Koloa rocks than in the Waimea Canyon. The Waimea Canyon Series consists chiefly of thin highly vesicular flows; Koloa rocks are mostly thick massive flows and commonly are much finer grained than those of the older series.

The youngest rocks on the island are sedimentary accumulations of alluvium, beach and dune sand, and lagoonal clays and marls. Much of the alluvium consists of gravels and weathered debris that have accumulated on the lower flanks of highlands. The calcareous beach and dune sand deposits occupy the lower stream valleys and coastal lowlands. The largest lagoonal deposits are in the western part of the island where they form a low flatland, the Mana Plain, which is as much as 2 miles wide and 10 miles long. The lagoonal deposits consist chiefly of coarse shells and skeletal remains and fine-grained calcarous sediments; locally, however, they contain very fine grained material that is chiefly gypsum.

SAPROLITE AND SOIL

Most areas in the eastern part of Kauai that have heavy rainfall are blanketed by a mantle of red, brown, and brownish-gray deeply weathered rock, commonly about 60 feet thick but ranging in thickness from a few feet to as much as 125 feet. Most of this rock is saprolite altered from basalt—except for the uppermost thoroughly weathered layers (A and B soil horizons), a few buried soils, scattered zones of altered volcanic ash, and plastic clay deposits. Structures preserved in the saprolite include flow contacts, joints, and vesicles (fig. 3); preserved textures are chiefly the interlocking grains inherited from the parent basalt (pl. 8). Spheroidally rounded residual boulders of hard basalt enclosed by concentric exfoliated layers of saprolite (fig. 4), represent an incomplete stage in the progress of weathering toward the centers of joint blocks; they are abundant at depth, but decrease in number upward and are rare at the surface, except in scattered areas of incompletely weathered young flows. The residual boulders and concentric exfoliated layers are similar to those on Oahu described by Chapman and Greenfield (1949). The typical saprolite is sufficiently soft to be easily removed with a pick, and it erodes rapidly where protective vegetation has been removed. It is sufficiently cohesive to stand in steep hillsides and roadcuts without sliding, but wet auger cuttings of the saprolite are very plastic or fluid. The A soil horizon, which is rarely as much as 1 foot thick, and the underlying B horizon, which ranges in thickness from 0 to 5 feet and is generally about 3 feet thick, have both been weathered so thoroughly that saprolite textures are destroyed. Lumps and chunks of saprolite, however, do persist even in the A soil horizon, and at places the B horizon is nearly all saprolite and is distinguished from the underlying saprolite principally by color differences. The saprolite below the B horizon corresponds approximately to the C horizon, but it is as much as 125 feet thick and may be too thick to be considered a soil horizon.

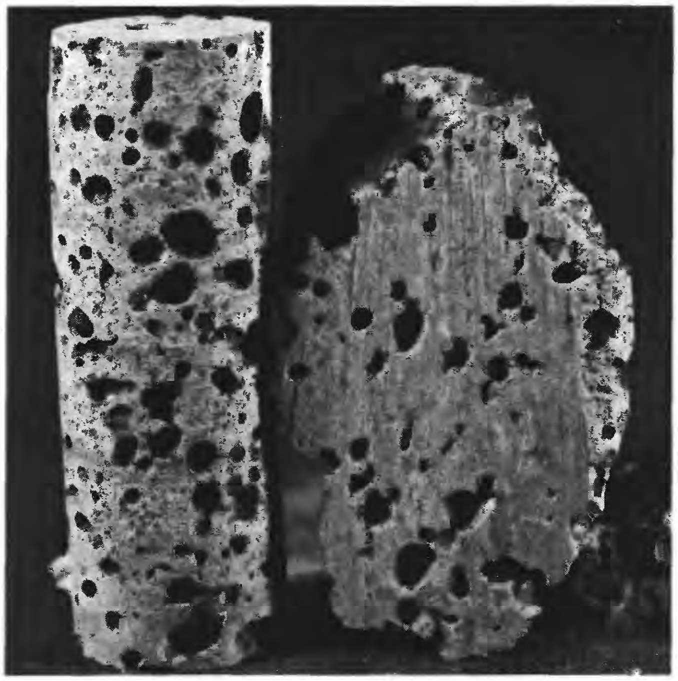


FIGURE 3.—One-inch-diameter core of fresh basalt from a residual boulder and a chunk of saprolite weathered from the same flow, exposed in cut of Highway 56, 1.6 miles south of bridge at Anahola.

FIGURE 4.—Residual boulder of hard basalt enclosed by concentric layers of saprolite, exposed in cut along field road approximately 0.2 mile north of Kapaia Reservoir.

The soil and upper parts of the saprolite are so porous that ordinary rainfall is absorbed, and surface runoff takes place only during very heavy storms or when gentle rains fall for long periods. Below depths of 20–50 feet the presence of abundant clay minerals in the saprolite reduces permeability, impedes ground-water movement, and causes ephemeral perched water tables. In most places the saprolite is more permeable than the underlying hard rock, and a second zone of perched water is commonly present in the lower part of the saprolite. In areas of poor drainage, the permanent water table is very near the surface.

MINERAL CHARACTER OF THE SOIL AND SAPROLITE

The minerals discussed in this section, except where otherwise noted, are those occurring in soil and saprolite formed on the Koloa Volcanic Series in areas of good surface and subsurface drainage. Somewhat different minerals form the deposits in swampy areas, and those minerals will be discussed in the section on plastic clays. Amorphous inorganic material is not mineral because it is noncrystalline, but it is intimately associated with the minerals that form the saprolite, and organic matter in the soil, and saprolite will be discussed in this section.

Many minerals other than those of igneous origin in the parent volcanic rock occur in weathered rock, and only a few minerals of the parent rock are sufficiently resistant to remain within the most thoroughly weathered soil and saprolite. The greatest number of new minerals occur in the less thor-

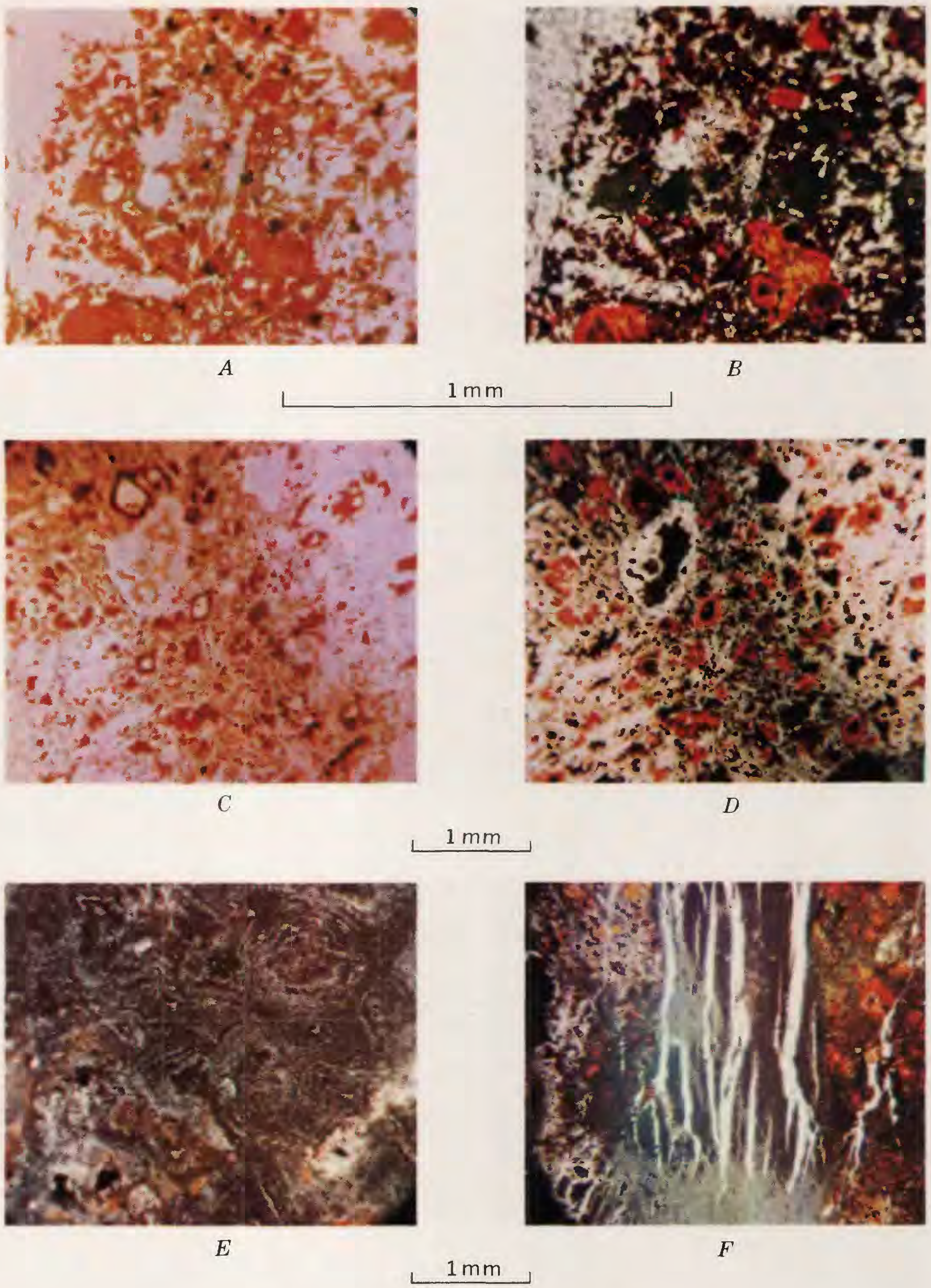
PLATE 8

A, *B*. Thoroughly weathered reddish-brown saprolite. *A*, polarized light; *B*, crossed polarizers. Round white areas in *A*, which are black in *B*, are vesicles; other white areas are gibbsite; lath-shaped grains are pseudomorphs after feldspar; finely granular white gibbsite is chiefly a replacement of pyroxene. Brownish-orange areas in *A* (black in *B*) are chiefly a mixture of goethite and hematite. Reddish brown in *B* is glassy goethite forming rim of pseudomorph after olivine. Yellowish-brown open-textured goethite replacing internal parts of olivine crystals. Sample from prospect pit on east rim of Kilohana Crater.

C, *D*. Same sample as *A*. *C*, polarized light; *D*, crossed polarizers. White and brown oval mass above and to left of center is a mixture of goethite and gibbsite filling a vesicle.

E. Gibbsite nodule showing involute, interlaminated growth structures of pure white gibbsite and gibbsite contaminated with iron oxide, halloysite, and anatase; crossed polarizers. Nodule from exposures in cut along powerline trail, 2.9 miles south of Princeville Ranch headquarters.

F. Vein deposit in saprolite close to fresh rock; crossed polarizers. Lithiophorite (black) intergrown with halloysite (light-gray) and gibbsite (white). Sample from cut on powerline trail, 7.3 airline miles south of Princeville Ranch headquarters.



PHOTOMICROGRAPHS OF THIN SECTIONS OF SAPROLITE, A GIBBSITE NODULE, AND VEIN DEPOSIT, KAUAI

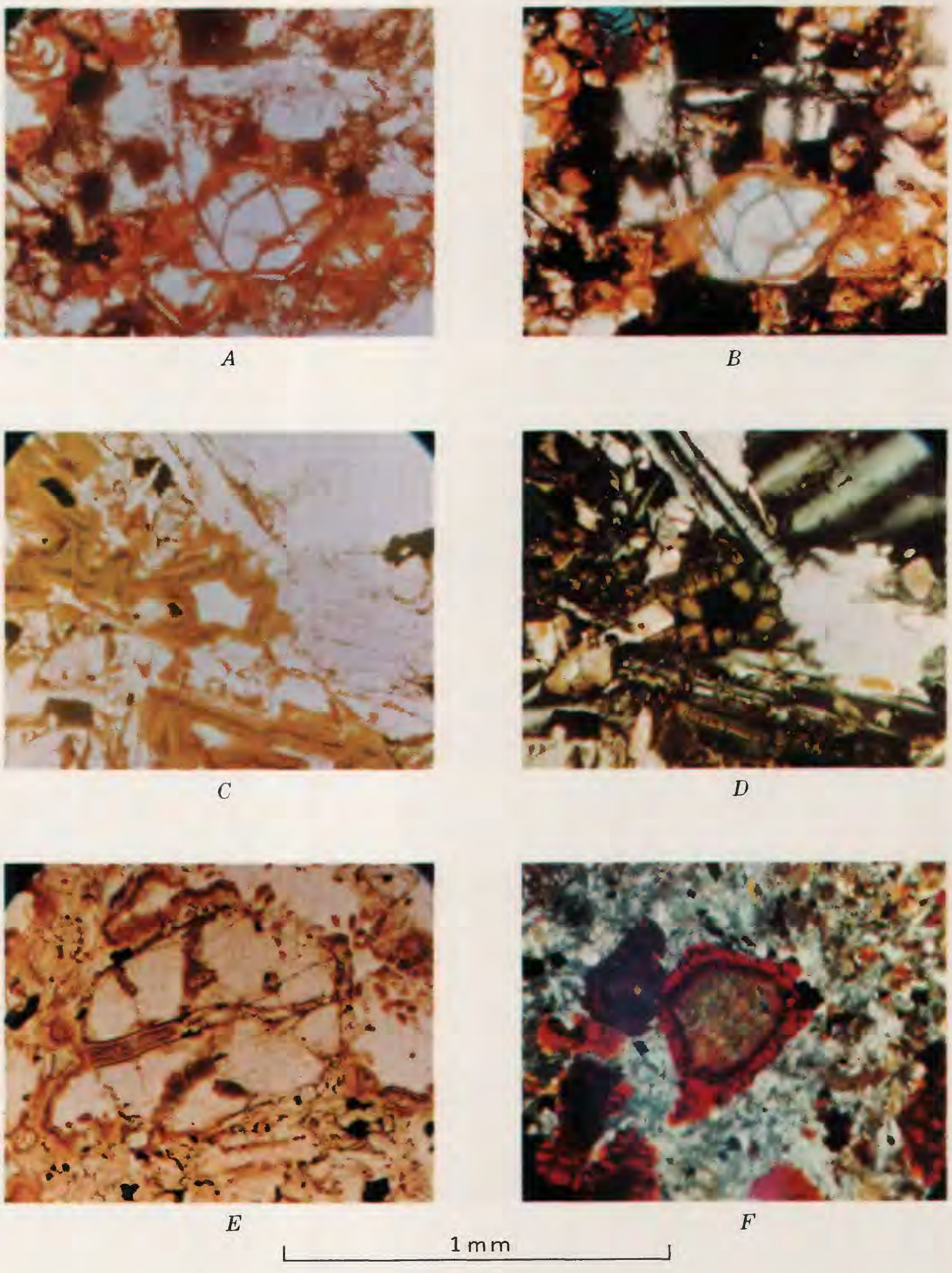
PLATE 9

A, *B*. Partly weathered basalt in polarized light *(A)* and crossed polarizers *(B)*. Black grains are magnetic. Brown is goethite and iron-oxide replacement of olivine. The dark material along internal cleavage planes in feldspar laths in *B* is probably amorphous. Sample is from residual boulder exposed in cut in field road, 1.5 miles southeast of Hanahanapuni.

C, *D*. Brown nontronite coating vesicle; *C*, polarized light; *D*, crossed polarizers. Sample is from residual boulder exposed along the powerline trail, 0.4 mile south of the South Fork Wailua River (pl. 3).

E. Brown nontronite is replacing large crystal of olivine; polarized light. Section cut from same boulder as in *C*.

F. Red glassy goethite replacing outer parts of olivine crystal; brown feltlike centers of olivine crystals are iron-stained antigorite; crossed polarizers. Sample is from residual boulder exposed in cut along Highway 56, 1.4 miles north of bridge over Anahola Stream.



PHOTOMICROGRAPHS OF PARTLY WEATHERED BASALT FROM THE KOLOA VOLCANIC SERIES, KAUAI oughly weathered rock. Several of these are unable to withstand severe weathering; thus, the most thoroughly weathered rock consists of only a few mineral species. All minerals formed by weathering of igneous rock are referred to in this report as "secondary minerals."

Most secondary minerals have formed by processes related to weathering at surface temperatures, but some in this group may have formed in the presence of water at temperatures higher than those at the surface. Warm or hot water cannot be ruled out as a possible influence on all secondary mineral formation because some of these minerals occur only at depth or in rocks that were once buried. Any buried rock on Kauai could have been host to subsurface water heated by younger lava flows or related volcanic activity. The lack of evidence for baking below lava flows and the general absence of secondary minerals in the vicinities of modern volcanism on the island of Hawaii suggest that the influence of heated water is of minor importance in their formation. Nevertheless, secondary minerals that may have formed in the presence of heated water include lithiophorite, "swelling chlorite," the zeolite minerals, some of the carbonate minerals, and some of the montmorillonite in the quarry west of Puhi. Virtually all minerals in the thoroughly weathered rock —except for magnetite and ilmenite which are residual from the parent rock—are the products of weathering and formed at surface temperatures. Those which occur in residual boulders or associated partially weathered rock near the surfaces of planezes, which therefore are unlikely to have been influenced by heated water, include antigorite, nontronite, calcite, and siderite.

MINERALS IN LESS THOROUGHLY WEATHERED ROCK

ANTIGORITE

Small quantities of the serpentine mineral, antigorite, $Mg_6(Si_4O_{10})(OH)_8$, are an alteration product of olivine. Antigorite forms in some olivine crystals before the rock loses its hardness and persists locally in the saprolite until fairly advanced stages of weathering are reached. The mineral occurs chiefly at depth and is generally more common as hard rock is approached. No antigorite was identified in any rock that is sufficiently rich in Al_2O_3 to be considered bauxite; however, small quantities are difficult to identify, and sufficient quantities to account for the very small amounts of MgO in the bauxite (table 2) may be present. Antigorite is difficult to identify because it forms such a small part of the total saprolite, occurs as minute grains, is ordinarily iron stained, and invariably is closely associated with halloysite-metahalloysite from which it is not easily distinguished. Even the X-ray reflections of antigorite and metahalloysite are similar; however, the (001) reflection at 7.29 A and a prominent one at 3.62 A for antigorite (pl. 10*Ag*) are much stronger and less diffuse than any corresponding reflections for metahalloysite. Thus, using this criteria, antigorite is recognizable in diffraction traces of hand-picked pseudomorphs of olivine. In thin section (pl. 9*F*), antigorite has a feltlike microtexture and is brown because of iron impurities. The close association of antigorite with iron minerals is also shown by the prominent reflections for goethite in the X-rayed specimen (pl. 10*Ag*).

CARBONATE MINERALS

Small quantities of aragonite ($CaCO_3$), calcite ($CaCO_3$), and siderite ($FeCO_3$) occur in hard basalt as veins and crystal coatings on the walls of vesicles and cracks. Aragonite is commonly in clusters of fine acicular crystals. Both calcite and siderite commonly occur as semispherical spherulites on the walls of vesicles. These spherulites have a vitreous pearly luster, and are known as "Pele's pearls" (Stearns, 1966, p. 228) after the Hawaiian goddess of fire. The occurrence of the carbonate minerals indicates that they were deposited by ground water, and their wide distribution and lack of relation to volcanic vents suggest crystallization at normal temperatures. However, warm ground water in the late stages of volcanic activity may have been the transporting agent of some of the carbonate. The carbonate minerals rarely remain after the hard rock alters to saprolite; calcite and aragonite generally are leached completely, and the iron in siderite is converted to goethite or hematite.

LITHIOPHORITE

Lithiophorite $(Li,Al)MnO_3 \cdot H_2O$ occurs in minor quantities as black films and veinlets along joints in saprolite at depth and is present near the surface only at those localities where the saprolite is not thoroughly weathered. Samples identified as lithiophorite were collected from a fresh roadcut along Highway 56, about half a mile north of Anahola Stream and in a freshly bulldozed cut excavated along the powerline trail, 7.3 airline miles south of the Princeville Ranch headquarters. Neither point is shown on the accompanying maps, but Highway 56 crossing Anahola Stream is shown on plate 2, and the ranch, on plate 1. Trace amounts of lithiophorite were also identified in handpicked specimens from samples taken at depths of 35 feet in holes augered southeast of Kilauea (pl. 1). In nearly all

TABLE 2.—*Chemical analyses, in percent, of saprolite and soil formed on the Koloa Volcanic Series, Hawaii*

[Samples analyzed by rapid methods described by Shapiro and Brannock (1956); I. H. Barlow and Gillison Chloe, analysts. All percentage figures for CaO, except for samples from auger hole PR-32 and at depth of 35–35.5 ft in hole Ki-64, obtained by quantitative spectrographic analysis; Sol Berman, analyst]

Auger hole	Laboratory No.	Sample depth interval (feet)	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	TiO_2	P_2O_5	MnO	CO_2	Loss on ignition	Total
PR–29 (pl. 1)	155283	1–4	1.0	24.9	43.5	1.1	0.55	------	0.10	0.09	18.7	7.3	0.64	0.08	<0.05	21.0	98
	155284	4–9	1.0	25.6	42.3	1.0	.70	------	.08	.08	19.0	7.0	.85	.10	< .05	20.9	98
	155285	9–14	2.9	26.9	39.7	1.1	.88	------	.06	.03	18.8	5.8	1.2	.34	< .05	20.2	98
	155286	14–19	4.6	27.4	35.6	2.7	.78	------	.08	.04	19.0	6.7	1.1	.26	< .05	20.1	98
	155287	19–29	14.3	24.6	33.5	1.1	.70	------	.08	.04	16.0	6.2	1.1	.32	< .05	17.4	98
	155288	29–39	17.0	24.8	32.2	1.1	.69	------	.09	.04	15.6	5.9	.88	.32	< .05	17.0	99
PR–32 (pl. 1)	155565	1–4	5.1	25.9	38.0	.51	.14	<0.10	.05	.22	20.0	5.5	.28	.07	< .05	24.0	[1]96
	155566	4–9	4.2	29.6	35.6	.71	.10	< .10	.05	.10	21.7	5.4	.31	.06	< .05	23.6	[1]98
	155567	9–14	4.6	33.1	31.7	1.0	.12	< .10	.03	.03	22.2	5.4	.43	.11	< .05	------	99
	155568	14–22	7.5	28.9	33.9	1.0	.16	< .10	.04	.04	20.2	5.6	.48	.12	< .05	21.4	[1]98
	155569	22–24	15.1	28.2	29.9	1.3	.17	< .10	.08	.02	17.8	5.0	.74	.17	< .05	18.8	[1]98
	155570	24–34	13.0	29.3	29.8	1.3	.19	< .10	.06	.04	19.2	5.0	.77	.16	< .05	------	99
	155571	34–54	24.9	25.8	26.5	1.3	.37	< .10	.06	.02	14.8	4.5	.76	.27	< .05	------	99
HO–3 (pl. 3)	155309	0–2	9.6	18.5	38.5	3.5	.58	------	.07	.26	15.3	7.9	.30	.03	< .05	20.4	[1]95
	155310	2–3	2.5	28.9	35.0	2.9	.40	------	.04	.09	20.6	6.5	.42	.03	< .05	22.8	[1]97
	155311	4–9	.94	26.6	41.6	.91	.41	------	.04	.04	19.8	7.0	.53	.04	< .05	21.4	98
	155312	24–29	11.8	28.5	29.5	3.4	.64	------	.04	.01	18.1	5.8	1.0	.27	< .05	18.9	99
	155313	39–44	25.7	24.4	24.2	3.0	.66	------	.06	.02	14.5	4.9	1.1	.32	< .05	15.2	99
HO–25 (pl. 3)	155289	1–4	10.7	22.5	37.4	2.0	.94	------	.06	.04	16.3	7.3	.52	.12	< .05	18.4	98
	155290	4–9	14.4	21.3	36.0	2.5	.55	------	.06	.03	14.5	7.0	.61	.18	< .05	16.3	97
	155291	9–14	16.8	23.4	33.0	1.6	.63	------	.06	.02	14.8	6.5	.69	.17	< .05	16.4	98
	155293	14–19	21.0	23.1	32.0	------	------	------	------	------	------	6.2	------	------	------	------	------
	155294	19–24	20.1	22.0	33.4	------	------	------	------	------	------	6.3	------	------	------	------	------
	155295	24–34	21.8	22.6	32.3	------	------	------	------	------	------	6.2	------	------	------	------	------
	155296	34–44	24.0	23.1	30.0	------	------	------	------	------	------	5.7	------	------	------	------	------
	155297	44–46	26.3	23.4	28.5	------	------	------	------	------	------	5.3	------	------	------	------	------
	155292	46–49	27.3	23.8	26.8	.62	.80	------	.06	.02	13.0	4.9	.81	.32	< .05	14.1	98
Ki–50 (pl. 3)	155519	.5–2	2.4	21.7	44.1	.93	.36	.07	.06	.15	18.3	6.5	.29	.08	< .05	23.6	[1]95
	155520	2–4	2.0	21.7	45.8	1.6	.44	.11	.06	.12	18.7	6.8	.33	.12	< .05	21.7	[1]98
	155521	4–9	3.5	26.5	40.8	1.5	.47	.09	.04	.11	19.5	6.2	.35	.17	< .05	------	99
	155522	9–14	3.0	28.2	38.6	2.1	.44	.05	.04	.05	20.7	6.0	.41	.18	< .05	------	100
	155523	14–19	2.5	32.4	33.9	2.5	.47	.06	.04	.03	22.0	5.4	.47	.16	< .05	------	100
	155524	19–24	4.7	30.5	34.7	2.0	.60	.07	.06	.04	20.7	5.4	.51	.44	< .05	------	100
	155525	24–29	7.8	28.9	34.6	1.8	.64	.06	.06	.03	19.5	5.4	.55	.42	< .05	------	100
	155526	29–39	14.0	27.4	32.9	1.6	.64	.07	.06	.02	17.5	5.2	.56	.40	< .05	------	100
	155527	39–49	15.6	27.2	32.2	1.2	.72	.07	.04	.01	17.4	4.8	.56	.36	< .05	------	100
	155528	49–54	20.8	26.2	29.7	1.0	.68	.07	.05	.01	16.3	4.6	.56	.33	< .05	----	100
Ki–64 (pl. 3)	155541	0–2	16.7	23.7	31.7	.89	.09	.09	.06	.14	16.9	6.2	.21	.08	< .05	19.6	[1]97
	155542	2–4	16.8	23.6	31.7	1.7	.14	.09	.05	.10	16.9	6.2	.27	.10	< .05	18.3	[1]98
	155543	4–9	15.7	25.7	31.7	1.4	.12	.07	.04	.06	18.3	5.3	.30	.10	< .05	------	99
	155544	9–14	15.8	29.4	28.3	1.2	.18	.07	.03	.03	18.8	5.0	.47	.19	< .05	------	99
	155545	14–19	26.1	26.9	24.1	1.2	.58	.06	.04	.02	16.1	4.0	4.0	.45	< .05	------	100
	155546	19–24	23.0	27.7	24.7	1.4	.47	.07	.07	.02	16.8	4.4	.60	.28	< .05	------	99
	155547	24–29	23.2	28.1	24.6	1.2	.52	.06	.09	.02	16.8	4.3	.50	.28	< .05	------	100
	155548	29–35	25.9	27.2	24.6	.69	.43	.06	.06	.02	16.4	4.2	.44	.26	< .05	------	100
	155549	35–35.5	42.1	14.0	13.0	2.5	7.9	6.4	.76	.62	10.2	2.4	.33	.26	< .05	------	100
Ki–67 (pl. 3)	155533	1–4	3.3	23.4	43.9	1.2	.47	.08	.07	.10	18.7	5.8	.25	.14	< .05	------	[1]97
	155534	4–7	3.7	28.9	38.6	1.3	.40	.06	.08	.08	20.8	5.5	.28	.14	< .05	------	100
	155535	7–9	3.9	28.3	38.3	1.8	.47	.08	.07	.04	20.1	5.8	.35	.22	< .05	------	99
	155536	9–14	4.8	23.0	43.6	2.1	.61	.08	.06	.06	17.6	6.6	.42	.25	< .05	------	99
	155537	14–19	8.5	22.9	40.6	2.2	.59	.09	.07	.03	17.0	6.2	.45	.35	< .05	------	99
	155538	19–24	13.7	24.4	34.9	1.9	.53	.08	.06	.03	15.7	5.5	.47	.34	< .05	17.2	[1]98
	155539	24–34	18.2	26.7	30.1	1.1	.38	.06	.04	.02	16.4	4.7	.49	.33	< .05	17.0	[1]98
	155540	34–39	23.2	24.6	29.3	1.0	.41	.07	.07	.02	15.0	4.7	.56	.32	< .05	------	99
Ki–81 (pl. 3)	155551	1–4	5.7	25.6	40.2	.40	.65	.08	.04	.12	18.6	5.6	.27	.12	< .05	21.5	[1]97
	155552	4–10	8.6	25.5	39.1	.37	.72	.08	.05	.09	17.8	5.6	.30	.14	< .05	19.6	[1]98
	155553	10–14	11.4	24.6	37.8	.82	.91	.09	.06	.05	17.2	5.7	.36	.20	< .05	------	99
	155554	14–19	17.1	26.2	32.7	.58	.83	.08	.06	.03	15.8	5.1	.31	.25	< .05	------	99
	155555	19–24	19.7	25.8	32.1	.50	1.0	.07	.06	.03	15.0	4.9	.32	.27	< .05	------	100
	155556	24–34	21.5	25.1	30.7	.53	1.0	.08	.06	.03	14.6	4.9	.36	.27	< .05	------	99
	155557	34–39	25.3	24.4	29.1	.44	.87	.08	.06	.02	13.9	4.5	.48	.25	< .05	------	99

[1] Sample contained an appreciable amount of organic matter.

TABLE 2.—*Chemical analyses, in percent, of saprolite and soil formed on the Koloa Volcanic Series, Hawaii*—Continued

Auger hole	Laboratory No.	Sample depth interval (feet)	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	TiO_2	P_2O_5	MnO	CO_2	Loss ignition	Total
Ki–85 (pl. 3)	155558	.5–4	3.7	21.6	44.0	0.70	0.49	0.07	0.06	0.14	17.7	6.1	.34	.09	$<$ .05	22.6	[1]95
	155559	4–9	4.5	22.3	44.5	.52	.49	.03	.04	.10	18.3	6.4	.43	.11	$<$ .05	20.5	[1]98
	155560	9–14	6.6	23.9	42.7	.39	.56	.08	.06	.06	17.6	6.4	.43	.16	$<$ .05		99
	155561	14–19	7.8	23.4	41.9	.27	.62	.06	.07	.05	17.3	6.4	.45	.18	$<$ .05	18.5	[1]98
	155562	19–24	14.4	24.0	36.4	.21	.59	.08	.06	.03	16.4	5.6	.55	.24	$<$ .05	17.2	[1]98
	155563	24–34	20.8	25.2	30.9	.14	.65	.06	.06	.02	15.4	4.8	.63	.28	$<$ .05		99
	155564	34–44	19.1	25.0	32.4	.07	.64	.07	.05	.02	16.0	5.1	.56	.24	$<$ .05		99

[1] Sample contained an appreciable amount of organic matter.

samples in which lithiophorite was identified, it was intermixed with white halloysite or gibbsite (pl. 8*F*), and in some samples it was also closely associated with gibbsite and goethite. Some of the manganese, which amounts to less than half a percent of the saprolite, may be amorphous or very imperfectly crystalline.

Lithiophorite was identified by X-ray methods and by its chemical composition. X-ray traces of this mineral (pl. 10*Ab*) have strong reflections at 4.79 and 9.60 A and weak ones at 3.18, 2.38, and 1.88 A. The purest lithiophorite samples collected contain 8.5 and 6.0 percent MnO; however, appreciable quantities of Al_2O_3, SiO_2, and Fe_2O_3 (table 3, samples 8, 9) indicate minerals or amorphous matter other than lithiophorite is present. No lithium was detected in a semiquantitative spectrographic analysis of the purest sample; therefore, the aluminum member of this mineral is probably the form present.

MONTMORILLONITE GROUP

Nontronite, the iron-rich member, and saponite, the magnesium member, of the montmorillonite group occur in small quantities in incompletely weathered rocks on Kauai but were not identified in bauxite. The structural formula of nontronite, fol-

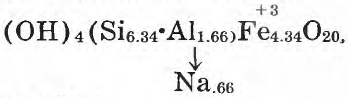
TABLE 3.—*Chemical analyses, in percent, of nodules and minerals from weathered parts of the Koloa Volcanic Series, Kauai*

[Analysis of samples 1–6 by P. L. D. Elmore, S. D. Botts, and H. H. Thomas; samples 7–10 by P. L. D. Elmore, S. D. Botts, I. H. Barlow, and Gillison Chloe; samples 11–15 by R. M. Bromery. Samples 1–10 analyzed by rapid chemical methods described by Shapiro and Brannock (1956); samples 11–15 by X-ray spectrographic method]

Sample No.	Laboratory No.	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	H_2O	Loss on ignition	Total
1	265023	4.5	22.4	44.8					8.6				20.1	
2	265014	9.0	54.0	4.0					1.4				31.0	
3	265020	34.5	35.0	3.3					5.2				19.6	
4	265017	15.2	32.0	26.6					4.1				20.4	
5	265016	4.2	37.8	27.5					4.0				25.0	
6	265012	1.9	53.7	9.8					2.2				31.3	
7	155305	3.4	47.0									23.6		
8	156941	16.7	40.7	6.3			0.07	0.02	1.0	0.66	8.5	23.2		97.15
9	156943	9.9	16.9	40.2			.04	.17	4.6	.98	6.0	18.8		97.59
10	156944	38.3	16.5	12.4	12.2	0.40	.06	.09	.48	.08	.16	19.7		100.37
11		43.0	4.7	8.5	19.0									
12		54.5	3.5	10.0	21.0									
13		45.2	4.7	4.5	18.0									
14		44.2	3.5	16.5	18.5									
15		38.7	9.7	27.5	0									

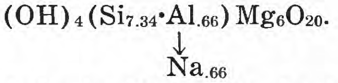
1. Reddish-brown pea-sized ferruginous nodules in A soil horizon, exposed in cut in field road, 3.3 miles southeast of Kilauea (pl. 1).
2. Hard brown vesicular saprolite fragments from depths of 2–4 ft. in cut in field road near Kaneha Reservoirs (pl. 2).
3. Cream-colored fragment of hard clay vein exposed in cut in field road on east side of Hanahanapuni vent (pl. 3).
4. Hard reddish-brown gibbsitic saprolite containing yellow gibbsite nodules, exposed in roadcut, 3.5 airline miles northwest of Lihue (pl. 3).
5. Hard reddish-brown saprolite fragment exposed in roadcut, 1.5 airline miles northwest of Lihue (pl. 3).
6. Fragment of yellow gibbsite vein exposed in cut in field road on southwest side of Kilohana Crater (pl. 3).
7. Fragment of white gibbsite vein exposed in saprolite in cut of powerline trail, 2.9 airline miles south of Princeville Ranch headquarters (pl. 1).
8. Black lithiophorite vein deposit in saprolite exposed in fresh cut of powerline trail, 7.3 airline miles south of Princeville Ranch headquarters.
9. Black spongy-textured lithiophorite from reservoir excavation on northwest flank of Kalepa Ridge (pl. 3).
10. Very dark brown scalelike "swelling chlorite" from veins in basalt quarry west of Puhi (pl. 3).
11. Greenish-gray mealy-textured saponite fillings of vesicles in basalt quarry west of Puhi (pl. 3).
12. 2μ clay fraction from gray-weathered peridotite inclusion in basalt quarry.
13. 2μ clay fraction from yellow-weathered peridotite inclusion from basalt quarry west of Puhi (pl. 3).
14. 2μ clay fraction from orange-weathered peridotite inclusion from basalt quarry of Puhi (pl. 3).
15. Green waxy nontronite fillings of vesicles in residual boulders exposed in powerline trail south of the South Fork Wailua River (pl. 3).

lowing calculations by Ross and Hendricks (1945, p. 23), is commonly considered to be



$$(OH)_4(Si_{6.34}\cdot \underset{\substack{\downarrow \\ Na_{.66}}}{Al_{1.66}})\overset{+3}{Fe}_{4.34}O_{20},$$

and that of saponite is



$$(OH)_4(Si_{7.34}\cdot \underset{\substack{\downarrow \\ Na_{.66}}}{Al_{.66}})Mg_6O_{20}.$$

The arrows indicate the group having the deficiency of charge which requires an additional exchangeable ion external to the silicate sheet. Here, this charge is arbitrarily shown as balanced by Na. Sufficient samples of high enough purity for base exchange determinations were not obtained; therefore, the exchangeable ions present were not determined. Some exchangeable Na may be present, but more likely the ions are Mg, Ca, and H, and perhaps others; amounts and type of exchangeable ion present probably vary considerably from place to place.

Saponite and nontronite occur in several forms and may be intermixed with other minerals. Saponite was identified only in samples collected from the basalt quarry west of Puhi, where it occurs as (1) greenish-gray loose mealy-textured clay filling vesicles; (2) moderate-brown blocky clay filling vesicles and veins; and (3) weathered peridotite inclusions of the type described by Ross, Foster, and Myers (1954, p. 697), which alter to yellow, orange, and greenish-gray clay-rich material. These clays contain excess iron for saponite and may be mixed with nontronite or other iron-bearing minerals; some of the inclusions contain partially altered olivine.

Nontronite occurs as green waxy clay in fillings of vesicles in residual boulders south of the South Fork Wailua River, north of the North Fork Wailua River (Wailua Reservoir locality described by Sherman and others, 1962, p. 58–59), and elsewhere. Nontronite replacing olivine crystals was observed in thin sections of basalt (pl. 9*E*) from several scattered localities. An impure brown bedded clay that crops out at the foot of the falls of the South Fork Wailua River is also montmorillonitic. Its color suggests that it is rich in iron, and nontronite may be the principal mineral present.

The montmorillonites were identified by X-ray, chemical, and microscopic methods. The purest montmorillonite obtained was the <2-micron fraction from a yellow weathered peridotite inclusion collected in the quarry west of Puhi. The strong basal (001) X-ray reflection from this clay was at 14.7 A after air drying (pl. 10 *Ac*), collapsed at 9.8 A with heating at 300°C, and expanded to 16.7 A after treatment with ethylene glycol. Most other montmorillonites investigated gave weaker, more diffuse, reflections than this sample, but all basal reflections collapsed with heating and expanded when treated with ethylene glycol. The weak diffuse reflections of these clays probably indicate that their crystal structures are disordered, or that they contain very fine grained impurities. The montmorillonite from the quarry was identified as saponite, because it contains 18–21 percent MgO (table 3, samples 11–13), which is only slightly lower than the 22.96–25.91 percent MgO in representative saponites (Ross and Hendricks, 1945, p. 35). The samples from Kauai contain 3.5–4.7 percent Fe_2O_3, which together with the slight deficiency in MgO suggest that nontronite may also be present. The sample of nontronite (table 3, sample 15) contains 27.5 percent Fe_2O_3, and no MgO was detected. This iron content is within the range for other nontronites (Ross and Hendricks, 1945, p. 35).

"SWELLING CHLORITE"(?)

An unusual mineral that is probably related or similar to the poorly defined minerals referred to as "swelling chlorites or silicates with imperfect layers" (Brindley, 1961, p. 283–287) occurs in the Grove Farm Co., Ltd. quarry west of Puhi. The mineral occurs as very dark brown nonplastic shinglelike crusts as much as one-eighth inch thick along joints and the walls of large vugs in fresh basalt. It is greenish gray after drying and grinding. This mineral, in air-dried condition, gives a strong X-ray reflection at 15.49 A (pl. 10*Ad*) and weak diffuse ones at 4.41 and 2.55 A. After drying at 200°C, the strongest reflection is a diffuse one at about 14 A, which probably indicates a very imperfect crystalline structure. After treatment with ethylene glycol, the peak reappears at about 15.5 A. Samples heated at 300°C gave only very weak diffuse peaks; presumably, heating at this temperature destroys part of the mineral structure. The differential thermal analysis curve for this "swelling chlorite"(?), not illustrated in this report, has a broad endothermic peak between 100° and 150°C and a second strong endothermic peak between 500° and 600°C, which are similar to those of "swelling chlorite"(?) illustrated by Cole and Hosking (1957, fig. X-6).

The "swelling chlorite" (?) consists chiefly of SiO_2, Al_2O_3, iron and magnesium oxides, and water (table 3, sample 10). Although similar to other chlorites in composition, it contains appreciably more SiO_2 and iron oxide and less Al_2O_3 and MgO than typical chlorites listed by Foster (1962, table 2).

ZEOLITE FAMILY

Thompsonite.—A mineral identified by X-ray methods as thompsonite $(Ca,Na_2)(Al_2Si_2O_8\cdot 2\frac{1}{2}H_2O)$

was collected from basalt 1–5 feet above sea level at the Kahili quarry on the west side of Kilauea Bay (pl. 1). The mineral occurs as small stubby prismatic crystals lining cavities and cracks.

Harmotome(?).—A zeolite mineral that has similar, but not identical, X-ray reflections and optical properties to those for harmotome was identified in samples collected in the Grove Farm Co., Ltd., quarry west of Puhi (pl. 3). The occurrence of this mineral is similar to that of thompsonite, except that harmotome(?) is in extremely small crystals that are intergrown with clay minerals and other secondary minerals.

MINERALS IN THOROUGHLY WEATHERED ROCK (SAPROLITE AND SOIL)

ANATASE

Extremely fine grains of anatase (TiO_2) were identified in only a few samples of soil and saprolite. Probably anatase is present in nearly all the titanium-rich soil and saprolite; in most samples, however, the quantity is insufficient to produce identifiable X-ray reflections, and this mineral is too fine grained to be studied with a microscope. Anatase is much more abundant in the plastic clays in bog deposits than in the saprolite (p. 48).

GIBBSITE

Gibbsite—aluminum trihydroxide ($Al(OH)_3$), or alumina trihydrate, ($Al_2O_3 \cdot 3H_2O$)—is the bauxite mineral in the soil and saprolite. Probably most gibbsite is disseminated throughout the saprolite as pseudomorphic replacement of feldspar, feldspathoids, and other aluminous minerals in the parent rock. Most pseudomorphs are very fine grained (pl. 8*A-D*), but a few replacements of lath-shaped crystals are as much as a quarter of an inch long. Much gibbsite also occurs as light-gray, yellow, brown, and reddish-brown nodules, veinlets, and vesicle fillings. The gibbsite in vesicles forms subspherical accumulations that are commonly less than a quarter of an inch in diameter, and the veinlets are rarely as much as half an inch thick. The nodules are irregularly shaped, and most are less than an inch in longest dimension. In a few scattered localities, particularly in cuts and ditches along the powerline trail south of Princeville Ranch (pl. 1) and west of Kilohana Crater (pl. 3), gibbsite occurs in white corallike nodules (fig. 5) that are as much as 10 inches long.

All the gibbsite nodules and masses investigated in the laboratory contained impurities. A thin section of a white corallike nodule (pl. 8*E*), selected because of its pure appearance, revealed a complexly involuted interlamination of paper-thin gibbsite layers with laminae of other minerals, a few scattered dark mineral grains, and irregular areas stained with iron oxide. An X-ray diffraction trace of the nodules (pl. 10*Aa*) shows that gibbsite is the major mineral, but anatase and a minor amount of magnetite are also present. Chemical analyses of gibbsitic veins and nodules made during the present investigations (table 3, samples 3–7) and those reported by Cathcart (1958, tables 5, 9) all contain appreciably less Al_2O_3 than the 64.5 percent in pure gibbsite. Iron oxide is the principal impurity in most forms of gibbsite. The iron-bearing minerals goethite, hematite, and magnetite are identifiable by X-ray methods in some gibbsite nodules and vein deposits, but in others the identifiable iron minerals are insufficient to account for the iron oxide present. Probably iron replaces aluminum in the gibbsite structure in some grains. This possibility is suggested by the precipitation of ferruginous aluminum hydroxide from an aluminum-iron chloride solution in the laboratory by Caillère and Hénin (1961); also, ferruginous boehmite, in which iron is substituted for aluminum in a 1:1 ratio with appreciable distortion of the lattice, was discovered in bauxite deposits in France (Caillère and Pobeguin, 1961).

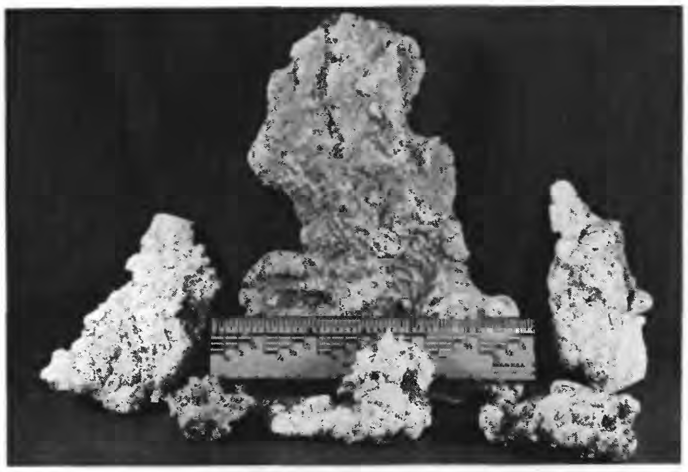


FIGURE 5.—Nodules of gibbsite collected along the powerline trail, 3.5 miles south of Princeville Ranch headquarters. Scale in inches.

GOETHITE

Goethite (FeO·OH), the most abundant iron-bearing mineral in the weathered rocks, occurs as nodules; vein deposits; pseudomorphs after olivine; mixtures with hematite, gibbsite, or other minerals; and as earthy material disseminated throughout the soil and saprolite. Nodules of various sizes and shapes are most abundant in soils and the upper part of the saprolite. Many of the nodules formed as vesicle fillings and have concentrated in the thoroughly weathered zones by residual accumulation. Goethite in vein deposits is commonly associated with hematite. Veins are as much as 2 inches thick and are particularly abundant beneath, and surrounding, iron-poor plastic clay deposits in swamp areas. The surface of nodules and vein deposits are commonly coated with earthy brown, reddish-brown, or yellow powdery material, and freshly broken surfaces have a glassy or waxy luster. Light-yellowish-brown pseudomorphs after olivine occur throughout the saprolite and are characterized by a spongy latticelike open structure and very low density. Fine-grained disseminated goethite is very abundant and produces the brown shades of most of the saprolite.

Most samples of soil and saprolite from Kauai, which were examined by X-ray methods, contain goethite. In typical samples, goethite is diluted, and only broad diffuse X-ray reflections at 4.18 A (pl. 10B) can be obtained; commonly, this is the only recognizable reflection of this mineral. The purest goethite found on Kauai is light-brown very light-weight spongy material that occurs in thoroughly weathered dunite inclusions exposed in a cut of Highway 50, 1.1 miles east of Kalaheo. An X-ray trace of this material (pl. 10*Af*) indicates it is chiefly goethite contaminated only by minor halloysite-metahalloysite.

HEMATITE

Hematite (Fe_2O_3), a common mineral formed during the weathering of basalt, occurs in soil, saprolite, and buried soil. Most of the hematite is red, very fine grained, and intermixed with other minerals (pl. 8*A*,*B*). Earthy red hematite crusts form on magnetite grains; dark-reddish-brown glassy hematite is concentrated in concretions, vein deposits, and irregular masses. Hematite is most abundant in the greatly weathered parts of the saprolite near the surface, but it also occurs at depth. The red color that is typical of soil and saprolite in areas which have low rainfall is caused by fine-grained hematite and probably amorphous iron oxides and hydroxides.

ILMENITE

Ilmenite ($FeTiO_3$) is not an abundant mineral in the soil and saprolite, but it is present in several samples in sufficient quantities to be detected by X-ray diffraction methods. No ilmenite grains were isolated for study; however, very fine lamellar ilmenite is intergrown with magnetite in one polished section of basalt. Macdonald (1960, p. 105) observed ilmenite in specimens from rocks of the Koloa Volcanic Series at a few localities. Very fine grained ilmenite in close association with magnetite is probably widely distributed throughout the weathered rocks as a relatively unaltered residual mineral from the parent basalt.

KAOLIN MINERALS

HALLOYSITE-METAHALLOYSITE[1]

Halloysite ($(OH)_8Si_4Al_4O_{10}\cdot 4H_2O$), which dehydrates at surface temperatures to metahalloysite ($(OH)_8Si_4Al_4O_{10}$), is a major rock-forming mineral in the saprolite, and variable amounts were found in nearly all the bauxite. Virtually all the silica and part of the alumina in the bauxite and saprolite are in halloysite. Halloysite occurs as fillings of vesicles and veinlets and in pseudomorphic replacements of all aluminous minerals in the parent rock. Metahalloysite occurs only in the A soil horizon and where saprolite crops out and has been sufficiently dried for the dehydration to take place.

Halloysite can be identified only in samples that have their natural moisture preserved. It is recognized by its 10 A reflection (pl. 10*Bc*) which shifts to about 7 A (pl. 10*Bd*) after conversion to metahalloysite takes place with drying at room temperature. All samples analyzed by differential thermal analysis had dehydrated during sample preparation, and metahalloysite is indicated by its broad intense endothermic reaction at 575°–590°C (fig. 6). Metahalloysite is also identified by its tubular structure observed in electron micrographs (Bates and others, 1950). Tubular structure in metahalloysite from plastic clay, that was halloysite when collected, is shown in figure 12.

KAOLINITE

Kaolinite ($(OH)_8Si_4Al_4O_{10}$) was recognized only in samples from one locality. However, it is particularly difficult to identify small quantities of koalinite in minerals having similar X-ray diffraction patterns. The identification of kaolinite in this investigation is based on vermicular crystal form, of the type illustrated by Ross and Kerr (1931, pls. 41–43), observed in thin section. The thin section was of a sample from the B soil horizon collected in the upper part of a roadcut on Highway 56 about 1.7 miles north of Anahola in an area of low rainfall.

MAGNETITE AND MAGHEMITE(?)

Fine-grained euhedral and subhedral magnetite ($FeFe_2O_4$) is virtually ubiquitous in the unweathered basalts on Kauai and is widely distributed throughout the soil and saprolite. Magnetite is so common

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[1] Halloysite is the $4H_2O$ form and metahalloysite is the $2H_2O$ form, in accordance with the majority preference of the International Mineralogical Association (Brindley, 1966, p. 30).

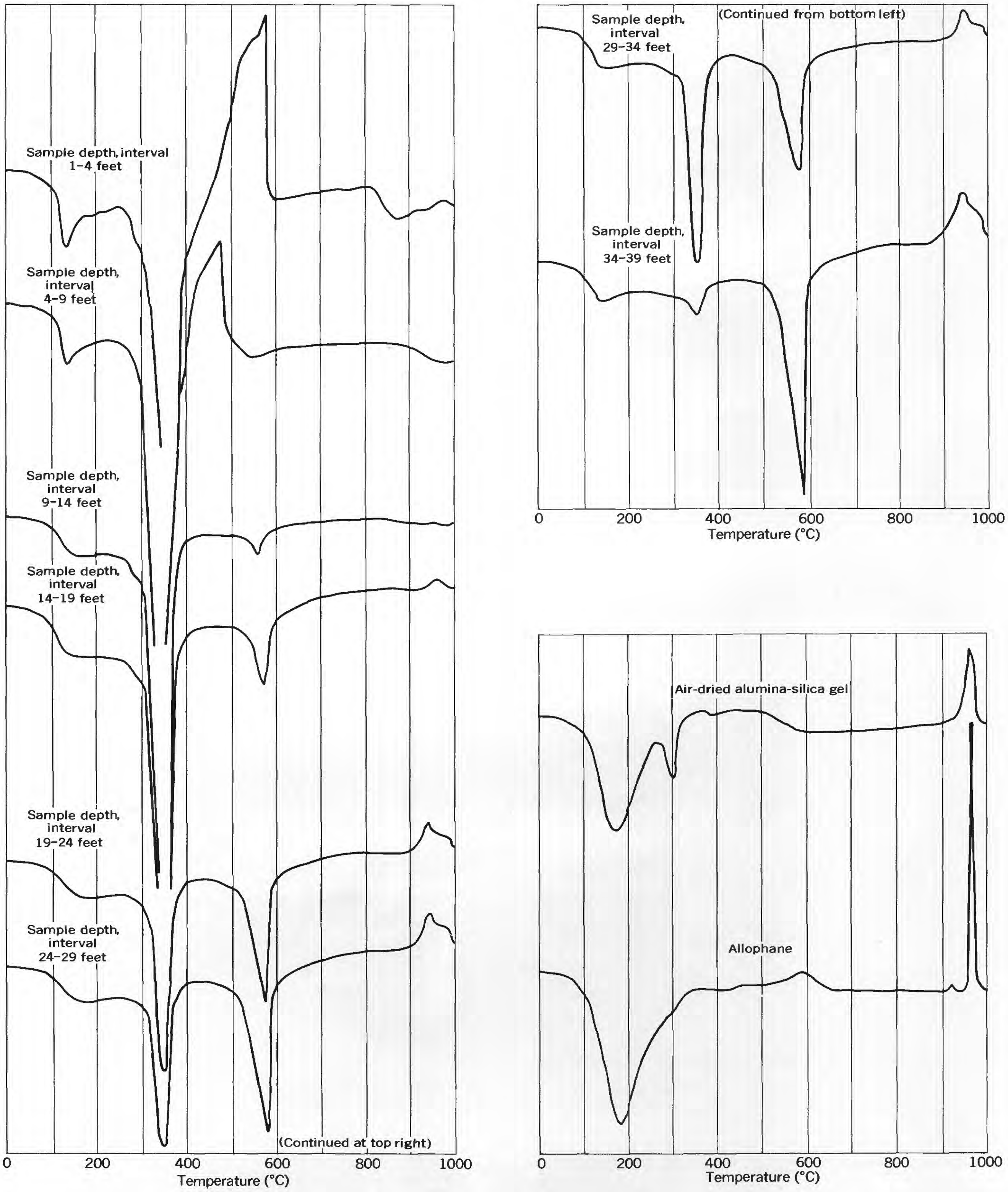


FIGURE 6.—Differential thermal analysis curves of whole samples of ferruginous bauxite and saprolite from auger hole PR–29, Kauai (pl. 1), and alumina-silica gel and allophane, Maui.

that nearly all dry fragments of saprolite and soil can be picked up with a hand magnet. Magnetite occurs chiefly as silt-sized euhedral grains and is the principal residual mineral of the parent basalt in the soil and saprolite. It commonly makes up more than 10 percent of the saprolite by weight, but its volume percent is much lower because its specific gravity (5.18) is about 4.5 times the bulk density of most saprolite. An impure concentrate of one sample of magnetite from saprolite was analyzed by X-ray fluorescence spectrographic methods and contained 15.3 percent TiO_2; titanium is also abundant in magnetite concentrates analyzed by semiquantitative spectrographic methods (p. 35). Probably most titanium in the saprolite is in magnetite or in ilmenite intergrown with it.

Maghemite (γFe_2O_3) may occur in small quantities in much of the saprolite. This mineral is brown and earthy in appearance; but it is similar to magnetite in being magnetic, and its color differs little from mixtures of goethite and hematite. Maghemite is difficult to identify in saprolite because magnetite is virtually always present in sufficient quantities to cause magnetism, and goethite and hematite are so abundant that the brown color of maghemite is a useless criterion for identification. Maghemite and magnetite also have such similar atomic structures that they have very similar X-ray reflection properties and can rarely be distinguished with certainty by this method. However, maghemite was identified by metallographic microscope techniques in samples of soils from Kauai (Katsura and others, 1962) that were taken along the Kekaha-Kokee road outside the areas described in this report. Probably small quantities of maghemite occur widely in the saprolite where maghemite is chiefly an alteration product of magnetite, as suggested by Walker (1964, p. 200). Some magnetite grains are coated by brown and reddish-brown material that may be a mixture of maghemite, hematite, and possibly other iron-bearing minerals.

AMORPHOUS INORGANIC MATERIALS

Gels and amorphous inorganic materials in soils and weathered rocks in Hawaii have been recognized for several years (Sherman, 1958, fig. 8; Kanehiro and Whittig, 1961; Bates, 1962, p. 325–327; Lai and Swindale, 1967; Moberly, 1963, p. 767–769). The presence of amorphous inorganic matter in saprolite on Kauai is suggested by the absence of adequate quantities of minerals in many samples, as revealed by X-ray reflections, to account for the total composition.

The amorphous matter occurs as solids, gels, and sols. Probably the most common type observed is a gel-sol mixture, which contains algae and very fine grained mineral impurities, that accumulates in drainage ditches and small streams where shallow ground water seeps for extended periods. Gel-sol material of this type, which is not eroded, dries to thin impure crusts when rainy periods terminate. The amorphous matter below the surface is so disseminated through fine-grained saprolite that it is rarely recognizable even in freshly excavated cuts or auger cuttings.

Most amorphous matter probably consists of mixtures of hydrous oxides of aluminum, iron, and silicon with varying quantities of water, and probably much of it contains organic matter. One sample of a very dilute impure gel-sol mixture collected in bottles from a drainage ditch on the west side of Kilohana Crater in December 1960 remained in suspension until examined in the laboratory 5 years later. This gel-sol mixture contained approximately 0.035 percent dissolved material, which consisted chiefly of iron oxide, but alumina and silica were also present. A weak reflection at 4.18 A, the strongest one for goethite, was present in an X-ray diffraction trace of the dried material; but whether extremely fine grained goethite was in suspension in the gel, or whether this mineral crystallized with drying could not be determined.

The purest inorganic amorphous material found during the present investigations occurred in weathered parts of the Kula Volcanic Series on Maui, which is here described because it is probably similar to some of the amorphous matter associated with saprolite and ferruginous bauxite on Kauai. The sample was collected on July 4, 1960, from a freshly bulldozed cut at an altitude of 4,240 feet on the northwest slope of Haleakala Volcano. The cut is a quarter of a mile west of where Waikamoi Stream is crossed by a trail that extends eastward from Olinda prison. The average annual rainfall in this vicinity is 250 inches, according to U.S. Weather Bureau maps, and the vegetation is typical of the wettest rain forest environment (Selling, 1948, p. 42). The amorphous matter occurred 2–6 feet below the surface that existed before the excavation. Both seepage and surface water were flowing over the face of the cut at the time samples were collected. The A soil horizon at the top of the cut is about 6 inches thick and extremely rich in decaying organic matter.

The host rock of the amorphous materials on Maui is a saprolite formed on the jointed vesicular basalt of the Kula Volcanic Series. The alteration of basalt to saprolite has progressed from the outer parts toward the centers of joint blocks, and most blocks still contain irregularly rounded residual boulders of hard rock in their centers. The amorphous materials fill or coat structures inherited from the parent basalt—such as vesicles and small depressions on the walls of vugs and cracks.

The amorphous matter consists of both solid and very hydrous gel materials. The solid matter is allophane; when dry, it is white, soft, and open textured, and some of it has a sugary appearance. At the time samples were collected, most of the allophane was coated with gel which gave it an appearance of flowstone or a sheet of ice. The gel occurs partly in clear irregular masses that resemble frog eggs or thick gelatin and range from microscopic specks to lumps about a quarter of an inch in longest dimension, and partly in cloudy laminated paper-thin layers a square inch or more in area. Most masses of clear gel extend laterally into laminae of cloudy gel. Parts of the gel contain small nuclei of light-colored semisolid matter, and the laminated gel encloses specks of semisolid(?) brown and dark-colored matter.

The identification of the solid material as allophane is based on X-ray diffraction traces, differential thermal analysis curves, electron micrographs, and chemical composition. The lack of well-formed orderly arrangement of atoms in the allophane is indicated in the X-ray diffraction trace (pl. 10*C*), which shows only a broad low bulge typical of amorphous materials. The differential thermal analysis curve of the allophane (fig. 6) has a very strong endothermic reaction at low temperature corresponding to loss of water, which is similar to that described and illustrated by Holdridge and Vaughan (1957, p. 128–129, fig. IV–7). The curve (fig. 6) also has a weak endothermic reaction at 300°C, suggesting the presence of very minor quantities of gibbsite. The cause of the slight exothermic reaction at 600°C is unknown, but it may be due to iron or other impurities. The very strong exothermic reaction at 950°–970°C is probably due to the development of new mineral phases, but only weak reflections for mullite were present in X-ray diffraction traces of allophane heated to 1,000°C. The electron micrograph of the allophane (fig. 7*A*) shows diffuse masses and a peculiar filiform material similar to that recognized in weathered volcanic ash in Japan by Aomine and Wada (1962, fig. 3) and Wada (1967, fig. 3), which has been called "imogolite" (Aomine, 1969, p. 173). The diffuse material is typical of most noncrystalline substances, and it seems unlikely that the filiform material consists of molecules in a very well ordered arrangement. The allophane is about a quarter SiO_2, a half Al_2O_3, and a quarter water, and contains only very minor quantities of iron and titanium oxides. It is much higher in Al_2O_3 than the typical allophane described by Ross and Kerr (1934, p. 145), but allophanes are known to vary appre-

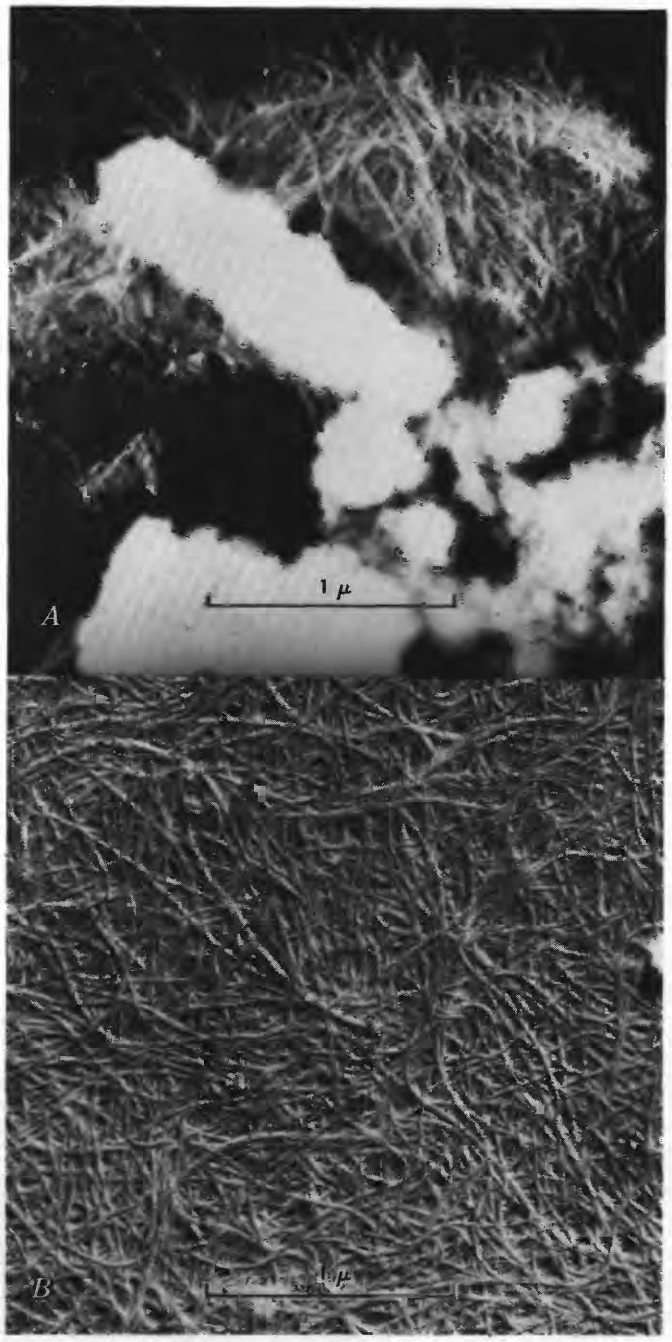


FIGURE 7.—Electron micrographs of allophane *(A)* and air-dried silica-alumina gel *(B)* from Maui, Hawaii. Micrographs by E. J. Dwornik, U.S. Geological Survey.

ciably in composition. The composition of the allophane from Maui corresponds to that of a mixture of halloysite and gibbsite in approximately equal proportions. Mixtures of this type are common in the saprolite in Hawaii.

The gel is chiefly an amorphous very hydrous material and, after drying, is similar in composition to the allophane, except that it contains small quantities of gibbsite. X-ray diffraction patterns of the gel, not illustrated, contain even less evidence of crystalline material than does the pattern for allophane (pl. 10*C*). After air drying at room temperature most of the gel is amorphous, but weak reflections for gibbsite are identifiable in X-ray traces (pl. 10*C*). The differential thermal analysis curve for the dried gel (fig. 6), is similar to that for allophane (fig. 6), but the endothermic peak at about 300°C is much more pronounced. This increase in peak intensity is probably due to the small quantities of gibbsite, though the endothermic peak for gibbsite is at 350°C. Such a shift might be expected if the particles are extremely fine, or if the hydroxyls, the loss of which causes the reaction, are imperfectly bonded. An electron micrograph of the air-dried gel (fig. 7*B*) shows it to be filiform material similar to that making up part of the allophane. That the gel is extremely hydrous is indicated by the approximately 90-percent weight loss from drying at room temperature. The Al_2O_3 and SiO_2 contents of the dried gel are similar to those of the allophane (table 4).

TABLE 4.—*Partial chemical analyses, in weight percent, of allophane and alumina-silica gel*

[Percentage of oxides determined by X-ray fluorescence methods]

	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	Approximate percentage loss in air drying	Approximate percentage loss on ignition 1,000°C	Organic carbon	Loss on ignition 120° – 1,000°C
Allophane	26.0	50.5	1.0	0.1	—	25.0	—	—
Clear gel	2.2	4.9	.3	—	90	—	—	—
Laminated gel	2.2	4.6	.4	—	90	4.0	—	—
Air-dried clear gel	22.0	49.5	3.0	.6	—	—	[1]1.77	[2]18.5
Air-dried laminated gel	20.0	51.7	4.0	.9	—	—	—	—

[1] Percentage determined by induction-furnace method; I. C. Frost, analyst.
[2] Percentage determined gravimetrically; I. C. Frost, analyst.

The gel is appreciably richer in minor elements than the rocks in the Kula Volcanic Series from which it has formed. The rare-earth Ce, La, and Nd, as determined by semiquantitative spectrographic analyses (table 5), is much higher in the gel than in parent rocks. The gel is also richer in Mn, Be, and Co than the weathered rocks in the Koloa Volcanic Series, Kauai (table 10), though the minor-element contents in the parent rocks on the two islands do not differ greatly.

TABLE 5.—*Semiquantitative spectrographic analyses for minor elements in a sample of gel and the average of five samples of andesite, Kula Volcanic Series, East Maui*

[Analyses by J. C. Hamilton. Results are reported in percent to the nearest number in the series 1, 0.7, 0.5, 0.3, 0.15, 0.1, and so on, which represent approximate midpoints of group data on a geometric scale. The assigned group for semiquantitative results will include the quantitative value about 30 percent of the time. Symbols used are: M, major constituent, greater than 10 percent; O, looked for but not detected; ..., not looked for]

Element	Gel (lab. No. D110807)	Andesite (average of 5 samples)	Element	Gel (lab. No. D110807)	Andesite (average of 5 samples)
Si	M	M	Cr	0.003	0.001
Al	M	M	Cu	.015	.001
Fe	2.0	M	Ga	.005	.0025
Mg	.3	1.5	La	.03	.007
Na	.1	3.4	Mo	.0007	.0001
Ca	.2	5.1	Nb	0	.0003
K	0	2.25	Ni	.015	.0006
Ti	.5	1.04	Pb	.003	0
P	.5	0	Sc	.003	.001
Mn	.5	.15	Sr	.007	.2
Ag	.0005	0	V	.01	.019
Ba	.015	.088	Y	.02	.003
Be	.001	.00007	Yb	.0015	...
Ce	.07	.004	Zr	.007	.025
Co	.02	.0015	Nd	.03	.009

Looked for, but not detected in both gel and andesite: As, Au, B, Bi, Cd, Ge, Hf, In, Li, Pd, Pt, Re, Sb, Sn, Ta, Te, Th, Tl, U, Zn, Pr, Sm, and Eu; in gel only, Gd, Tb, Dy, Ho, Er, Tm, and Lu.

The related origin of the gel and allophane is indicated by their close association in the weathered rocks, similar composition, and colors which contrast distinctly with the host rock. The weak gibbsite reflection in the air-dried gel suggests incipient crystallization is taking place as the gel dries, but the virtual absence of gibbsite in the allophane and the filiform character of the air-dried gel do not support this possibility. The filiform character in both the air-dried gel and allophane suggests some sort of an accumulation of submicroscopic appendages of plants or animals. However, the chemical composition (table 4), including the low organic carbon content which is also indicated by the absence of strong exothermic reactions in differential thermal analysis (fig. 6), are not suggestive of organic remains.

ORGANIC MATTER

Appreciable quantities of organic matter are present in the saprolite and soil, and chemical analysis totals for some samples (table 2) are low because of this material. Although no determinations of organic carbon were made, much of the material lost on ignition to 1,000°C is organic matter and water. Accordingly, estimates of the quantity of organic

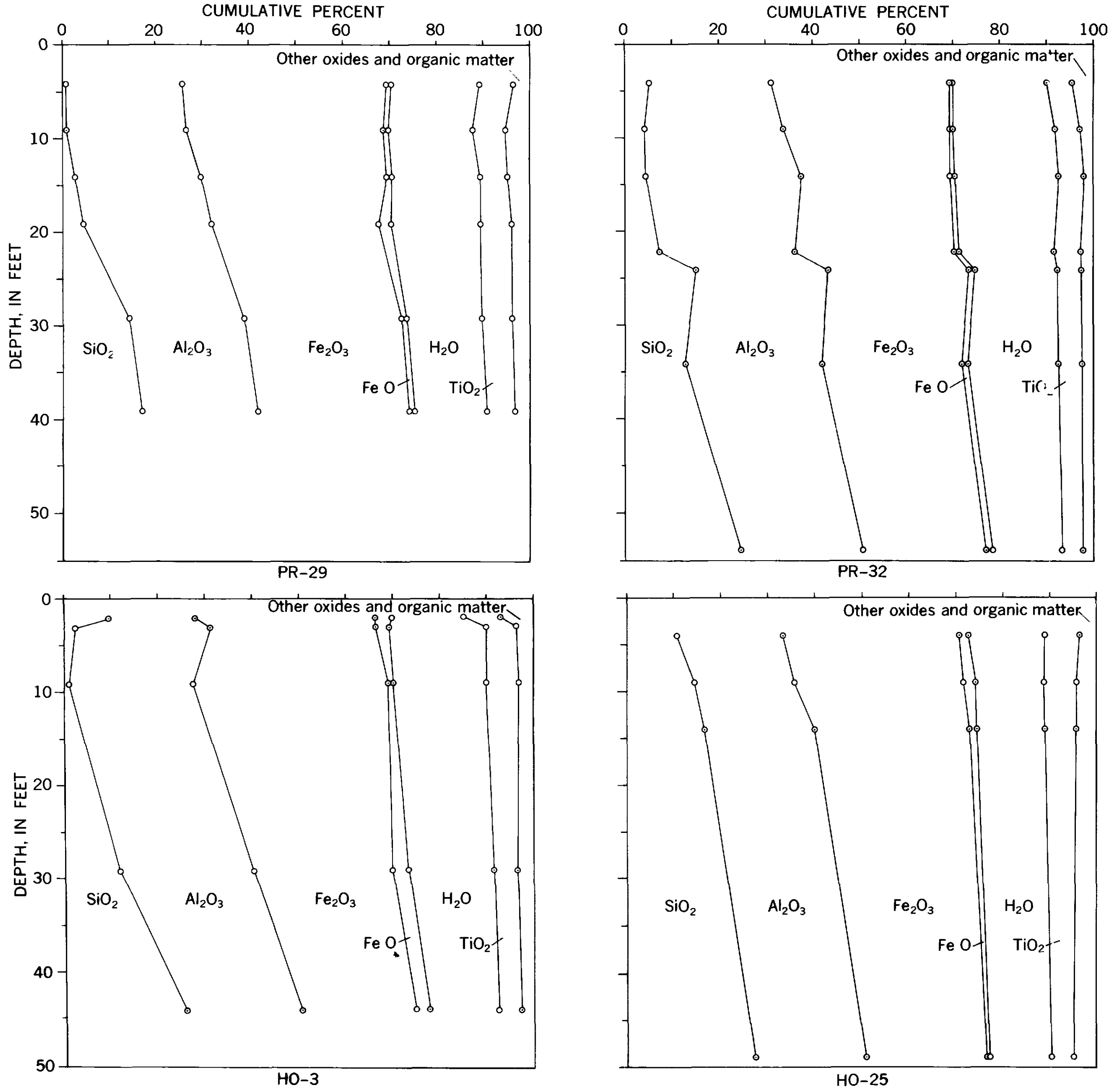


FIGURE 8.—Geochemical profiles of soil and saprolite formed on the Koloa Volcanic Series, Kauai. Profiles were plotted by R. M. Bromery from chemical analyses of samples from auger holes (table 2). Circled points are plotted at bottom of sample depth interval. Location of all auger holes shown on plate 3, except PR–29 and PR–32 which are shown on plate 1.

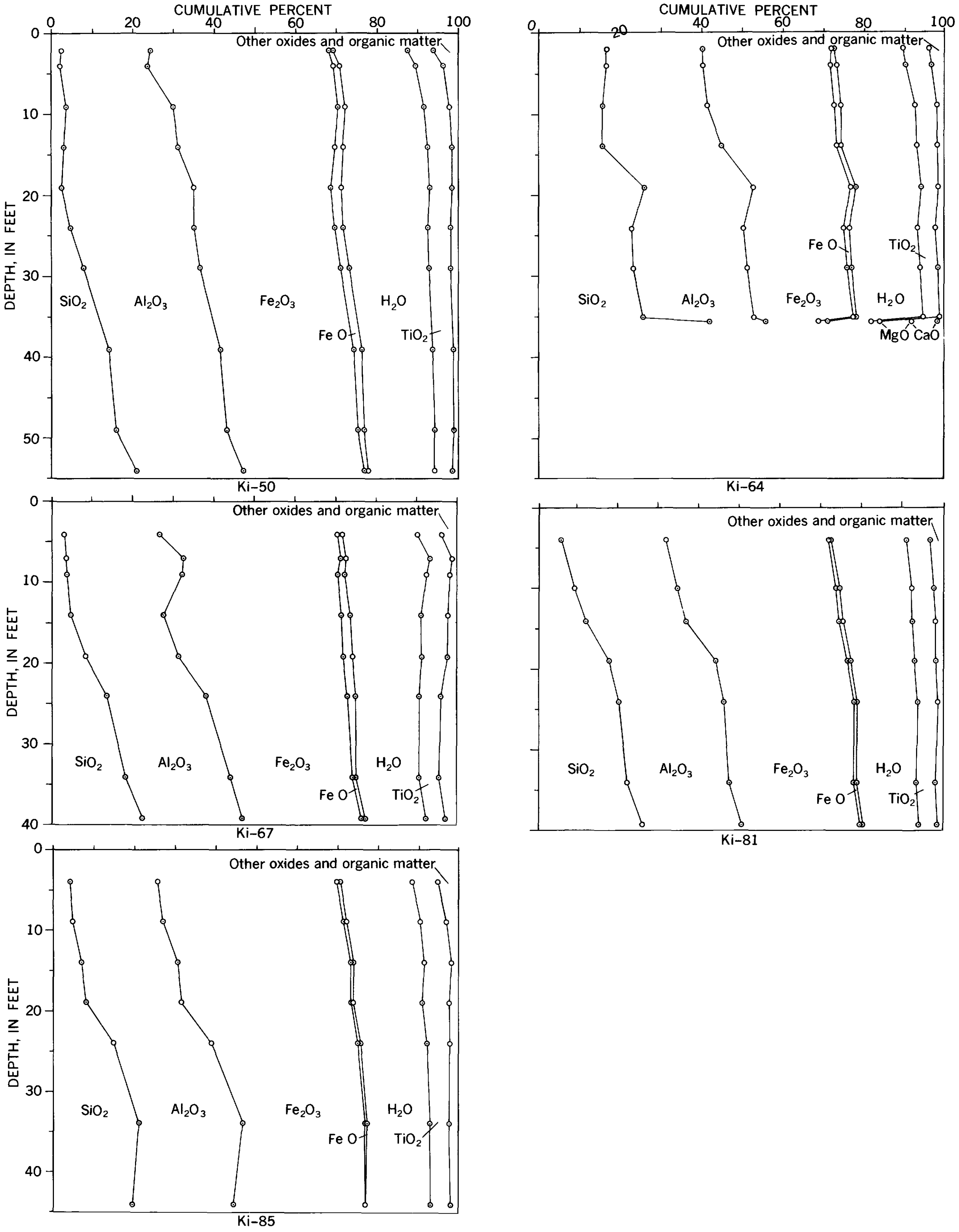

CUMULATIVE PERCENT
0
20
40
60
80
100
DEPTH, IN FEET
0
10
20
30
40
50
Other oxides and organic matter
SiO2
Al2O3
Fe2O3
H2O
Fe O
TiO2
MgO
CaO
Ki-50
Ki-64
Ki-67
Ki-81
Ki-85

TABLE 6.—*Variations in principal chemical and mineral constituents of ferruginous bauxite and saprolite with grain size and depth*

[Major oxides were determined by X-ray fluorescence methods, William M. Turner, analyst. Particle size: 10 mesh, granules and larger; 10–35 mesh, very coarse and coarse sand; 35–230 mesh, medium, fine, and very fine sand; 230 mesh, silt and clay. Mineral content: VA, very abundant; A, abundant; VC, very common; C, common; R, rare; VR, very rare; Tr., trace]

Auger hole	Sample depth interval (feet)	Particle size		Chemical analysis (in percent)						Mineral content						
		U.S. series sieve Nos.	Percent, dry weight	Al_2O_3	SiO_2	Fe_2O_3	TiO_2	H_2O-	H_2O+	Gibbsite	Halloysite	Goethite	Hematite	Magnetite	Anatase	Ilmenite
							Princeville ranch (pl. 1)									
PR-19	1-9	>10	7.3	35.7	1.2	29.2	3.8	1.51	26.32	VA	----------	C	R	C	----------	----------
		10-35	5.9	33.0	1.2	31.0	4.4	1.81	25.86	VA	----------	VC	C	R	----------	----------
		35-230	9.1	32.7	1.2	33.5	3.9	1.74	24.23	VA	----------	VC	C	R	----------	----------
		<230	77.7	19.5	3.0	41.5	7.9	2.97	17.56	VC	Tr.	VC	C	C	----------	----------
	9-19	>10	15.9	47.7	.7	19.5	1.6	1.62	27.57	VC	----------	A	R	VR	----------	----------
		10-35	6.7	46.7	1.5	17.0	2.8	.86	19.31	VA	----------	R	R	VR	----------	----------
		35-230	7.8	48.2	2.0	23.5	2.9	1.06	27.37	VA	Tr.	R	R	VR	----------	----------
		<230	69.6	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------
	19-29	>10	9.7	46.0	5.7	15.2	2.4	1.82	25.85	VA	R	R	R	Tr.	----------	----------
		10-35	4.2	43.0	4.7	18.5	2.8	.92	26.90	VA	R	R	R	VR	----------	----------
		35-230	9.9	28.7	14.5	29.0	2.9	1.89	19.27	VC	C	A	R	R	----------	----------
		<230	76.2	20.5	14.0	35.0	6.6	4.18	12.75	R	C	C	C	C	----------	----------
PR-24	.9-9	>10	10.2	33.0	1.2	35.0	3.2	2.43	23.47	VA	----------	C	R	C	----------	----------
		10-35	5.6	28.7	1.2	41.5	3.3	4.21	19.26	VA	----------	C	C	C	----------	----------
		35-230	8.9	27.2	2.0	40.0	4.0	4.10	16.91	VA	Tr.	VC	C	C	----------	----------
		<230	75.5	18.0	2.5	45.5	6.9	3.17	18.69	VA	----------	A	C	R	----------	----------
	9-19	>10	8.6	43.5	1.7	19.5	3.1	1.31	27.54	VA	----------	R	R	R	----------	----------
		10-35	5.5	37.7	1.2	30.5	2.7	.99	26.30	VA	----------	C	C	R	----------	----------
		35-230	6.6	30.5	1.5	36.0	4.0	1.61	22.75	VA	Tr.	VC	C	R	----------	----------
		< 230	79.3	18.0	2.5	46.0	7.3	3.98	16.49	C	Tr.	A	C	R	----------	----------
	19-24	>10	8.5	41.7	2.5	24.5	2.9	1.65	26.24	VA	Tr.	R	C	R	----------	----------
		10-35	7.8	42.0	7.5	21.2	2.6	2.58	23.63	VA	C	R	C	VR	----------	----------
		35-230	27.2	27.5	15.2	32.2	4.0	2.78	14.28	C	VC	A	R	C	----------	----------
		<230	56.5	24.0	15.2	33.0	5.0	4.04	14.37	C	VC	A	C	R	----------	----------
							Lihue plantation (pl. 3)									
Ki-40	0.5-9	>10	16.2	46.5	1.0	19.5	2.4	0.30	30.00	VA	----------	R	VR	C	----------	----------
		10-35	7.1	47.5	1.2	19.0	2.4	.70	29.50	VA	----------	R	Tt.	C	----------	----------
		35-230	14.9	27.0	1.7	43.2	3.4	1.90	23.50	VA	----------	A	C	C	----------	----------
		<230	61.8	17.5	2.2	46.7	7.8	1.90	19.40	C	----------	A	VC	VC	----------	----------
	9-19	>10	9.3	54.5	1.7	12.0	1.5	.71	30.91	VA	----------	VR	R	VR	----------	----------
		10-25	8.2	51.7	1.7	14.5	1.8	.65	31.13	VA	----------	VR	VR	VR	Tr.	----------
		35-230	22.3	27.5	3.0	42.5	2.8	1.40	21.00	VA	R	A	R	VR	Tr.	----------
		<230	60.2	19.0	7.0	42.7	8.0	2.86	15.31	C	C	VC	R	VC	Tr.	----------
	19-44	>10	6.8	47.5	3.2	18.0	2.2	.50	27.40	VA	R	R	Tr	VR	Tr.	----------
		10-35	7.7	50.0	3.7	15.8	2.0	.50	28.80	VA	R	VR	VR	Tr.	Tr.	Tr.
		35-230	26.2	25.7	8.7	39.2	3.5	2.96	17.89	VA	C	A	R	VR	Tr.	----------
		<230	59.0	23.2	14.2	35.2	6.4	2.30	16.10	A	VC	C	R	VC	----------	Tr.
Ki-46	1-4	> 10	16.3	35.7	5.2	29.0	3.2	1.30	24.30	VA	R	C	R	R	----------	----------
		10-35	19.5	23.2	10.7	38.5	4.5	2.30	19.50	VC	R	A	C	VR	----------	----------
		35-230	32.6	20.7	11.5	38.5	5.0	2.30	19.10	C	C	A	C	VR	----------	----------
		<230	31.5	19.7	12.0	37.7	5.8	1.90	19.30	C	C	A	C	C	----------	----------
	4-9	>10	6.3	36.0	9.5	26.0	2.0	1.47	25.18	VA	C	VC	C	VR	----------	----------
		10-35	11.1	29.2	14.5	30.5	2.7	2.10	21.40	A	C	A	C	VR	----------	----------
		35-230	28.7	21.7	17.5	38.7	3.0	1.80	17.10	R	C	A	C	VR	----------	----------
		<230	53.9	22.0	21.5	31.0	5.0	2.70	15.20	VR	C	C	C	C	----------	----------
	9-14	>10	20.0	36.7	5.0	26.5	3.0	.60	26.60	VA	R	C	R	VR	----------	----------
		10-35	8.4	29.2	7.2	34.7	3.0	5.52	20.71	VA	R	A	R	VR	----------	----------
		35-230	29.7	22.7	9.5	41.7	3.8	1.50	19.50	A	R	VC	R	VR	----------	----------
		<230	41.9	22.0	17.0	33.7	4.6	2.10	17.30	C	C	VC	R	VR	----------	----------
	14-19	>10	3.1	33.5	7.7	30.5	2.8	1.54	23.95	VA	R	C	R	VR	----------	----------
		10-35	7.4	26.2	11.5	37.5	2.4	2.31	19.79	VA	C	VA	R	VR	----------	----------
		35-230	31.0	24.0	19.2	33.7	2.9	2.30	17.20	C	C	VC	R	VR	----------	----------
		<230	58.4	23.7	22.0	30.0	4.8	2.00	15.50	C	A	VC	R	VR	Tr.	----------
	19-21	>10	8.2	29.0	8.5	28.7	2.8	3.37	20.07	VA	R	R	R	VR	----------	----------
		10-35	11.5	27.0	14.2	30.5	2.2	2.85	20.35	VA	C	R	Tr.	VR	----------	----------
		35-230	56.8	25.7	13.2	31.0	4.1	4.05	19.72	VA	C	C	Tr.	C	----------	----------
		<230	23.4	27.5	13.2	29.7	3.2	3.59	19.70	VA	C	C	VR	R	----------	----------
Ki-54	.5-9	>10	17.6	32.5	2.0	37.5	3.0	1.20	24.50	A	----------	VC	C	----------	Tr.	Tr.
		10-35	8.5	30.5	1.5	41.2	3.0	2.98	23.54	VA	----------	A	C	----------	Tr.	Tr.
		35-230	9.6	31.5	2.5	37.2	3.3	2.21	23.23	VA	Tr.	VC	R	R	----------	Tr.
		<230	64.4	18.5	5.0	43.2	7.0	1.50	20.80	C	R	A	R	C	Tr.	Tr.
	9-19	>10	5.3	42.2	2.5	24.0	3.4	1.10	25.78	VA	Tr.	R	R	C	Tr.	Tr.
		10-35	4.8	43.0	2.0	23.5	3.2	2.60	24.75	VA	Tr.	R	R	C	Tr.	Tr.
		35-230	26.2	26.2	3.0	42.7	3.8	.90	21.90	VA	R	VC	R	C	Tr.	----------
		<230	63.7	24.0	7.0	37.5	6.8	1.70	18.60	VA	R	C	R	C	VR	Tr.
	19-29	>10	3.0	42.2	4.0	23.0	2.9	1.60	31.10	VA	R	R	C	R	----------	Tr.
		10-35	5.5	41.5	8.0	21.0	2.8	4.03	22.42	VA	R	VR	R	R	----------	Tr.
		35-230	28.8	26.2	11.7	37.7	3.6	1.10	19.30	VC	C	C	C	R	----------	----------
		<230	62.7	26.0	16.0	31.5	5.4	1.90	16.90	C	A	R	R	----------	VR	----------
	29-39	>10	3.2	32.0	6.0	36.2	3.0	1.85	23.23	VA	C	C	C	Tr.	----------	----------
		10-35	4.6	35.7	14.2	23.5	2.8	1.60	20.15	VA	A	R	C	C	----------	----------
		35-230	33.0	26.5	20.7	32.5	3.6	1.30	15.70	VC	VA	R	R	C	----------	----------
		<230	59.3	28.2	23.5	26.7	4.0	2.10	16.00	VC	A	R	R	C	----------	----------
Ki-57	0-4	>10	17.0	28.5	2.0	44.5	3.0	2.26	23.71	VA	----------	A	C	C	----------	----------
		10-35	11.4	19.2	2.0	54.0	4.2	3.82	20.52	A	----------	VA	C	C	----------	----------
		35-230	11.8	21.7	3.7	43.0	5.0	2.15	19.38	VA	VR	A	C	C	----------	----------
		<230	59.7	19.2	9.2	38.5	7.2	2.30	22.00	C	R	A	C	R	----------	----------
	4-14	>10	9.1	43.2	3.0	20.7	2.8	.30	27.20	VA	VR	R	R	R	----------	----------
		10-35	3.7	46.5	3.2	21.0	2.6	1.01	20.74	VA	VR	R	R	R	----------	----------
		35-230	31.2	24.5	9.0	37.5	4.9	1.60	18.20	A	C	C	R	R	----------	----------
		<230	56.0	23.0	14.7	35.0	5.2	1.80	18.20	C	VC	VC	C	R	----------	----------
	14-24	>10	2.0	32.2	15.7	28.5	3.0	3.22	19.29	VA	C	R	C	VR	----------	----------
		10-35	5.8	32.2	28.5	18.7	2.7	1.10	17.60	C	A	R	C	VR	----------	----------
		35-230	36.3	27.5	25.7	28.0	3.0	1.40	15.00	R	A	R	C	VR	----------	----------
		<230	55.8	26.2	26.0	28.0	4.4	1.50	14.80	R	A	R	C	VR	----------	----------

TABLE 6.—*Variations in principal chemical and mineral contituents of ferruginous bauxite and saprolite with grain size and depth*—Continued

Auger hole	Sample depth interval (feet)	Particle size		Chemical analysis (in percent)						Mineral content						
		U.S. series sieve Nos.	Per-cent, dry weight	Al_2O_3	SiO_2	Fe_2O_3	TiO_2	H_2O-	H_2O+	Gibbsite	Halloysite	Goethite	Hematite	Magnetite	Anatase	Ilmenite
Lihue plantation (pl. 3)—Continued																
	24–29	>10	1.2	37.5	9.2	24.5	2.9	1.30	24.01	VA	C	R	R	VR	---	---
		10–35	4.6	32.2	24.0	20.7	2.8	3.53	16.00	VC	A	R	C	VR	---	---
		35–230	35.0	26.2	23.7	30.5	3.4	2.20	14.80	R	A	R	R	VR	---	---
		<230	59.2	26.2	25.5	27.7	4.0	1.70	15.40	R	A	R	C	VR	Tr.	---
Grove farm (pl. 3)																
GF-30	1–5	>10	1.6	29.0	19.5	26.0	3.0	---	---	C	C	VA	R	VR	---	---
		10–35	14.9	26.7	28.0	21.0	4.8	5.71	13.71	Tr.	A	A	R	VR	---	---
		35–230	45.0	25.2	27.0	22.0	4.9	4.83	14.99	Tr.	A	A	R	VR	---	VR
		<230	38.5	25.5	27.0	21.2	5.1	4.38	14.90	Tr.	VA	A	VR	VR	---	R
	5–9	>10	2.9	27.0	25.5	22.2	4.3	---	---	R	A	A	VR	R	---	R
		10–35	18.2	30.7	32.5	15.0	4.6	4.18	14.36	Tr.	VA	VC	VR	VR	---	R
		35–230	36.5	30.7	32.0	15.0	5.1	2.62	18.22	Tr.	VA	VC	VR	VR	---	VR
		<230	42.5	30.0	32.0	15.2	5.8	3.10	17.00	Tr.	VA	VC	R	VR	---	VR
	9–14	>10	3.5	27.5	27.5	24.0	3.6	3.41	14.74	VR	VA	A	R	VR	---	VR
		10–35	37.5	30.0	32.0	15.7	5.0	2.50	15.30	Tr.	VA	VC	Tr.	VR	---	VR
		35–230	40.0	29.7	32.0	15.5	5.1	2.40	15.40	Tr.	VA	C	VR	VR	---	VR
		<230	19.0	29.2	32.0	15.2	5.6	4.38	13.63	Tr.	VA	VC	VR	VR	---	R
	14–19	>10	1.7	23.5	21.5	35.0	2.8	3.34	16.55	Tr.	VA	VR	---	R	---	---
		10–35	14.9	30.5	34.5	15.5	4.2	4.99	13.18	Tr.	VA	VC	---	R	---	VR
		35–230	23.6	30.7	34.5	14.7	4.2	2.50	15.00	Tr.	VA	C	---	R	---	Tr.
		<230	59.8	29.7	34.0	14.5	5.8	2.80	14.40	Tr.	VA	VC	VR	R	---	R
	19–24	>10	2.2	24.5	32.7	18.7	3.4	1.32	10.93	Tr.	VA	VC	Tr.	R	---	VR
		10–35	8.2	26.7	36.0	15.5	4.0	4.54	12.41	Tr.	VA	R	Tr.	R	---	VR
		35–230	28.1	27.5	37.5	13.5	4.0	4.78	12.31	Tr.	VA	VC	---	---	VR	VR
		<230	61.5	27.0	36.5	14.2	5.6	3.20	13.00	---	VA	VR	VR	---	VR	R
	24–34	>10	7.6	16.7	35.0	24.0	3.2	8.87	10.42	Tr.	VA	C	---	VR	VR	---
		10–35	16.8	16.7	36.2	24.5	2.2	5.10	13.70	---	VA	C	Tr.	VR	VR	---
		35–230	26.1	16.2	33.7	25.2	3.0	9.14	10.45	Tr.	VA	C	---	---	---	---
		<230	49.4	16.7	31.0	23.0	6.2	4.20	13.70	---	VA	C	Tr.	R	Tr.	---
GF-46	0–4	>10	15.1	41.2	4.0	22.0	2.8	.97	27.31	VA	---	R	A	VR	VR	---
		10–35	30.5	23.0	8.5	37.2	5.6	2.54	19.09	VA	R	VC	A	VR	Tr.	---
		35–230	28.6	18.0	9.0	42.0	6.0	2.95	16.80	C	C	A	A	VR	---	---
		<230	25.8	17.5	10.5	41.2	7.0	2.58	16.08	C	C	A	VA	C	---	---
	4–9	>10	10.4	53.2	2.5	14.7	1.7	1.88	28.76	VA	---	R	C	Tr.	---	---
		10–35	9.5	46.7	4.0	17.7	2.5	.76	29.17	VA	---	C	VC	VR	---	---
		35–230	22.8	23.0	7.5	39.5	4.4	2.12	20.55	VA	R	VC	A	VR	---	---
		<230	57.3	20.0	12.0	37.5	6.2	2.94	15.69	C	C	A	VA	C	---	---
	9–14	>10	11.1	43.2	8.0	19.7	2.6	.68	24.61	VA	R	C	C	VR	---	---
		10–35	33.4	27.2	13.5	30.0	4.5	2.59	18.89	A	C	R	VC	VR	---	---
		35–230	29.9	21.5	16.0	35.7	5.0	2.13	19.40	C	C	A	VC	VR	---	---
		<230	25.6	21.5	17.0	35.0	5.8	2.41	15.16	C	C	VC	A	VR	---	---
	14–19	>10	7.7	46.7	7.5	16.7	2.0	.80	28.24	VA	R	C	C	VR	---	---
		10–35	8.8	34.0	15.0	23.5	3.4	2.00	22.78	VA	C	C	VC	VR	---	---
		35–230	28.4	22.0	18.5	35.0	4.2	3.33	16.02	R	C	A	C	VR	---	---
		<230	55.0	22.5	19.5	33.0	5.4	3.55	13.32	R	VC	VC	C	VR	---	---
	19–24	>10	4.9	37.2	6.5	30.0	2.3	.73	28.50	VA	R	A	C	Tr.	---	---
		10–35	5.5	35.0	21.5	19.5	2.6	1.65	21.92	VA	VC	C	R	VR	---	---
		35–230	17.1	25.0	24.0	30.7	3.2	3.50	14.46	R	A	VC	R	C	---	---
		<230	72.4	23.5	24.0	30.2	4.6	2.60	14.00	VR	A	VC	C	C	---	---
	24–34	>10	6.2	42.2	14.5	17.2	2.4	1.86	20.85	VA	C	R	R	C	---	---
		10–35	12.4	28.5	24.0	25.0	3.6	2.51	16.95	C	A	C	R	VC	---	---
		35–230	40.3	23.7	24.5	31.7	3.8	3.33	13.85	R	A	VC	R	VC	---	---
		<230	41.4	24.2	25.0	28.2	4.8	3.60	12.83	VR	A	A	C	VC	---	---
	34–44	>10	1.1	37.2	21.5	19.0	2.7	1.88	20.98	VA	A	C	---	VC	---	---
		10–35	6.4	31.0	29.0	20.2	2.8	2.57	16.08	R	A	C	---	VC	---	---
		35–230	32.9	23.2	25.0	31.7	3.2	2.59	14.65	Tr.	A	VA	R	A	---	---
		<230	59.6	25.0	27.5	27.5	4.4	3.53	12.42	Tr.	VA	A	R	VA	---	---
	44–49	>10	1.6	39.5	18.5	17.5	2.5	2.03	21.86	A	A	C	VR	C	---	---
		10–35	5.0	31.5	28.0	20.5	2.7	2.73	16.40	C	VC	A	VR	VC	---	---
		35–230	24.2	22.5	24.0	33.7	3.4	3.71	13.12	Tr.	VA	A	VR	VC	---	---
		<230	69.2	25.0	27.5	27.0	4.4	4.08	12.19	Tr.	VA	VC	VR	VA	---	---

matter present can be made by subtracting the percentage of water from the loss on ignition. The difference between these two percentages is as much as 5.3 percent. Ordinarily, organic matter is more abundant in the A and B soil horizons, which are represented by samples taken at depths of a maximum of 4 feet. However, samples from depths as great as 24 feet at a few localities (table 2, holes PR–32, Ki–67, Ki–85) also contain appreciable quantities of organic matter. Much organic matter at shallow depths occurs as roots, rootlets, and their rotted remains, but some is present in rocks in which plant structures could not be identified.

The presence of appreciable organic matter in soil and saprolite from shallow depths is also recognizable in differential thermal analyses. A very strong exothermic reaction between 450° and 580°C (fig. 6, sample depth 1–4 ft) and one between 410° and 490°C (fig. 6, sample depth 4–9 ft) are due chiefly to organic matter.

VARIATIONS IN CHEMICAL AND MINERAL COMPOSITION OF SAPROLITE WITH DEPTH AND PARTICLE SIZE

The composition of the saprolite formed on the Koloa Volcanic Series varies with depth (fig. 8; tables 2, 6). Ordinarily, the variations conform to trends representing gradual changes from thoroughly weathered saprolite near the surface to less weathered saprolite at depth. Trends are interrupted where younger flows overrode weathered surfaces, and the younger flows are not so completely weathered as the rocks below them. Al_2O_3 content in the saprolite tends to remain rather uniform at all depths, increasing only slightly toward the surface. At two localities (fig. 8, Ki–67 and HO–3), Al_2O_3 is concentrated at shallow depths, a type of concentration also occurring in ferruginous bauxite in Oregon (Allen, 1952, fig. 2). SiO_2 increases markedly with depth. Fe_2O_3 is the most abundant component of all the saprolite. With few exceptions Fe_2O_3 increases considerably toward the surface; whereas FeO is present in only small quantities and is uniformly distributed at all depths. TiO_2 is uniformly distributed throughout nearly all the saprolite, making up to 4–7 percent of the rock. Total alkalies and alkaline earths, chiefly CaO and MgO, make up only a small percentage of the saprolite, except in the least weathered part in contact with hard basalt—for example, the sample from the bottom of the hole Ki–64 (fig. 8), which penetrated to hard rock. The alkali and alkaline-earth content of this type of saprolite is intermediate between that of fresh basalt and typical saprolite.

Mineral composition of the soil and saprolite also varies with depth. Near the surface, gibbsite is the principal aluminous mineral and halloysite is rare. At depths greater than 15 or 20 feet, gibbsite is rarely present in more than minor quantities and halloysite is very abundant, a trend also noted by Holmes, Takahashi, and Sherman (1960).

Both mineral and chemical compositions of the saprolite vary with particle size; however, the range in these variations is difficult to determine because most particles are soft aggregates of more than one mineral that break down with continued washing or mixing. The samples in which particle size was investigated (table 6) were disaggregated by boiling in water followed by wet sieving. To prevent excessive destruction of particles, such as occurs when saprolite is mixed in a Waring Blendor, no mechanical separator methods were used. Natural moisture was preserved in these samples to prevent agglutination due to drying, and dry weights were calculated from moisture determinations. The results of these investigations (table 6) reveal several trends. Ordinarily, the saprolite and soil near the surface contain more coarse particles than the saprolite at depth, but there are many exceptions. Probably the most pronounced trend is that for gibbsite—and, therefore, Al_2O_3—to be most abundant in grains coarser than medium sand (>35 mesh) (pl. 10*E*); however, this mineral also occurs in finer grains including silt- and clay-sized particles (<230 mesh). Metahalloysite, to which all halloysite was converted by drying before mineralogic study, is very abundant in silt- and clay-sized particles and is ordinarily much less abundant in coarser particles. Iron-bearing minerals are abundant in all grain sizes.

ORIGIN OF SAPROLITE AND SOIL

The saprolite and soil are formed by weathering processes that are effective in removing major chemical constituents, destroying all but a very few minerals of the parent rock and forming new minerals. Downward-percolating ground water is the principal agent of weathering. Silica, calcium, and alkalies are the major constituents removed. Aluminum, iron and titanium, and water are the principal constituents of the new minerals that form during the weathering process and remain in the most weathered materials.

FACTORS INFLUENCING WEATHERING

Weathering of rocks on Kauai varies considerably and is controlled by topography, rainfall, temperature, permeability of rocks, vegetation, and the age, composition, and texture of the parent rocks. The precise influence of each factor is difficult to determine because the various factors are interrelated, and the role of one rarely can be separated from that of the others.

The principal influence of topography on weathering is in its control of rainfall, temperature, erosion, and drainage. On Kauai, as on other islands in Hawaii, the heavier rainfall belts are restricted to the higher mountains, and the lowest rainfall is near the coast on the leeward west side of the island. The mean annual rainfall at Mount Waialeale in the high central part of the island is 466 inches; 18 miles away at Mana, on the dry western side, it is only 21 inches. Except where dominated by other factors, the more thoroughly weathered rock occurs in belts of heaviest rainfall. Rock sufficiently weathered to be considered bauxite is rare near the coast, and most of the better grade deposits are above 500 feet altitude. The effect of topography on temperature is summarized by Macdonald, Davis, and Cox (1960, p. 113) as follows:

> at altitudes below about 300 feet the mean monthly temperature ranges from about 69°F in February and March to about 77°F during August through October. Differences in exposure to the trade winds apparently have no consistent effect on mean temperatures in the lowlands. Records are not available for higher altitudes, but the mean temperature decreases with height, probably dropping about 3°F for each 1,000-foot increase in altitude.

Topography influences erosion mainly through slope angle and altitudinal control of rainfall. Most thoroughly weathered rocks on Kauai are on planezes of the Koloa Volcanic Series, which form gently sloping uplands at altitudes as high as 1,200 feet. Most rocks at higher altitudes are older and in belts of much heavier rainfall; they should therefore, be more thoroughly weathered. However, these older rocks form rugged highlands characterized by sharp ridges, where erosion by surface runoff more nearly keeps pace with weathering than in the gently sloping areas at lower altitudes. Even in these lower gently sloping areas, local relief has a major influence on weathering. The planezes in these areas are separated by deep, steep-walled valleys, many of which contain permanent streams. This topography and the permeability of the weathered rocks provide excellent subsurface drainage. Subsurface drainage is a major factor in weathering, as indicated by the differences in mineral and chemical constituents between the typical well-drained saprolite (p. 14–23) and the plastic clay in swamps (p. 47, 48).

The age of the parent flows and, therefore, the time involved in weathering also affects saprolite formation; however, the Koloa Volcanic Series originated from many vents and the relative ages of only a few flows can be determined. The ages of parent rocks probably do differ considerably and are important in the formation of bauxite and soils; this relation is suggested by marked differences in weathering of rocks associated with the Kilohana and Hanahanapuni vents (pl. 3). The rocks associated with the Kilohana vent are so deeply weathered that auger holes nearly 60 feet deep, located near the rim and on the flanks of the crater, failed to penetrate to hard rock. Hanahanapuni, however, contains very porous ash and spatter so fresh that it has been dug for road metal, and extensive flows located seaward from this vent contain many residual boulders of basalt at or near the surface. The marked difference in weathering of the rocks associated with these two vents indicates an appreciable difference in their ages.

Evidence regarding the importance of chemical and mineral composition of parent rocks is obscured by the lack of knowledge of the relative ages of these rocks. Silica-deficient flows probably weather much more rapidly than those richer in silica, as suggested by very deep saprolite and large bauxite areas on nepheline basalt between the Hanalei and Kalihiwai Rivers (pl. 1); whereas saprolite and bauxite formation east of the Kalihiwai River in an area of olivine basalt is much less advanced. The rocks in these contrasting areas did not originate from the same vent, however, and their present difference may be due more to differences in age than to composition of the parent rocks.

Great textural differences in volcanic rocks result in large variations in permeability and, therefore, in the rates and products of weathering, as pointed out by Bates (1960, p. 4). As most investigations reported herein were restricted to the Koloa Volcanic Series, a denser and more uniform series than most rocks in Hawaii, only a few of the possible influences of texture on weathering were observed. The fine-grained character of the Koloa rocks tends to make them resistant to weathering and also to increase their resistance to erosion after weathering. Saprolite formed from these rocks consists of interlocking grains (pl. 8), preserving the texture of the parent rocks. Because of this texture, saprolite from the Koloa rocks tends to be more cohesive and resistant to erosion than that formed on the more open-textured and porous Waimea Canyon Volcanic Series. Resistance to erosion, in turn, enables the Koloa rocks to withstand longer periods of weathering and is one of the reasons they tend to be more thoroughly weathered than the older series. Two other examples of textural influence in weathered rock were observed: (1) A bed of ash, which must have originally been highly porous, shows evidence of being more weathered than associated rocks (p. 36); (2) buried soils, which have been sufficiently weathered to have their parent-rock textures destroyed and have undergone compaction by overlying rocks, are denser than the saprolite on which they formed (p. 37).

The influence of vegetation in weathering is probably major but cannot be fully appraised. Almost all the endemic vegetation has been affected by the activities of European man in Hawaii (Fosberg, 1961, p. 17); whole vegetation types have been destroyed, and few areas exist where plant population is not dominated by introduced species. However, several types of evidence indicate that the growth and decay of plants have contributed to the weathering of volcanic rocks. Twenty species of plants established themselves on recent flows on the island of Hawaii within 1 year after the surface of lavas cooled (Doty, 1961, p. 139), indicating that most surficial rocks have been under the influence of vegetation throughout virtually their entire history. Thick local deposits of both surficial peat (p. 55), and pollen contained in them (Selling, 1948), indicate that heavy growths of vegetation existed in many places since the close of the best glacial period, and buried peat (p. 55) is probably older. Probably the major role played by vegetation in weathering is the contribution of organic acids released in plant decay to the acidity of water passing through the rock. However, minor quantities of silica may be added to the weathered rock by the vegetation cycle, and *Melastoma* has been recognized to be an aluminum accumulator plant (Sherman and others, 1967, p. 45).

LOSS IN DENSITY DURING WEATHERING OF FRESH ROCK TO SAPROLITE

Significant changes in density with only very slight volume changes take place during the weathering of fresh rock to saprolite. A measurement of the loss in density during weathering was obtained by determining the bulk densities of 60 samples of saprolite and 120 samples of fresh volcanic rock from the Koloa Volcanic Series. The saprolite was found to have an average dry weight of less than 70 pounds per cubic foot, and the fresh rock has an average dry weight of 174 pounds per cubic foot. Accordingly, it can be concluded that about 60 percent of the density of the fresh rock is lost during weathering to saprolite. Volume loss is only slight, as indicated by the preservation in the saprolite of vesicles (fig. 3) and other structures and textures of the parent rock, as well as the lack of evidence of collapse.

MINERAL ALTERATION DURING WEATHERING

FELDSPAR AND FELDSPATHOIDS

Feldspar and feldspathoids are the principal aluminum-bearing minerals in the parent rock, and they are completely destroyed during weathering. Alteration of these minerals commonly begins along cleavages in the central parts of lath-shaped crystals, as has also been noted in feldspar from Maui (Bates, 1962, p. 324–325) and California (Snetsinger, 1967, p. 254–255). The first alteration occurs as microscopic patches of material that has very low birefringence (pl. 9D). As weathering progresses, the low birefringent material spreads through entire crystals, and still later, much of this material changes over to a material that has the slightly higher birefringence of metahalloysite. The initial very low birefringent material is probably allophane; however, the amorphous material in feldspar or feldspathoid crystals is difficult to identify because grains are too small to isolate. Weak, extremely diffuse X-ray reflections for metahalloysite, and broad low bulges that suggest the presence of amorphous material, were present in X-ray traces from the -1μ fraction separated from a sample of the outer rim of one residual boulder. Previous microscopic examination had indicated that this weathered rim consists chiefly of feldspar in early stages of alteration—goethite formed from olivine, and unaltered pyroxene and magnetite.

Whether or not an intermediate amorphous phase exists, most feldspar and feldspathoids alter to halloysite, which, in turn, alters to gibbsite; the direct alteration from feldspar and feldspathoids to gibbsite takes place only on a small scale, if such a transition takes place at all. Halloysite is a major rock-forming mineral in saprolite at depth and in incompletely weathered rock near the surface, and much of this mineral occurs as pseudomorphs after feldspar and feldspathoids. As weathering advances, halloysite in feldspar pseudomorphs alters to gibbsite, as can be observed in thin sections of saprolite at intermediate stages of weathering, an observation also made by Bates (1962, p. 325). Alteration of halloysite to gibbsite is also indicated by the general abundance of gibbsite in near-surface saprolites that overlie high-silica saprolites, in which halloysite is the only mineral containing alumina and, therefore, the only possible parent from which gibbsite could form. Gibbsite pseudomorphs after feldspar and feldspathoids are abundant in thoroughly weathered saprolite, some of which has been found close to residual boulders of fresh basalt near the surface. The presence of these pseudomorphs in close association with hard basalt has led some authors (Abbott, 1958, p. 853; Sherman and others, 1967, p. 43) to conclude that feldspar alters directly to gibbsite.

MAGNETITE AND ILMENITE

Magnetite and ilmenite are virtually the only resistant minerals of the parent rock that remain in the saprolite. In most saprolite in well-drained areas, these minerals are altered very little but are commonly partially coated with hematite and agglutinated with goethite, gibbsite, and halloysite-metahalloysite into larger aggregates. In the most thoroughly weathered rock, hematite is commonly closely associated with magnetite, and almost certainly magnetite and ilmenite alter to hematite and probably to goethite during weathering. Probably anatase forms from the titanium in both magnetite and ilmenite, as is suggested by its abundance in swamp clays in which most of the magnetite and ilmenite have been destroyed (p. 15). The possibility that maghemite has formed from magnetite during weathering is discussed briefly on page 17.

OLIVINE

Most olivine phenocrysts in the Koloa Volcanic Series are green, but some are brownish green, brown, and almost black (Macdonald, 1960, p. 103).

Iron and magnesium contents of these olivines probably vary considerably between the end members, fosterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4). The one sample from the Koloa Series that has been analyzed (Ross and others, 1954, table 4) was of the typical green type found in the Grove Farm Co., Ltd., quarry southwest of Lihue. This sample contained 8.89 percent FeO and 49.56 percent MgO. Probably the browner olivines are much richer in iron than this sample.

Olivine alters to several minerals during weathering, and which type forms depends largely on the intensity of the process. In the less weathered saprolite the outer rims of olivine phenocrysts are typically atlered to reddish-brown glassy goethite (pl. 9*F*) and the center parts to iron-stained antigorite. In advanced stages of weathering, all antigorite is removed, and former olivine grains are commonly represented only by soft open-textured pseudomorphs of yellowish-brown geothite having an extremely low bulk density. Where olivine in hard basalt is being altered by the action of ground water, nontronite, some of which probably contains excess iron, commonly occurs as growths along fractures and as replacement of olivine grains. Nontronite is destroyed by intense weathering, and the principal mineral remaining after intense weathering is goethite. Both saponite and a mineral tentatively identified as "swelling chlorite"(?) probably form from components released in the destruction of olivine; however, neither mineral was found as a replacement or direct alteration product of olivine. Ferruginous gels and other amorphous matter may form from the destruction of olivine, a possibility also noted by Bates (1962, p. 316). The only evidence found to support this suggestion is that X-ray diffractometer traces of hand-picked pseudomorphs after olivine contain only weak diffuse reflections for goethite, which indicate amorphous or poorly crystalline materials may be present.

PYROXENE

In the fresh rock, pyroxene is very fine grained, and its alteration during weathering could not be investigated satisfactorily. In thin sections from the outer part of several different residual boulders, the pyroxene was almost fresh, whereas the feldspar and olivine were completely altered. In the saprolite adjacent to these boulders, the pyroxene was completely altered to extremely fine grained iron-stained material that is probably chiefly halloysite-metahalloysite and goethite. Members of the pyroxene group are the last minerals to be destroyed as the rock weathers to saprolite. Pyroxene minerals are also the most resistant minerals in andesite in the Cascade Range, Calif. (Hendricks and others, 1966, p. 51), and weather later than feldspar in volcanic rocks in Japan (Aomine and Wada, 1962, p. 1040; Hendricks and Whittig, 1968a, p. 145). Probably when pyroxene does weather, most tends to alter initially to halloysite and goethite, but other minerals may also form under differing conditions of leaching; an amorphous phase may or may not occur before the first secondary minerals form from the pyroxene. Much fresh pyroxene in the Koloa Volcanic Series is purple, indicating that it is titaniferous (Macdonald, 1960, p. 103–105). This titanium may be altered to anatase as the pyroxene is destroyed, but no evidence that such a transition takes place was obtained.

VOLCANIC GLASS

The weathering of volcanic glass is probably important in the formation of saprolite and soil in Hawaii (Allen and Sherman, 1965, p. 90, 95; Bates, 1962, fig. 1). However, the ferruginous bauxite is formed on the Koloa Volcanic Series, which is more crystalline and contains much more massive flows than most volcanic rocks in Hawaii. Some rocks in the upper parts of flows are extremely vesicular and undoubtedly were originally clinkery and contained some volcanic glass. The samples examined microscopically were either fairly fresh glass from hard basalt or completely altered fine-grained iron-stained material that could not be separated from the alteration products of the original minerals. One bed of weathered volcanic ash (p. 36), which must have originally contained abundant glass, is now altered to products very similar to those formed from crystalline rocks.

CHEMICAL CHANGES DURING WEATHERING

Chemical changes during weathering can be investigated in several ways. One method is to compare chemical analyses of rocks that represent all stages of weathering. This method can be applied to rocks on Kauai because fresh rock in residual boulders occurs near the surface in close association with thoroughly weathered rock of the same flows. One group of samples (table 7, samples 1–4), representing the change from basalt to saprolite, was taken in a roadcut at the time of excavation in the summer of 1959. This cut is along Highway 56, 1.4 miles north of the bridge across Anahola Stream; it is at an altitude of 120 feet, and the area has 40–50 inches of rainfall yearly. Another group of samples was collected in a bulldozed cut along the powerline trail 0.4 mile south of the Wailua River (pl. 3). This location, at an altitude of 560 feet, is within a belt where rainfall exceeds 100 inches annually and subsurface drainage is good. It is approximately 1.8 miles south of the locations where chemical changes during weathering were investigated by Sherman (1958, table 2) and Abbott (1958, p. 852).

A second method of investigation is to analyze samples of weathered rock near the surface and at progressively greater depths (tables 2, 6; fig. 8), which has also been done for rocks on Kauai by Holmes, Takahashi, and Sherman (1960) and Allen and Sherman (1965). This method of investigation reveals the transition from the more thoroughly weathered rocks at the surface to less weathered rocks at depth. Most investigations of this type fail to show the complete changes during weathering, because of the difficulty in penetrating to and into fresh rock at depth. One auger hole (Ki–64, pl. 3) from which samples were analyzed (table 2; fig. 8) penetrated to a residual boulder. The sample of dark-gray saprolite in the 6-inch zone above this boulder contains chemical constituents similar to, but even less weathered than, the saprolite that encloses residual boulders near the surface. A third method of investigating weathering is to analyze water from fresh and weathered rocks (table 8) to obtain information on the elements taken into solution by ground water.

TABLE 7.—*Chemical analyses, in percent, of fresh basalt and saprolite of the Koloa Volcanic Series, Kauai*

[Analyzed by rapid methods described by Shapiro and Brannock (1956). Samples 1–7 analyzed by P. L. D. Elmore, S. D. Botts, I. H. Barlow, and Gillison Chloe. Sample 8 is an average of several analyses by these and other analysts]

Sample No.	1	2	3	4	5	6	7	8
Lab. No.	155281	155280	155279	155282	155529	155530	155531	
SiO_2	46.4	25.2	27.5	26.1	45.0	8.9	1.1	42.27
Al_2O_3	12.6	23.2	25.4	23.7	11.8	31.0	34.7	10.90
Fe_2O_3	2.0	27.4	25.6	27.8	4.3	30.0	31.9	4.32
FeO	10.6	2.8	1.3	1.6	9.3	1.8	1.3	8.66
MgO	11.9	.59	.38	.58	12.0	.36	.19	12.77
CaO	10.0				9.7	[1].06	[1].04	11.67
Na_2O	2.0	.08	.12	.08	1.8	.05	.02	2.85
K_2O	.48	.06	.02	.08	.62	.01	.01	.83
H_2O+	1.4	14.2	14.2	14.0	3.1	22.8	24.5	1.31
TiO_2	2.2	4.7	4.1	4.6	1.9	4.4	4.6	2.69
P_2O_5	.24	.21	.48	.25	.30	.28	.35	.69
MnO	.13	.05	.02	.05	.26	.08	.08	.13
CO_2	<.05	<.05	<.05	<.05	.09	<.05	<.05	
Loss on ignition		14.8	15.0	15.4				
Total	100	98	99	99	100	100	99	

[1] Percentage determined by quantitative spectrographic analyses by Sol Berman.

1. Residual boulder of basalt, 1 ft in diameter, exposed in cut made during construction of Highway 56, 1.4 miles north of bridge over Anahola Stream.
2. Saprolite, gray, soft, about 5 ft away, formed from the same flow as residual boulder, sample 1.
3. Saprolite, gray, occurring above and similar to sample 2, but in contact with overlying dark-red saprolitic B soil horizon.
4. B soil horizon, saprolitic, dark-red, 2 in. above sample 3.
5. Residual boulder of basalt, 10 in. in diameter, exposed in bulldozed cut along powerline trail, 0.4 mile south of Wailua River (pl. 3).
6. Saprolite exfoliated layer, 1.5 in. thick, enclosing residual boulder of sample 5.
7. Saprolite, reddish-brown, 1 ft from residual boulder, sample 5.
8. Average of available analyses of fresh basalt from the Koloa Volcanic Series, including samples 1 and 5 in this table and 11 samples previously analyzed (Macdonald and others, 1960, p. 110–111).

SILICA REMOVAL

Silica is the most abundant constituent of the parent rocks, and very little remains in the most thoroughly weathered rock. The average SiO_2 content of the fresh rock in the Koloa Volcanic Series is 42.27 percent (table 7). Much thoroughly weathered rock near the surface contains less than 5 percent SiO_2, and some saprolite and soil locally contains less than 1 percent SiO_2. Most saprolite at depth (table 2; fig. 8) and much near the surface in areas of low rainfall or poor drainage (table 7, samples 2, 3) contains about half as much SiO_2 as the parent rock. The most rapid loss of SiO_2 occurs in rocks near the surface in areas of good subsurface drainage and heavy rainfall. One thin exfoliated layer enclosing a residual basalt boulder, under such conditions, contains only 8.9 percent SiO_2, and saprolite 1 foot from this same boulder contains only 1.1 percent SiO_2 (table 7, samples 6, 7). This relation is similar to the one described by Sherman (1958, table 2) and Abbott (1958, p. 852). Analyses of auger-hole samples (table 2; fig. 8) show that saprolite below about 20-foot depths at most places contains appreciably more SiO_2 than the more thoroughly weathered saprolite nearer the surface. These analyses show that SiO_2 is removed very gradually after the initial large loss that takes place when hard rock alters to saprolite.

LOSS OF ALKALIES AND ALKALINE EARTHS

Calcium, magnesium, potassium, sodium, and other alkalies are almost completely removed during weathering. Fresh rock of the Koloa Volcanic Series contains an average of 12.77 percent MgO, 11.67 percent CaO, 0.83 percent K_2O, and 2.85 percent Na_2O (table 7). These elements are contained in olivine, pyroxene, feldspar, and feldspathoids, and a small quantity of Mg occurs in magnetite. The content of alkalies and alkaline earths in the parent rock is reduced even before it loses its hardness, as part of the feldspar and much of the olivine in the outer parts of residual boulders show evidence of alteration; by the time the rock loses its hardness nearly all the alkalies and alkaline earths are gone (table 7, samples 1, 2, 5, 6). Very minor quantities of alkalies and alkaline earths, however, are present in all saprolite. Much of the Mg, which rarely exceeds a few tenths of a percent of the saprolite, is contained in unaltered magnetite. Na, Ca, and K, reported as the oxides, rarely constitute more than a tenth of a percent and commonly are only a few hundredths of a percent of the saprolite (table 2). The form in which these elements occur is unknown; however,

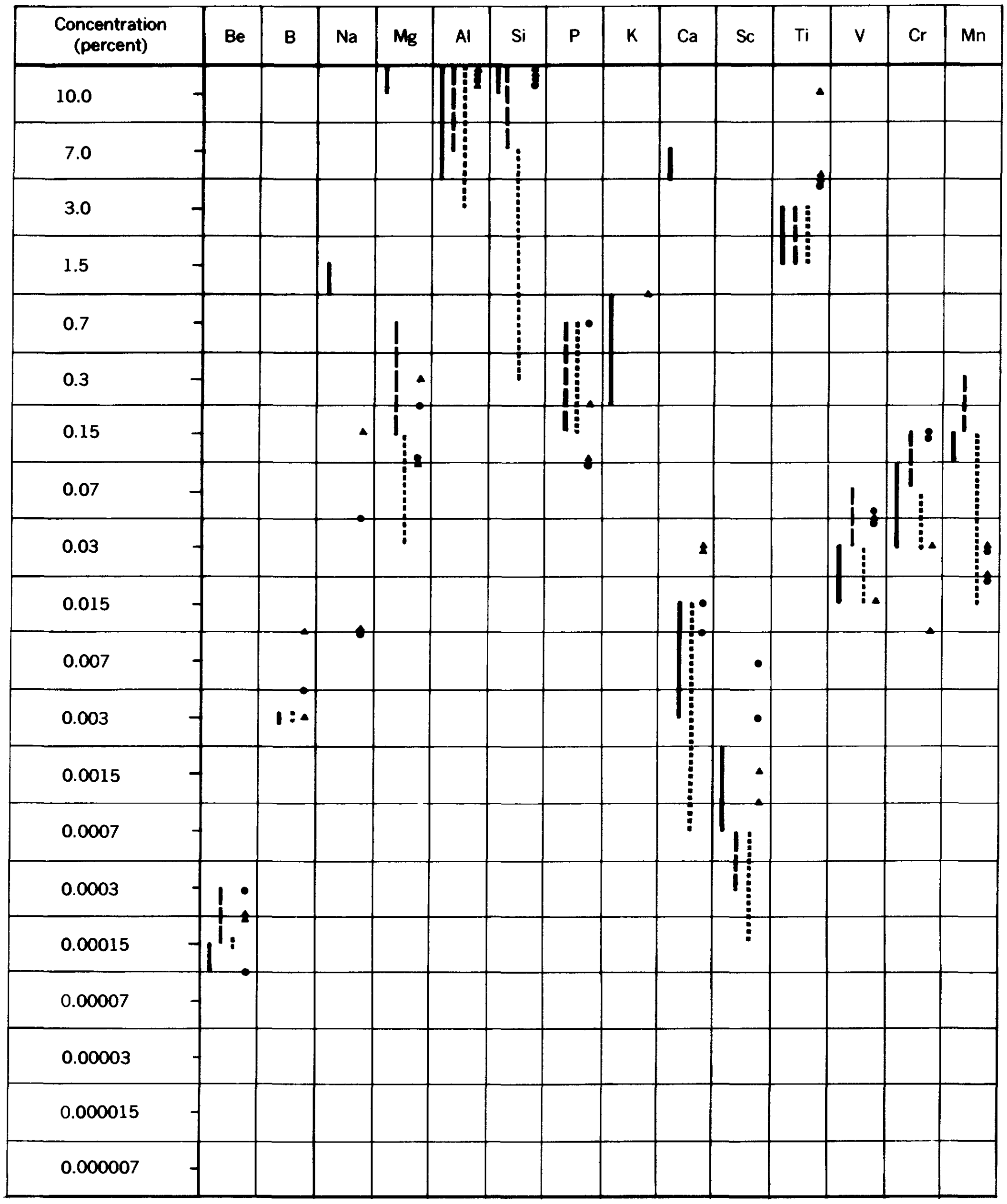
TABLE 8.—*Chemical analyses of water samples from saprolite and fresh basalt of the Koloa Volcanic Series and rain, Kauai*

[Analysts, A. S. VanDenburgh and C. E. Roberson]

Sample	Chemical constituents (parts per million)																		Cation total	Anion total	Dissolved solids calculated	Hardness as $CaCO_3$	Noncarbonate hardness as $CaCO_3$	Specific conductance (micromhos at 25°C)	pH
	SiO_2	Al	Fe	Mn	Ca^{+2}	Mg^{+2}	Na^{+1}	K^{+1}	Li^{+1}	NH_4	HCO_3^{-1}	SO_4^{-2}	Cl^{-1}	F^{-1}	I	NO_3^{-1}	PO_4	B	(epm)		(ppm)				
1	2.9	0.11	0.00	0.26	0.8	1.9	11.0	0.6	0.00	0.02	1	2.7	19.0	0.1	0.008	0.6	0.02	0.04	0.70	0.64	41.0	10.0	9	90	4.6
2	1.2	.00	.18	.13	.9	1.9	6.3	.6	.00	.02	6	4.0	9.1	.1	.006	.7	.04	.02	.49	.46	28.0	10.0	5	60	5.1
3	4.1	.01	.00	.07	1.0	1.2	6.9	.3	.00	.03	3	2.3	12.0	.1	.003	.4	.03	.03	.46	.46	30.0	7.4	5	56	5.6
4	3.0	.04	.00	.12	.4	.7	7.2	.0	.00	.02	2	3.2	12.0	.2	.006	.1	.02	.03	.39	.45	28.0	4.0	2	54	4.8
5	2.6	.03	.06	.54	1.0	2.3	8.6	.6	.00	.01	6	6.5	16.0	.1	.004	.9	.02	.05	.63	.71	42.0	12.0	7	78	5.3
6	2.5	.12	.00	.11	.6	1.5	8.5	.5	.00	.02	0	2.7	13.0	.1	.002	.8	.00	.05	.53	.45	30.0	7.6	8	67	4.7
7	32.0	.03	.00	.00	13.0	14.0	30.0	1.3	.00	------	96	37.0	30.0	.2	.002	2.0	.43	.05	3.13	3.23	207.0	92.0	12	331	7.8
8	42.0	.06	.00	.00	13.0	11.0	21.0	.8	.00	.01	78	5.2	34.0	.1	.001	1.5	.16	.01	2.28	2.38	167.0	77.0	14	265	7.6
9	34.0	.48	.49	.00	3.0	.7	5.7	.5	.01	------	0	25.0	8.3	.3	.012	.1	.14	.06	.67	.77	79.0	10.0	10	150	3.7
10	.1	.00	.00	.03	.6	.3	.8	.0	.00	.05	3	1.3	2.0	.0	.006	.2	.04	.00	.08	.14	6.9	2.6	0	18	5.7
11	.2	.00	.00	.01	.7	.4	5.3	.3	.01	------	1	4.1	8.8	.1	.005	.0	.10	.04	.30	.37	21.0	3.6	2.0	43	4.9

NOTE.—Chemical constituents looked for, but not found: OH^{-1} and CO_3^{-2} in all samples; Cr in samples 1, 3–6, and 8; NO_2^{-1} in samples 1–6, 8, and 10.

1. Water sample in auger hole in saprolite (hole PR–41, pl. 1) at depths of 35–65 ft.
2. Water sampled in auger hole in saprolite (hole PR–42, pl. 1) at depths of 15–19 ft.
3. Water sampled in auger hole in brown clay and saprolite surrounding light-colored plastic clay (hole PR–43, pl. 1) at depths of 14–19 ft.
4. Water sampled in auger hole in saprolite (hole 17, pl. 2) at depths of 19–29 ft.
5. Water sampled in auger hole in saprolite (hole Ki–45, pl. 3) at depths of 25–49 ft.
6. Water sampled in auger hole in saprolite (hole GF–12, pl. 3) at depths of 24–39 ft.
7. Sample from Anahola town water-supply well, collected Jan. 29, 1960.
8. Sample from Kealia town water-supply well, collected Jan. 22, 1960.
9. Rainwater which fell during dense smog from Kapoho eruptions; collected on plastic sheet, Jan. 26, 1960, Wailua, Kauai, Hawaii.
10. Rainwater, collected Jan. 28, 1960, Wailua, Kauai, Hawaii.
11. Rainwater, collected Feb. 9, 1960, Wailua, Kauai, Hawaii.

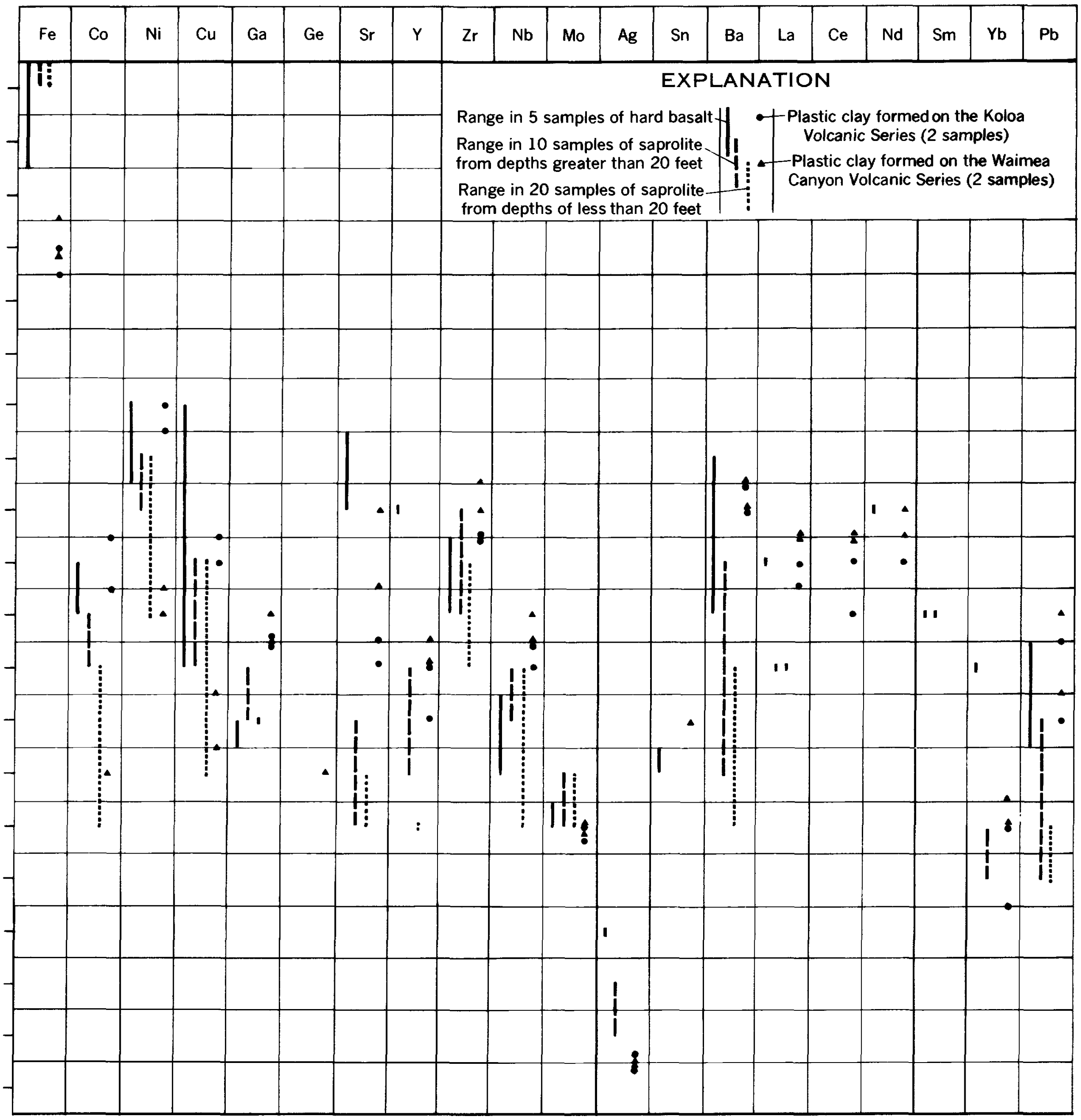


Number of samples in which

	Be	B	Na	Mg	Al	Si	P	K	Ca	Sc	Ti	V	Cr	Mn
Hard basalt	1	5					5	2						
Saprolite >20 ft deep		9	10					10						
Saprolite <20 ft deep	13	13	20				13	20						
Clay formed on the Koloa Volcanic Series		1						2						
Clay formed on the Waimea Canyon Volcanic Series								1						

[1] Not looked for in 4 samples

FIGURE 9.—Distribution of elements in hard basalt, saprolite, and plastic clay formed on the Koloa Volcanic Series and plastic
ages shown are the results of analyses reported to the nearest number in the series 1, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1, and so on.



element was looked for but not found

Fe	Co	Ni	Cu	Ga	Ge	Sr	Y	Zr	Nb	Mo	Ag	Sn	Ba	La	Ce	Nd	Sm	Yb	Pb
					5		4			1	4	3		4	5	(1)	(1)	4	3
					10	1	4				2	10		9	10	10	9	6	7
	5				20	10	19				20	20		18	20	20	20	20	15
					2							2				1	2		
	1				1							1					2		

clay formed on the Waimea Canyon Volcanic Series, as determined by semiquantitative spectrographic analyses. Percent-The assigned group will include the quantitative value about 60 percent of the time.

they are introduced as constituents of rainwater (table 8), and they may be concentrated by evapotranspiration. Possibly these elements are transient in the saprolite and are introduced at about the same rate as they are leached.

ALUMINA CONCENTRATION

The average Al_2O_3 content of the parent rock in the Koloa Volcanic Series is 10.90 percent, and the average ferruginous bauxite (table 12) is 25.9 percent, a 2.5-fold increase. Some nodules of purer gibbsite contain more than 50 percent Al_2O_3, which represents about a fivefold increase. Most concentration of Al takes place when SiO_2, alkalies, and alkaline earths are leached from the parent rock (table 7, samples 1, 2, 5, 6; Sherman, 1958, table 2; Abbott, 1958, p. 852). Saprolite at depth contains almost as much Al as the more thoroughly weathered material near the surface (table 2; fig. 8), but the Al tends to occur in different minerals at different depths. Most of the Al in thoroughly weathered rock near the surface is in gibbsite; as silica contents increase, however, greater proportions of the Al are combined with SiO_2, hydroxyls, and water in the halloysite. Generally, more Al is in gibbsite than halloysite-metahalloysite where SiO_2 contents are less than 20 percent; however, halloysite-metahalloysite makes up more of the very large volume of weathered rocks on Kauai than gibbsite, according to the results of chemical and mineralogical studies reported herein and by Patterson (1962, app.).

Much of the Al accumulation is a residual concentration, but Al is transported in the weathered rocks by ground water, as is indicated by the common occurrence of nodules, concretions, vein deposits, and pseudomorphs after feldspar and other minerals, and the presence of Al in ground water in both saprolite and hard basalt. The concentration of Al in these forms may give misleading information on the Al content of the saprolite—for example, the concentration of Al (expressed as Al_2O_3) at depths of 7–9 feet in auger hole Ki–67 (table 2; fig. 8), though similar to subsurface concentrations in Oregon bauxite noted by Allen (1952, fig. 2), may result from the auger penetrating a vein deposit that is much richer in Al_2O_3 than rock a few inches on either side.

IRON-OXIDE CONCENTRATION

Rocks of the Koloa Volcanic Series contain an average of 4.32 percent Fe_2O_3 and 8.66 percent FeO (table 7). Ferrous iron occurs in pyroxenes, olivine, magnetite, and possibly ilmenite, and probably most of the ferric iron is in magnetite. Chemical analyses of a sample of hard basalt in a residual boulder and the inner exfoliated layer of saprolite derived from this boulder (table 7, samples 5, 6) show that by the time the rock loses its hardness most of the ferrous iron is converted to the ferric form and that iron content is increased about twofold. The small quantities of ferrous iron remaining in the weathered rock are probably in magnetite. The ferric iron formed during weathering is chiefly in goethite and hematite, and appreciable quantities may also be in amorphous form.

Iron is mobilized to some extent by ground water; however, some is in pseudomorphs after olivine, which are so open textured that no iron may have been introduced. Evidence that iron is mobilized lies in its occurrence in concretions, veins, and other forms similar to those of gibbsite. According to analyses of many samples taken at different depths (tables 2, 6; fig. 8); iron is concentrated more effectively during weathering than all other oxides, a conclusion also supported by the small quantities in solution in ground water from both saprolite and hard basalt (table 8, samples 1–8).

TITANIA CONCENTRATION

The range in TiO_2 content of the two samples of fresh basalt from the Koloa Volcanic Series analyzed during this investigation and the 11 samples for which analyses were previously available is 1.90–4.05 percent, and the average is 2.69 percent. The average TiO_2 content in many samples of ferruginous bauxite (the most thoroughly weathered saprolite) is 6.7 percent and that of saprolite mostly at depth is about 5 percent (Patterson, 1962, p. 2, 4). The average increase of TiO_2 in the saprolite at depth is slightly less than twofold, and the increase in the shallow, thoroughly weathered saprolite is a little more than 2.5-fold, or about the same as for Al_2O_3. A comparison of the TiO_2 contents of two residual boulders with those of the exfoliated layers enclosing them (table 7, samples 1–2, 5–6) reveals that the concentration as the rock loses its hardness is somewhat greater than twofold.

BEHAVIOR OF MINOR ELEMENTS IN WEATHERING

The results of semiquantitative spectrographic analyses, though subject to some error, reveal trends in the behavior of minor elements during weathering. These trends were investigated by comparing the results of analyses of hard rocks with those of saprolite derived from them (table 9); also, analyses of five samples of hard rock were compared with those of 20 samples of thoroughly weathered saprolite at depths of less than 20 feet and with those of 10 samples of less thoroughly weathered saprolite at depths greater than 20 feet (table 10; fig. 9), all of which were collected from the Koloa Volcanic Series at scattered localities. All trends discussed here apply to rocks weathering under conditions of good subsurface drainage. The greatest changes in the distribution of minor elements accompany the alteration of parent rock to saprolite; later changes, as saprolite is more intensely weathered, are minor and take place gradually. Accordingly, trends in the distribution of most minor elements in weathering show more clearly in the differences between analyses of hard rock and those of saprolite derived from it (table 9, samples 1–2, 5–6), than in the ranges and averages of abundance of minor elements in fresh rock and saprolite in different stages of weathering (table 10; fig. 9). Most minor elements are depleted during weathering, but some are concentrated.

TABLE 9.—*Semiquantitative spectrographic analyses of samples of residual basalt boulders and associated saprolite of the Koloa Volcanic Series*

[Analyses 1–4 by C. L. Waring and 5–6 by J. L. Harris. Figures are reported to the nearest number in the series 7, 3, 1.5, 0.7, 0.3, 0.15, and so on, in percent. These numbers represent midpoints of group data on a geometric scale. Comparison of this type of semiquantitative results with data obtained by quantitative methods, either chemical or spectrographic, show that the assigned group includes the quantitative value about 60 percent of the time. Symbols used are ---, not looked for; 0, looked for, but not found; M, major constituent, greater than 10 percent]

Sample No. Lab. No.	1 155281	2 155280	3 155279	4 155282	5 164715	6 164716
Si	M	M	M	M	M	3.0
Al	M	M	M	M	5.0	7.
Fe	7.0	M	M	M	5.	M
Mg	M	0.3	0.3	0.3	10.	.5
Ca	7.	.015	.007	.015	5.	.03
Na	1.5	0	.015	0	1.	.2
Ti	1.5	3.	3.	3.	1.5	3.
Mn	.15	.07	.07	.07	.15	.03
Ag	.00007	0	0	0	0	0
Ba	.007	.0003	.0003	.0003	.03	.01
Be	.00015	0	0	.00015	0	0
Co	.007	.003	.003	.003	.007	.005
Cr	.03	.07	.07	.07	.05	.1
Cu	.003	.015	.015	0	.015	.03
Dy	.007	0	0	0	---	---
Er	.007	0	0	0	---	---
Ga	.0015	.0015	.0015	.0015	.001	.002
Gd	.007	0	0	0	---	---
La	.015	0	0	0	0	0
Mo	.0003	.0007	.0007	.0007	.0003	.0007
Nb	.0007	.0015	.0015	.0015	.001	.002
Nd	.03	0	0	0	---	---
Ni	.07	.07	.07	.07	.05	.05
Sc	.0007	.0003	.0007	.0007	.0015	.003
Sr	.03	0	0	0	.03	0
Sm	.007	0	0	0	---	---
Sn	0	0	0	0	0	.001
V	.03	.07	.07	.03	.015	.03
Y	.03	0	0	0	0	0
Yb	.003	0	0	0	0	0
Zr	.007	.015	.015	.015	.007	.02

NOTE.—The following elements were looked for, but not found; in all samples—K, P, Au, B, Bi, Cd, Ce, Ge, Hf, Hg, Ho, In, La, Li, Pb, Pd, Pt, Re, Sb, Ta, Te, Th, Tl, Tm, U, W, Zn; in samples 1–4—Eu, Ir, Lu, Os, Pr, Rh, Ru, and Tb.

1. Residual boulder of basalt, 1 ft. in diameter, exposed in cut made during construction of Highway 56, 1.4 miles north of bridge over Anahola Stream.
2. Saprolite, gray, soft, about 5 ft. away, formed from same flow as residual boulder, sample 1.
3. Saprolite, gray, occurring above and similar to sample 2, but in contact with overlying dark-red saprolitic B soil horizon.
4. B soil horizon, saprolitic, dark-red, 2 in. above sample 3.
5. Residual boulder of basalt, 10 in. in diameter, exposed in bulldozed cut along powerline trail 0.4 mile south of Wailua River (pl. 3).
6. Saprolite, exfoliated layer, 1.5 in. thick, enclosing residual boulder of sample 5.

In addition to the major elements Si, Mg, and Ca, minor elements lost during weathering are Ba, Co, Pb, Sn, and Sr (tables 9, 10; fig. 9). Nd and Sm were looked for and found in only one sample of hard rock. Both were looked for in all samples of saprolite; and Sm was found in only one sample and Nd in none, and both are presumably lost in weathering. Ag was found in only one of the five hard rock samples and was present in lower concentrations in eight of 10 samples of deep saprolite but was not found in the more weathered shallow saprolite. Ni is the same concentration in residual boulders as in associated saprolite, which indicates a gradual loss because of the lower density of the saprolite. Gradual loss of Ni during weathering is also indicated by its lower range in the shallow saprolite. Much loss of this element during the early stages of weathering is probably related to the destruction of olivine, as one sample of this mineral from the Koloa Volcanic Series analyzed by M. D. Foster (in Ross and others, 1954, table 4) contains 0.30 percent NiO.

In addition to the major elements Al, Fe, and Ti, several minor elements are concentrated in the incompletely weathered rocks, but none of the minor elements are significantly more abundant in the thoroughly weathered rock than in the fresh basalt. Be, Cr, Cu, Ga, Mo, Nb, and Zr are more abundant in the saprolite than in associated fresh basalt (table 9), but most occur in thoroughly weathered shallow saprolite in about the same quantities as in the fresh rock (table 10; fig. 9). P was found in saprolite but not in the fresh rock, thereby suggesting a concentration with weathering; however, it is much less abundant in saprolite from depths of less than 20 feet than in that from greater depths, indicating a loss with advancing weathering. The average Mn content of deep saprolite is higher than that of the hard rock (fig. 9), but the saprolite associated with residual boulders is lower in Mn than the boulders. Many X-ray spectrographic analyses made during the appraisal of the bauxite deposits (Patterson, 1962, app.) also show that Mn is more abundant in the deep saprolite than in the hard rock (table 2). Therefore, the concentration of Mn in deep saprolite and its loss with more intense weathering is more typical of the behavior of this element than that in-

TABLE 10.—*Semiquantitative spectrographic analyses for minor elements in hard basalt, saprolite, and plastic clay, Kauai*

[Analyses by Helen W. Worthing. Results are reported in percent to the nearest number in the series 7, 3, 1.5, .7, .3, .15, and so on, which represent approximate midpoints of group data on a geometric scale. The assigned group for semiquantitative results will include the quantitative value about 60 percent of the time. Symbols used are M, --- major constituent, greater than 10 percent; 0, --- looked for, but not detected; --- not looked for]

Element	5 samples of hard basalt			10 samples of saprolite from > 20-foot depths[1]			20 samples of saprolite from < 20-foot depths[1]			Plastic clay			
										Koloa Volcanic Series		Waimea Canyon Volcanic Series	
	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	1	2	3	4
Si	M	M	M	M	7.0	7.0	7.0	0.3	3.65	M	M	M	M
Al	M	5.0	7.0	M	7.	M	M	3.0	7.0	M	M	M	10.
Fe	M	5.	10.	M	M	M	M	M	M	1.5	1.0	1.5	2.
Mg	M	10.	10.	.7	.15	.47	.15	.03	.12	.2	.1	.1	.3
Ca	7.0	5.	6.6	.015	.003	.007	.015	.0007	.004	.01	.015	.03	.03
Na	1.5	1.	1.2	0	0	0	0	0	0	.05	.01	.01	.15
K	1.0	0	.3	0	0	0	0	0	0	0	0	0	1.
Ti	3.	1.5	2.4	3.	1.5	2.55	3.	1.5	1.65	5.	5.	5.	10.
P	0	0	0	.7	.15	.51	.7	0	.095	.1	.7	.2	.1
Mn	.15	.1	.12	.3	.15	.195	.15	.015	.045	.03	.02	.02	.03
Ag	.00007	0	.000014	.00003	0	.00002	0	0	0	.00001	.00001	.00001	.00001
B	0	0	0	.003	0	.0003	.003	0	.0003	.005	0	.003	.01
Ba	.07	.007	.041	.015	.0007	.0045	.003	.0003	.0008	.03	.05	.03	.05
Be	.00015	0	.00009	.0003	.00015	.00018	.00015	0	.00005	.0001	.0003	.0002	.0002
Ce	0	0	0	0	0	0	0	0	0	.007	.015	.02	.02
Co	.015	.007	.009	.007	.003	.005	.003	0	.0018	.002	.001	0	.0007
Cr	.1	.03	.04	.15	.07	.86	.07	.03	.056	.15	.15	.01	.03
Cu	.15	.003	.029	.015	.003	.008	.015	.0007	.0033	.015	.02	.002	.001
Ga	.0015	.001	.0013	.003	.0015	.0016	.0015	.0015	.0015	.005	.005	.005	.007
Ge	0	0	0	0	0	0	0	0	0	0	0	0	.0007
La	.015	0	.003	.003	0	.0003	.003	0	.0003	.01	.015	.02	.02
Mo	.0005	0	.00028	.0007	.0003	.0006	.0007	.0003	.00035	.0003	.0003	.0003	.0003
Nb	.002	.0007	.0015	.003	.0015	.0025	.003	.0003	.0015	.003	.005	.005	.007
Nd	---	---	---	0	0	0	0	0	0	0	.015	.02	.03
Ni	.15	.05	.084	.07	.03	.058	.07	.007	.025	.1	.15	.01	.007
Pb	.005	0	.0012	.0015	0	.0003	.0003	0	.00005	.005	.0015	.002	.007
Sc	.002	.0007	.0018	.0007	.0003	.0005	.0007	.00015	.0003	.003	.007	.001	.0015
Sn	.001	0	.0003	0	0	0	0	0	0	0	0	0	.0015
Sr	.1	.03	.072	.0015	0	.0008	.0007	0	.0002	.003	.005	.01	.03
Sm	.007	---	---	.007	0	.0007	0	0	0	0	0	0	0
V	.03	.015	.021	.07	.03	.06	.03	.015	.025	.05	.05	.015	.05
Y	.03	0	.006	.003	0	.0008	.0003	0	.00001	.0015	.003	.003	.005
Yb	.003	---	---	.0003	0	.0007	0	0	0	.0001	.0003	.0003	.0005
Zr	.02	.007	.019	.03	.007	.014	.015	.003	.006	.02	.02	.05	.03

[1] All samples of hard basalt and saprolite are from the Koloa Volcanic Series.

NOTE:—The following elements were looked for, but not found: As, Au, Bi, Cd, Cs, Dy, Er, Eu, F, Gd, Hf, Hg, Ho, In, Ir, Li, Lu, Os, Pd, Pr, Pt, Rb, Re, Rh, Ru, Sb, Ta, Tb, Te, Th, Tl, Tm, U, W, and Zn. Sm and Yb were looked for in only 1 sample of hard basalt.

1. Surficial gray clay 9.7 ft thick (pl. 3, hole GF–2: section, p. 47).
2. Surficial light-gray clay 9.3 ft thick (pl. 1, hole PR–46; section, p. 47).
3. Surficial light-gray clay 14.3 ft thick (pl. 5, hole 6; section, p. 47).
4. Surficial gray clay 7 ft thick (pl. 5, hole 10; section, p. 47).

dicated by the analyses of the residual boulders and associated saprolite.

Although minor elements occur in many forms in weathered rocks, several are preserved and a few are concentrated in the less weathered rocks because they occur in or are closely associated with resistant magnetite. This conclusion is based on the results of semiquantitative spectrographic analyses of magnetite fractions concentrated from a saprolite, a buried soil, and a residual boulder of hard basalt, all part of the Koloa Volcanic Series. The magnetite fractions were separated magnetically and were sufficiently pure to be black, but all mineral impurities could not be removed because of the difficulty in separating the fine-grained magnetite into discrete grains. The elements occurring in or closely associated with magnetite are as follows:

Semiquantitative spectrographic analyses of magnetite fractions of a saprolite, buried soil, and residual boulder of hard basalt of the Koloa Volcanic Series, Kauai

[Analyzed by J. L. Harris. Means of expressing results are the same as in table 10]

	1	2	3
Al	2.	1.	7.
Mg	1.	.7	3.
Ca	.02	.002	5.
Ti	M	M	10.
Mn	.3	.3	.3
Ba	.03	.007	.03
Co	.02	.03	.015
Cr	.3	.3	.05
Cu	.02	.03	.03
Ga	.005	.005	.003
Mo	.002	.003	.0015
Nb	.03	.03	.003
V	.1	.1	.5

1. Magnetite concentrated from saprolite at depth of 30–40 ft penetrated by auger hole, 1 mile northwest of Kapaa.
2. Magnetite concentrated from buried soil at depth of 10–12.5 ft (table 11).
3. Magnetite concentrated from residual boulder (table 9, sample 5).

Manganese, in addition to being contained in magnetite, tends to accumulate in deep saprolite as black veinlets along joints and in vesicle fillings. Some of these accumulations are lithiophorite and others may be noncrystalline (p. 10).

ROLE OF WATER IN WEATHERING

Inasmuch as downward-percolating ground water is the principal weathering agent in altering basalt to saprolite, chemical analyses and pH measurements were made of water from saprolite and fresh basalt of the Koloa Volcanic Series and rainwater (table 8). The analyzed samples from saprolite were passed through filter paper and collected in plastic bottles immediately after bailing from auger holes to separate and discard mud stirred into suspension during augering and sampling. The water from fresh basalt was taken from town water-supply wells, and samples were drawn from stopcocks at the well heads. Rainwater was collected on plastic sheets spread over a drainboard. The pH measurements were made in the field on the filtered water with two Beckman meters, at the time the water was collected. The wells from which the water in fresh basalt was sampled were both contaminated with sea water, which presumably results from subsurface encroachment or ocean spray. This contamination, which causes the 30 and 21 ppm Na and the 30 and 34 ppm Cl in the two samples (table 8, samples 7, 8), is slight, as is demonstrated by comparing these samples with normal sea water, which has 10,556 ppm Na and 18,980 ppm Cl (Sverdrup and others, 1946, p. 173). Na and Cl are so much more abundant in sea water than other dissolved solids, the samples from these two wells can be considered to be virtually uncontaminated for components other than Na and Cl. All holes from which water is saprolite was sampled were augered at localities above cultivated lands to avoid any possible contamination by artificial fertilizer. The wells yielding the water from fresh rock are situated where some of the water reaching them may have percolated through fertilized soil. Contamination from this source, however, would be so diluted that it might not be detected.

Concentrations of SiO_2, Ca, Mg, and K are much lower in water from the saprolite (table 8, samples 1–6) than in water from the fresh basalt (table 8, samples 7, 8). The concentrations in saprolite water are low because this rock had been leached previously, and the higher concentrations in water in fresh rock result from the passage of this water through the zone where hard rock is being leached and undergoing the change to saprolite.

Although very minor but variable quantities of both aluminum and iron are dissolved in the saprolite water, the average aluminum content is greater in water from saprolite than in water from fresh basalt, and no iron was detected in the water from unweathered rock. This relation for alumiuum conforms with other evidence that gibbsite is formed by precipitation from solution and that some alumina is lost during weathering. The iron in solution in saprolite water and its absence in the water from fresh rock is further evidence that some iron is moved by ground-water action, but that the weathering condition at most places on Kauai are more efficient in concentration of iron than of any other component of the parent rock.

Trace amounts of Mn are present in the water in saprolite, but this element was not found in water from fresh basalt (table 8). Mn occurs as secondary lithiophorite and as black films along joints in the deeper saprolite; it is apparently precipitated before the water passes from saprolite into hard rock, a possibility also suggested by analyses of samples of the deeper saprolite (table 2), which contain as much or more Mn as the parent rock.

Concentrations of several elements in the water in saprolite are unexpectedly high, because there are no minerals remaining that could contain more than traces of these ions. The obvious source of the Na^{+1} and Cl^{-1} in this water is the contribution of ocean spray to rainwater (table 8, samples 9–11), and the concentration partly results from the influence of evapotranspiration. Ca^{+2}, HCO_3^{-1}, K^{+1}, Mg^{+2}, and SO_4^{-2} may also have been introduced from the ocean by rain. Some other elements in saprolite water—such as F^{-1}, I^{-1}, and P (as PO_4), which occur in very weak concentrations in sea water—are more difficult to account for. However, they may have been introduced into the atmosphere during volcanic eruptions, as is suggested by their higher concentrations in rainwater that fell during a volcanic smog (table 8, sample 9) than in the following period (table 8, samples 10, 11).

The water in saprolite is acid, and the water from fresh rock is weakly alkaline. The six samples of analyzed saprolite water (table 8, samples 1–6) ranged in pH from 4.6 to 5.6; samples from 36 other auger holes that penetrated perched water tables ranged in pH from 4.0 to 5.9, and the average was 4.9. The water in fresh basalt in the two wells sampled had pH 7.6 and 7.8. The low pH in water from saprolite is probably due chiefly to organic acids and carbon dioxide produced by the oxidation of organic matter in the overlying soil. Carbon dioxide,

SO_4, and other acid-producing constituents of the atmosphere that are contained in rain may also contribute to the acidity of ground water, for the normal rainfall also has a low pH. The two samples of rainwater that have pH's of 5.7 and 4.9 (table 8, samples 10, 11) represent normal rainwater. The rainfall that has a pH of only 3.7 (table 8, sample 9), however, fell when a dense smog that evolved from the Kapoho eruption on the Island of Hawaii blanketed Kauai for several days; this rainfall was much more acid than normal. The alkaline pH of the water from fresh basalt may be due to the slight contamination by sea water; however, the enrichment of Ca and Mg ions in this water indicate that the pH would be appreciably higher than in water from saprolite, even if the wells were uncontaminated.

RATE OF WEATHERING

Only a few generalized inferences can be drawn regarding the rate of weathering of the Koloa Volcanic Series, because these rocks accumulated intermittently and maximum depth of weathering are not known. However, all the rocks in this series are younger than about 1.5 million years (p. 8), and the saprolite and soil of this series have, therefore, formed within this time interval. A few auger holes penetrated to depths of 64 feet, and many to 49 feet, without reaching unweathered rocks. Most of these holes are on planezes that preserve the original configuration of flows, indicating little rock was eroded. The maximum thickness of weathered Koloa Series rocks may be more than twice the maximum augered depth (drill log data in Macdonald and others, 1960, p. 149–199). In these logs, however, the Koloa is not distinguished from the Waimea Canyon Volcanic Series, and some of the older rocks may be included in the weathered material.

Weathering began on all rocks shortly after lavas cooled, a conclusion supported by the observance of a primary fern leaf growing on lava in Hawaii 4 months after the flow terminated (Doty, 1961, p. 140). However, the rapid establishment of vegetation on a flow surface does not mean clayey and earthy soil formed at such a rate. Several historic flows on Hawaii are now covered by dense vegetation, but little true soil has formed in these areas.

The rate of low-iron plastic clay formation is suggested by the age of overlying peat, as the two are related in origin (p. 50). The oldest known peat on Kauai, under which the plastic clay is more than 20 feet thick, has been dated by pollen analysis (Selling, 1948, p. 140) as late Quaternary in age and corresponds approximately to the end of the last glacial period. Although this relation indicates a rapid removal of iron oxide and the formation of plastic clay, it does not establish that basaltic lavas weathered at such a rate. Some rocks on which the peat swamps formed were probably already altered to saprolite.

WEATHERED PYROCLASTIC ROCKS

Most saprolite and soils described in this section are derived from lava flows, but several types of weathered pyroclastic rocks—including volcanic ash, cinder, and spatter—also occur on Kauai. These materials are difficult to identify in poorly exposed weathered rocks and are probably much more common than recognized. Probably most of the pyroclastic rocks were similar in composition and weather to the same types of materials as the flows with which they are associated. Most pyroclastic rocks are much more porous than the flows and are therefore likely to be much more thoroughly weathered.

In the northern part of the island, a prominent weathered ash is exposed in roadcuts of Highway 56 over a distance of nearly 6 miles, extending from the uplands west of Kalihiwai Bay to about 3 miles east of Kilauea. The ash, penetrated in several auger holes, has a loose porous texture and a distinctive red and green color that contrasts with the dark-brown saprolite formed from enclosing flows. The ash bed ranges in thickness from a little more than 1 inch to about 1.5 feet. Samples of both red and green clay from this bed examined by X-ray techniques consist chiefly of halloysite-metahalloysite and goethite, and minor quantities of magnetite were present in all samples investigated.

Weathered cinder and spatter are recognizable at several localities where roads have been cut in the sides of old vents. Among these localities are (1) a field roadcut on the east side of Hanahanapuni (pl. 3); (2) a roadcut along Highway 50, 0.75 mile west-southwest of the road junction at Knudsens Gap; and (3) cuts along a field road on the north and east flanks of Kamoku, a vent of 3.5 miles southeast of Kilauea (pl. 1).

BURIED SOIL

Buried soils are common on Kauai. They represent episodes of surface weathering that were terminated by overriding flows. Where associated with saprolite, these buried soils provide a basis for comparing both types of alteration in the same rocks under similar topographic conditions. The soils vary considerably from place to place as the result of differences in time of exposure and other factors influencing soil formation.

Where the weathering was brief and the rocks above and below the soil are within the zone that has been weathered to saprolite, little difference exists between the ancient soil and the enclosing saprolite. Such old soils are very difficult to recognize but are probably common. Where the weathering interval was sufficiently long, a red soil formed and is preserved as a prominent red clay zone interlayered with drab saprolite.

One very prominent and persistent buried soil, a less prominent buried soil, and several minor ones were found interlayered with weathered rocks on Kauai. The prominent buried soil zone occurs irregularly from the Hanalei River (pl. 1) to the vicinity of Knudsens Gap (pl. 3). It is assumed to be the same zone throughout this area, because wherever two or more zones are exposed, one (generally the upper of the group) is thicker and more persistent than the others. The reason the assumption is necessary is no accurate way of correlating a buried soil zone across areas where it is missing or covered is known.

Plant growth, weathering, and compaction features also indicate that the red clay zones were surficial soils overridden by the flows now above them. Carbonized plant roots and pieces of wood were found in the upper part of a buried soil exposed in a roadcut along Highway 56, 1.6 miles south of the bridge at Anahola. Chunks of saprolite similar to the underlying rock were found in the lower part of the soil at places and indicate an origin by residual accumulation of weathering products, similar to the origin of the modern soil. Compaction of the buried soils is indicated by their dense character, complete lack of preservation of vesicles and other basaltic structures typical of saprolite, and abundant slickensides. Some baking of the buried soils is suggested by the more indurated nature of the uppermost 2–4 inches exposed in a roadcut south of the bridge across Kapaa Stream at Kealia.

The bulk chemical compositions of the buried soil and the saprolite above and below it do not differ appreciably, but there are significant differences in mineral constituents. The quantities of silicon, aluminum, iron, and titanium oxides are comparable in both the buried soil and saprolite at most places (table 11); locally, however, the buried soils are enriched in iron oxide (table 11, hole PR–23) and may contain more silica than the overlying saprolite (table 11, hole 12). Hematite is common to abundant in the buried soil and generally rare in the enclosing saprolite, and goethite is generally less abundant in the buried soil than in the saprolite. Gibbsite is generally much more abundant in the saprolite above the soil and is rare or in trace amounts in saprolite below the soil.

The buried soils, which formed by surficial weathering, were altered further by the overriding flows and weathering at depth. The abundance of hematite and sparsity of goethite in the soils and the reverse relationship in saprolite strongly suggest that the hematite formed from goethite. Much of the water loss in the transition from goethite to hematite probably took place under surface conditions or during the period that the overriding flows were still hot. The distinct red colors of the buried soil are caused chiefly by hematite, and the brown shades of the saprolite, by goethite. The low content of gibbsite in the buried soils, which contrasts with its common occurrence in modern soils, suggests that gibbsite may have been much more aboundant before burial and that much of it has been altered to halloysite. The abundance of SiO_2 in these soils, as opposed to its low content in modern soils, also suggests that resilication has taken place. The local concentration of gibbsite in the saprolite above the soils may be partly due to deep surficial weathering, but most is probably related to the perched water above the comparatively tight soils. Several auger holes penetrated such water and passed into comparatively dry zones below the soil. Accordingly, the introduction of Al by ground water would be expected to be more effective above the soils than in or below them. The common occurrence of magnetite in both soil and saprolite conforms with other evidence that this is the most resistant mineral in the parent basaltic rock and remains unaltered until very advanced stages of weathering are reached.

ECONOMIC POTENTIAL OF FERRUGINOUS BAUXITE

ALUMINUM RESOURCES

The aluminum resources on Kauai are divided into ferruginous bauxite, which contains 10 percent SiO_2 or less, and aluminous saprolite which has more than 10 percent SiO_2. Both categories are considered resources rather than reserves because they are too low grade, or because other economic factors prevent their profitable use at the time this report was prepared. The aluminous saprolite, though occurring in very large deposits, is even less favorable than the ferruginous bauxite, because of its high silica content.

FERRUGINOUS BAUXITE

GEOLOGIC SETTING AND LOCATION OF DEPOSITS

The ferruginous bauxite deposits on Kauai occur only in the thoroughly weathered upper parts of lava flows and are restricted to planezes, the sloping interstream uplands. The stream valleys are cut into less weathered rock, as indicated by the presence of hard

TABLE 11.—*Descriptions, chemical and mineral constituents, particle size, and specific gravity of buried soils and associated saprolite, Kauai*

[Major oxides determined by X-ray fluorescence methods; J. H. Jolly, John Alishouse, and R. M. Bromery, analysts, under the supervision of J. W. Hosterman. Particle size determined by wet-sieve analysis of samples containing natural moisture; dry weight calculated from moisture determinations. Mineral content: VA, very abundant; A, abundant; C, common; R, rare, Tr., trace]

Auger hole	Sample depth interval (feet)	Description	Major oxides (percent)				Mineral content					Particle size (percent dry weight) U.S. series sieve Nos.				Specific gravity of powder
			SiO_2	Al_2O_3	Fe_2O_3	TiO_2	Gibbsite	Metahalloysite	Goethite	Hematite	Magnetite	>100	100–200	200–325	<325	
PR–23 (pl. 1)	35–40	Saprolite, brown, fluid	19.2	22.0	34.0	4.5	C	A	C	R	C	9.2	11.5	10.5	67.3	2.84
	40–45	Clay, dark-red, stiff plastic (buried soil)	19.2	19.0	37.5	5.2	Tr.	A	Tr.	A	C	10.5	4.8	3.9	79.8	3.08
	45–48	Saprolite, dark-reddish-brown, plastic	20.2	25.5	29.2	4.1	C	VA	C	R	C	13.4	6.9	7.2	67.2	2.73
3 (pl. 2)	24–29	Saprolite, dark-reddish-brown, plastic	23.5	26.5	28.2	3.7	C	C	C	R	C	11.1	12.7	11.8	57.5	2.78
	29–36	Clay, red, very plastic (buried soil)	28.7	25.7	22.5	4.6	R	A	C	C	C	15.0	7.9	8.0	67.1	2.83
	36–39	Saprolite, reddish-brown, plastic	23.5	23.7	25.5	5.4	R	A	A	R	C	14.1	7.5	6.7	66.7	2.73
12 (pl. 2)	24–28	Saprolite, brown, plastic	14.7	22.5	32.5	5.9	C	C	A	R	C	8.7	4.4	4.6	76.6	2.76
	28–29.5	Clay, dark-red, plastic (buried soil)	23.5	19.0	30.0	5.1	Tr.	A	R	C	C	4.4	10.7	9.0	74.1	2.82
	29.5–34	Saprolite, dark-gray, plastic	20.2	22.2	31.7	5.6	R	A	C	R	C	2.2	3.6	3.9	87.5	2.86
Ki–102 (pl. 3)	48–50	Saprolite or clay, gray, crumbly	30.0	23.0	27.5	4.5	Tr.	VA	A	R	C	5.1	10.2	9.8	74.0	2.87
	50–51	Clay, dark-red, plastic (buried soil, upper zone)	29.2	23.7	26.0	4.7	Tr.	VA	Tr.	A	C	6.1	7.0	7.7	80.6	2.77
	51–55	Clay, dark-red, stiff plastic (buried soil, middle zone)	28.7	24.5	28.0	3.7	Tr.	VA	R	VA	C	4.1	7.5	7.9	79.1	2.77
	55–57	Clay, red, very plastic (buried soil, lower zone)	29.2	23.0	28.2	4.5	Tr.	A	C	A	C	6.5	10.6	9.1	71.5	2.85
(1)	0–8	Saprolite, light-brownish-gray: dark mineral films along joints: goethite pseudomorphs after olivine: contains a few residual boulders of basalt	35.7	19.0	20.0	3.6	--	VA	R	Tr.	C	--	--	--	--	3.00
	8–8.9	Clay, dark-red, slightly undurated (baked?), a few white specks: thickness ranges from 2 to 8 in. (buried soil, upper zone)	28.5	20.5	29.7	5.5	--	VA	Tr.	A	C	--	--	--	--	3.20
	8.9–10	Clay, dark-red and very dark red, small white specks common (buried soil, middle zone)	32.2	19.2	26.5	4.5	--	VA	Tr.	A	C	--	--	--	--	3.11
	10–12.5	Clay, dusky-red, chunky (buried soil, lower zone)	29.7	21.0	29.2	5.2	--	VA	Tr.	A	C	--	--	--	--	3.12
	12.5–19	Saprolite, light-gray: vesicles, joints, and texture of basalt preserved: upper part altered along joints to red clay	33.2	16.7	27.5	3.6	--	VA	Tr.	Tr.	C	--	--	--	--	2.95

[1] Section exposed in roadcut, 50–100 yds. south of bridge over Kapaa Stream at Kealia (stream shown on pl. 2).

basalt in the beds of some streams and the abundance of silica-bearing halloysite-metahalloysite and paucity of gibbsite in saprolite in the valleys.

Nearly all the bauxite on Kauai has formed on the Koloa Volcanic Series, though minor quantities of bauxite may occur on the older Waimea Canyon Volcanic Series. The Waimea Canyon Series occurs in areas of heaviest rainfall, contains an average of about 2 percent more Al_2O_3 than the Koloa Series (Macdonald, 1960, p. 110–112), and is much coarser grained and distinctly more permeable than Koloa rocks. The Waimea Canyon Series has been eroded so thoroughly that few of its planezes remain, and the sharp ridges characteristic of the upland topography on these rocks are not sufficiently weathered to form bauxite. Minor quantities of bauxitic material occur in weathered parts of Waimea Canyon rocks in areas surrounding the clay deposits in Alakai Swamp (pl. 5). Bauxitic material from four auger holes penetrating these deposits was very ferruginous and rich in SiO_2 and, therefore, of little value (Patterson, 1962, p. 16). All further discussion of ferruginous bauxite will pertain to deposits on the Koloa Series.

Most ferruginous bauxite deposits on Kauai occur in the eastern part of the island (fig. 10; pls. 1–3) at altitudes ranging from 200 to 1,200 feet and in belts of annual rainfall ranging from 80 to 150 inches. Most deposits are on land cultivated for sugar cane and pineapple and on pasture lands, but a few are on undeveloped land and State-owned land now in game reserve. At most places the bauxite is only about 10 feet thick, but much thicker deposits occur locally. Ordinarily, the thinner deposits are on broad uplands, and the thicker ones are on narrow flat-topped ridges, such as in the vicinty of hole Ki–41 (pl. 3).

Most bauxite in eastern Kauai is in areas where the soils are classified as Humic Latosols of the Halii Series and Humic Ferruginous Latosols of the Haiku

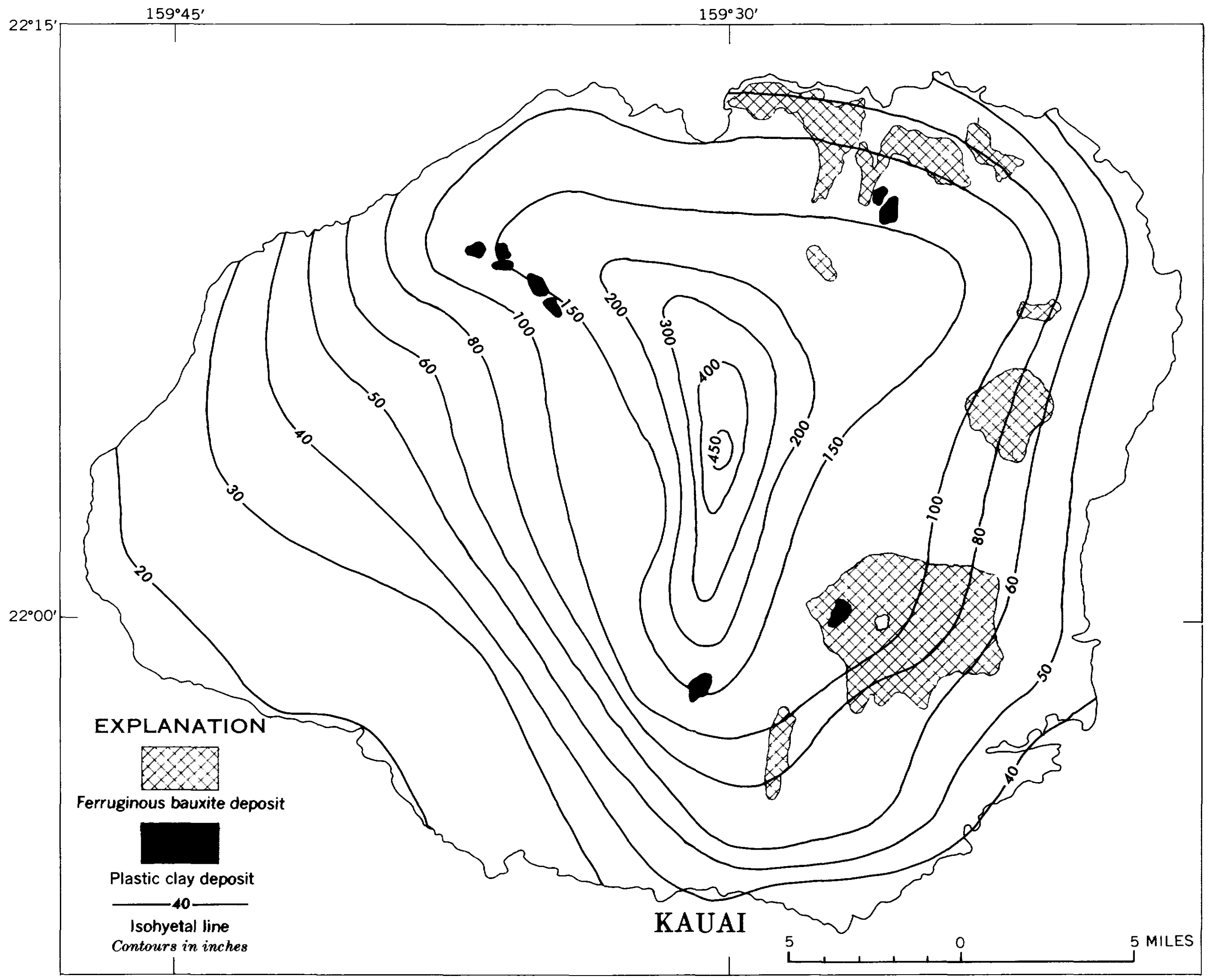


FIGURE 10.—Location of ferruginous bauxite and plastic clay deposits on Kauai. Distribution of annual rainfall shown by isohyetal lines. Compiled from U.S. Weather Bureau maps.

and Puhi Series (Cline and others, 1955, p. 340–342, 446–460, East Kauai sheet). Soils of the Halii Series are chiefly reddish-brown clays that contain pea-sized ferruginous concretions, which apparently are the principal characteristic by which these soils are distinguished from those of other series. Soils of the Puhi and Haiku Series are similar, except the Haiku Series is more depleted of bases. A typical soil profile of the Haiku Series, as described by Cline and others (1955, p. 449–450), follows:

A_1 0 to 9 inches, dark reddish-brown silty clay; strong medium granular structure; friable when moist, and nonplastic when wet; high bulk density; pH 5.0 to 6.5; roots very numerous; in cultivated areas the lower 3 inches is massive and silty.

B_2 9 to 24 inches, red silty clay; moderately developed medium blocky structure; friable when moist, and nonplastic when wet; moderate bulk density; pH 5.0 to 6.0; roots present.

B_3 or C_1 24 to 42 inches, reddish-brown silty clay similar to horizon B_2 but includes numerous soft highly weathered rock fragments.

C_2 42 inches +, gray, brown, and yellow soft weathered rock that retains the original rock structure and encloses solid rock cores that increase in number with depth; solid bedrock lies 10 to 50 feet below the surface.

METHODS OF EVALUATING

The ferruginous bauxite on Kauai is difficult to evaluate because gibbsite is irregularly distributed throughout the weathered rock. Variations in the abundance of gibbsite are due to (1) the tendency for this mineral to be concentrated along and near joints; (2) the manner in which weathering progresses inward from the outer parts of joint blocks, causing the centers of blocks to be less thoroughly weathered than the rims; (3) the occurrence of fresher rocks above more thoroughly weathered ones where lava flows have overridden rocks that had been previously weathered, though not necessarily to the red-soil stage; and (4) the tendency for the porous and permeable parts of lava flows to weather more rapidly than the dense parts. Because of any one or a combination of these factors, samples taken from one auger hole may have different Al_2O_3 contents, from those taken from an auger hole a few feet away. Accordingly, the results from a single auger hole cannot be considered hard and fast criteria for determining whether bauxite is present. To overcome some of this difficulty, an attempt was made to consider the results from more than one hole in outlining areas of bauxite (pls. 1–3). In a few places the results from a single hole were ignored in determining the presence or absence of bauxite, because of the likelihood that the hole penetrated rocks that were not representative.

SAMPLING

Samples were collected by augering with a jeep-mounted power auger. Most holes that did not penetrate to hard rock were augered to a depth of 39 feet; a few were augered to depths of 49–64 feet (intervals are 1 ft less than figures divisible by five because height of jeep-mounted auger above ground shortened penetration of first section to 4 ft). For most holes, samples were collected at 5-foot intervals or less, to depths of 19 or 24 feet, and at 10-foot intervals or more for greater depths. The sample interval was modified for some holes penetrating distinct rock units. The logs of all the holes augered are given in a preliminary report (Patterson, 1962, app.), and only the following three logs are given herein to show the type of rocks penetrated.

Log of auger hole PR–32 (pl. 1)

Depth (feet)	*Unit thickness (feet)*	
1	1	Soil.
4	3	Soil and saprolite, dark-reddish-brown (5*YR* 3/4.[1] Crumbly gibbsite nodules rare.
9	5	Saprolite, reddish-brown (4*YR* 4/4), crumbly and chunky; gibbsite nodules rare; glassy ferruginous veins in lower part.
22	13	Saprolite, reddish-brown (5*YR* 4/4), plastic; nodules rare.
34	12	Saprolite, somewhat more gray than reddish-brown (5*YR* 4/4), plastic.
54	20	Saprolite, dark-grayish-brown (10*YR* 4/2), plastic.

Log of auger hole Ki–50 (pl. 3)

Depth (feet)	*Unit thickness (feet)*	
0.5	0.5	Soil, dark-reddish-brown (5*YR* 3/4), ferruginous; contains abundant gibbsitic nodules.
2	1.5	Soil and saprolite, dark-reddish-brown (5*YR* 3/4), chunky; ferruginous and gibbsitic nodules abundant.
4	2	Soil and saprolite, darker than dark-reddish-brown (5*YR* 3/4), plastic; contains abundant ferruginous and gibbsitic nodules.
14	10	Saprolite, dark-reddish-brown (5*YR* 3/4), plastic; contains abundant nodules.
29	15	Saprolite, dark-reddish-brown (5*YR* 3/4) with some dark reddish brown (5*YR* 2/2) mixed; plastic.
54	25	Saprolite, very dark brown (10*YR* 2/2), very plastic.

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[1] Color designations given in this report are those of the Munsell Soil Color Charts (Munsell Color Co., 1954).

Log of auger hole Ki–67 (pl. 1)

Depth (feet)	*Unit thickness (feet)*	
1	1	Soil, yellowish-brown (10*YR* 5/4); contains abundant ferruginous and gibbsitic nodules.
4	3	Soil and saprolite, redder than reddish-brown (5*YR* 4/4), plastic; contains abundant gibbsite nodules.
7	3	Saprolite, dark-reddish-brown (5*YR* 3/4), plastic; contains abundant nodules.
9	2	Saprolite, very dark brown (10*YR* 2/2) and dark-reddish-brown (5*YR* 3/4) mixed, plastic; contains abundant nodules.
14	5	Saprolite, very dark brown (10*YR* 2/2), plastic; nodules are common.
19	5	Saprolite, very dark brown (10*YR* 2/2), plastic; nodules are rare.
39	20	Saprolite, very dark brown (10*YR* 2/2), crumbly to plastic.

SAMPLE ANALYSIS

Selected samples were analyzed for major elements by rapid chemical and X-ray fluorescence methods (pls. 1–3), and a few were analyzed for the standard oxides (table 2). Most samples, however, were investigated only by differential thermal analysis methods, using portable apparatus similar to that described by Parker, Hathaway, and Blackmon (1956). The results permitted the determination of the amount of metahalloysite present within accuracy limits of about 1 part in 10. The approximate amount of silica could then be calculated, as metahalloysite is the only silica-bearing mineral in the bauxite in significant quantities. This method also enabled the determination of whether major quantities of gibbsite and goethite were present; however, these two minerals cannot be distinguished with the portable apparatus, as both have major endothermic reactions in similar temperature ranges. In evaluating samples, only those that contain less than 2 parts in 10 of metahalloysite are considered to contain 10 percent SiO_2 or less. Because gibbsite and goethite could not be separated and both are abundant in the bauxite, estimates of these minerals are of little value, except that samples containing less than 7 parts in 10 of these minerals are not likely to be rich enough in alumnia to be considered bauxite. Mineral estimates from differential thermal analyses made with the portable apparatus are listed in the preliminary report (Patterson, 1962, app.), and only summary data of these results for appropriate holes are given herein (pls. 1–7).

CALCULATION OF RESOURCES

Areas that contain ferruginous bauxite (pls. 1–3) were outlined from the drill-hole and analytical data. A maximum cutoff of 10 percent SiO_2 was used; no cutoffs were placed on Al_2O_3, TiO_2, and Fe_2O_3, because these constituents do not vary significantly in most large deposits. All evaluations are based on whole rock, without consideration of possible beneficiation, which will be discussed in a separate section (p. 41). A minimum thickness of 10 feet was applied to that bauxite considered to be a resource, because this seems a logical minimum thickness for profitable mining. The 9-foot thickness listed for several holes was considered to be rounded at 10 feet, an adaptation within the overall limits of accuracy of the methods used.

Outlined bauxite areas (pls. 1–3) were measured with a polar planimeter and converted to acres. The figures for acres were then converted to square feet and multiplied by thicknesses from the drill-hole and analytical data to obtain volumes, in cubic feet. Volume of the bauxite was converted to tons using a conversion factor of 70 pounds per cubic foot of dry rock in place, the approximate average of 60 measured samples. These samples ranged from 53 to 88 pounds per cubic foot, and their variations were due chiefly to differences in abundances of vesicles and pore spaces. Water loss during drying ranged from 22 to 45 percent, and the average was 34 percent. Water contents of rock in the ground are probably somewhat higher than the figures measured because all measurements were from rock at the surface.

RESOURCES

The resources of low-grade ferruginous bauxite on Kauai are calculated to be 110 million tons, dry weight, containing an average of 4.7 percent SiO_2, 25.9 percent Al_2O_3, 39.4 percent iron oxides, and 6.7 percent TiO_2 (table 12). About 20 percent of the ferruginous bauxite is combined water (hydroxyls), organic matter, and other volatiles that would be driven off by calcining. Removal of the thickness limitation and the addition of some of the bauxite in the Wailua-Kapaa homesteads (pl. 3), excluded because it lies on very valuable property, would increase the resources by about 25 percent.

POSSIBILITIES FOR BENEFICIATION OF FERRUGINOUS BAUXITE

Because of the tendency for gibbsite to occur in nodules and other coarse forms, the ferruginous bauxite can be upgraded by washing out the fine-grained material. In wet-screening tests of three samples from Kauai, Calhoun and Hill (1962, p. 33–35) found 26.7—32.6 percent of the bauxite by

TABLE 12.—*Tonnage estimates of ferruginous bauxite resources on Kauai*

[Tonnages are for deposits that are 10 ft or more thick and contain 10 percent silica or less; N.d., not determined]

Area	Landowner	Dry tons	Average partial chemical analyses (percent)			
			SiO_2	Al_2O_3	Fe_2O_3	TiO_2
Princeville Ranch (pl. 1).	American Factors Co., Ltd.	32,800,000	3.3	26.3	40.1	7.0
Kilauea (pl. 1)	C. Brewer Co., Ltd., and private land owners.	15,100,000	5.2	23.0	37.6	7.0
	State of Hawaii	300,000	N.d.	N.d.	N.d.	N.d.
Anahola-Kealia (pl. 2).	American Factors Co., Ltd.	400,000	N.d.	N.d.	N.d.	N.d.
	State of Hawaii	1,600,000	5.0	20.5	41.5	5.5
Wailua Game Reserve (pl. 3).	State of Hawaii	3,600,000	4.6	24.5	39.7	7.0
Wailua-Kapaa Homesteads (pl. 3).	Many private owners.	[1]6,000,000	2.3	26.1	40.2	7.0
Land south of Wailua River leased to Lihue Plantation (pl. 3).	State of Hawaii	1,000,000	N.d.	N.d.	N.d.	N.d.
North side of Kilohana Crater and adjoining lands (pl. 3).	American Factors Co., Ltd.	22,200,000	5.6	27.1	38.7	6.1
South side of Kilohana Crater and adjoining lands (pl. 3).	Grove Farm Co., Ltd.	20,000,000	5.8	26.6	39.2	6.2
Knudsen lands (pl. 3).	Knudsen Estate	7,000,000	6.2	26.0	40.8	7.6
Total tons and weighted average composition		110,000,000	4.7	25.9	39.4	6.7

[1] Approximately twice this amount present but scattered on small valuable farms and acreages which probably could not be obtained for mining.

weight occurs in the +80-mesh (fine sand) fraction; the Al_2O_3 content of this fraction is 37.0–42.4 percent. Investigations of the variations of mineral composition with particle size described in this report (table 6, p. 23) reveal that the coarse fractions from only a few localities are sufficiently rich in gibbsite to compare favorably with bauxite ore currently used in the United States. In wet-sieving tests of bauxite from seven localities (table 6), only 22.7 percent of the bauxite was found to be coarser than 35 mesh (coarse sand). The average alumina content of this material is 35.7 percent, about 10 percent higher than the average for all the ferruginous bauxite on Kauai (table 12). Although the grade of the washed bauxite is significantly higher, beneficiation in this way would reduce the total alumina recoverable by 70–75 percent.

TABLE 13.—*Summary of variations in chemical composition of ferruginous bauxite from Kauai with grain size*

[An average of data given in table 6 for holes PR–19, PR–24, Ki–40, Ki–46, Ki–54, and GF–46 to a depth of 9 ft and hole Ki–57 to a depth of 14 ft]

Grain size	Sieve No.	Percent of sample by weight	Major oxides (percent)				
			Al_2O_3	SiO_2	Fe_2O_3	TiO_2	H_2O
Granules and larger	>10	12.7	38.1	2.6	28.5	2.8	26.07
Very coarse and coarse sand	10–35	10.0	33.3	3.8	33.2	3.4	23.33
Medium to very fine sand	35–230	17.2	26.1	5.2	39.0	4.1	20.49
Silt and clay	<230	60.1	19.1	7.5	41.0	6.8	18.52

Possibilities for upgrading the ferruginous bauxite by separating the iron and titanium minerals by (1) tabling, (2) reduction roasting and magnetic separation, and (3) wet-cyclone and hydraulic classification were investigated by Calhoun and Hill (1962, p. 6, 11–14). They were able to remove only a small quantity of the iron- and titaninum-bearing minerals by tabling. The increase in Al_2O_3 content in material that was roasted and passed through a magnetic separator was so small that most of it could be accounted for by the loss of moisture from hydrous minerals during roasting. Some iron and titanium was removed by the wet-cyclone method, but treatment by this technique also removed considerable quantities of alumina. According to the results of these investigations, the possibilites for upgrading the ferruginous bauxite at a low cost by removing iron and titanium minerals are not good. This conclusion is supported by the fact that iron and titanium tend to be concentrated in clay- and silt-sized particles (table 6), which also contain aluminum.

POTENTIAL RESOURCES OF ALUMINOUS SAPROLITE

Zones of aluminous saprolite 20–60 feet thick below the bauxite and a thick blanket of aluminous saprolite cover most interstream uplands in eastern Kauai that do not contain bauxite (pls. 1–3). This saprolite consists of the same minerals that form the bauxite; however, halloysite-metahalloysite is more abundant, and gibbsite and iron minerals are less abundant in this saprolite than in the bauxite. The total potential resource of aluminous saprolite on Kauai is estimated to be 500 million dry tons. The average partial composition of this material before drying is approximately 20 percent SiO_2, 27 percent Al_2O_3, 27 percent Fe_2O_3, and 5 percent TiO_2.

ECONOMIC POTENTIAL OF OTHER MINERAL RESOURCES

BLACK CORAL, SHELLS, AND HOBBY-COLLECTING MATERIAL

A small quantity of black coral suitable for making jewelry was collected by a diver in deep water off Waimea in 1961 (Ashizawa, 1962, p. 320). According to unconfirmed reports, black coral also has been found by divers off the eastern coast of Kauai.

Many species of mollusks thrive on the tidal reefs at several places on the island. A local sea-shell-collecting group is active, and shell collectors from the mainland and distant countries visit Kauai from time to time to collect specimens. Minor quantities of shells are also used in making jewelry for local markets and sale to tourists.

Local hobbyists have collected wave-worn fragments of broken bottles and other varicolored forms of glass that accumulate on a beach close to a dumping area near Port Allen. These fragments are used as a substitute for ceramic blocks in making terrazzo hobbycraft items and other forms of attractive decorative objects.

Several little-known mineral occurrences on Kauai might be of interest to collectors. Intricate tiny growths of calcite, aragonite, and zeolite microcrystals occur in vesicles, veins, and vugs in basalt in the Grove Farm Co., Ltd., quarry west of Puhi (pl. 3) and the quarry at Kilauea Bay (pl. 1). The so-called "Pele's pearls" (Stearns, 1966, p. 228) that are hemispherical spherulites of calcite and siderite (p. 10) might also be interesting additions to mineral collections. Although specimens retaining their pearly luster are not abundant, they can be found in the quarries, some roadcuts, and other places where fresh rock is broken.

CONSTRUCTION MATERIALS

CORAL, BEACH SAND, AND LIMESTONE

The Hawaiian Dredging and Construction Co., Ltd., dredged 180,000 cubic yards of coral from the reef off Kapaa (pl. 11) in 1961 for the Lihue Plantation Co., Ltd. (Davis and Ashizawa, 1960, p. 305). All this coral supply was consumed within 3 years in surfacing and maintaining sugarcane haul roads. Much coral was also dredged and stockpiled at Nawiliwili Harbor in 1956 and used chiefly in the construction of plantation roads.

Calcareous sediments occur in older dune sands in various stages of consolidation, in sand deposits blown inland from modern beaches, and in modern beach sand deposits (pl. 11). The older dune sands are in scattered patches on the Mana Plain in the southwestern part of the island and along the southeastern coast southeast of Koloa. The deposits on the Mana Plain are only a few feet above sea level, and those along the southeastern coast extend from below sea level to as much as 500 feet above sea level (Macdonald and others, 1960, p. 85). These older dunes consist of fragments of shells, coral, and skeletons of foraminifers blown inland from beaches. These deposits range from friable sand to fairly dense limestone in which solution and pecipitation of calcium carbonate has obscured the original bedding characteristics. The dune sand blown inland from modern beaches occurs chiefly along the coast in the northern part of the Mana Plain and at scattered localities along the southeastern coast of Kauai. Extensive modern beach sand deposits occur discontinuously along much of the shore. The largest beach deposits are between Haena and Lumahai and at Hanalei Bay on the north side of the island; at Kapaa and Wailua on the east side, and along the long stretch of shore between Waimea and Polihale on the west side. Most beach sand deposits are cream-colored to white calcareous material; but grains of volcanic rock are abundant locally, and some beaches in the western part of the northern coastal deposits are sufficiently rich in olivine to have a greenish tinge. The total quantity of sand in beaches on Kauai has been calculated by Chamberlain (1968, p. 179) to be 14 million cubic yards.

For several years, the Grove Farm Co., Ltd., has produced minor quantities of limestone from consolidated older dune deposits southeast of Koloa. The limestone is crushed and used for building and road construction materials, and some of the finer screenings are suitable for agricultural lime. The calcareous beach-sand deposits and those blown inland are dug at several places for use in construction and concrete products.

The resources of coral reefs are extremely large, but many reefs are natural barriers that protect against beach erosion, and they may not be available for dredging. For example, a small beach area was destroyed by beach erosion after the dredging at Kapaa was completed. Although this erosion was minor, extensive coral dredging would probably have a serious effect. The potential value of coral in reefs is greatly reduced because of the danger of erosion when it is removed, and the locations of coral that could be used most economically commonly coincide with areas where erosion protection is essential. The approximate extent of reefs surrounding Kauai (pl. 11) was sketched from information shown on U.S. Coast and Geodetic Survey navigation charts. The data available, however, do not indicate the thickness or purity of the coral, and the quantity and grade of coral surrounding Kauai cannot be estimated.

The quantity of limestone and sand in older dune deposits has not been determined, but resources are probably sufficient to supply Kauai's requirements for many years. Areas covered by older dune sand, as mapped by Macdonald, Davis, and Cox (1960, pl. 1), amount to about 300 acres southeast of Koloa and 200 acres on the Mana Plain. Limestone is the most valuable resource in these deposits, and virtually all deposits on the island are southeast of Koloa. The total limestone in this area has not been determined; but it crops out in several places, and resources are probably adequate to last several decades at the present rate of consumption.

Modern beach-sand deposits along the shore and those blown inland are also large; but they cannot be considered inexhaustible, and their use is supervised by local officials. Supplies for local construction needs, road repair, and other purposes are available at several localities. One source of sand, which conserves sand resources, becomes available when sandbars built by high seas across the mouths of streams must be removed. These sandbars occasionally dam streams and cause flooding of valleys unless removed.

CRUSHED BASALT

Crushed basalt is probably the most satisfactory aggregate used in construction on Kauai, because it is the hardest material available on the island and several sizes can be obtained by crushing and screening. Most of Kauai's requirements for crushed basalt, including a product known as bluestone, have been quarried by the Grove Farm Co., Ltd., 3.5 miles west of Puhi. A small quantity of basalt was quarried at a site along the South Fork Wailua River, about 4 miles northwest of Lihue. A third quarry was opened in the Kapaia Valley in 1963 by the Grove Farm Co., Ltd., and operated primarily for coarse materials used in cane haul road maintenance on Lihue Plantation Co., Ltd., lands. A material similar to the basalt crushed at quarries is occasionally made from field stones. These stones are rounded residual boulders ranging in diameter from a few inches to several feet. They are particularly abundant where fields are on incompletely weathered flows of the Koloa Volcanic Series. The stones are encountered during cultivation and are gathered into piles to avoid damaging farm machinery. Occasionally, portable crushers are used in breaking the stones into usable sizes. Road construction material, which is somewhat softer, but otherwise similar to basalt, is also prepared from vitric tuff. Such tuff and small quantities of massive lava are quarried at the Kahili quarry on the west side of Kilauea Bay. This quarry is operated intermittently by the Kilauea Sugar Co., Ltd.; it was leased to the Grove Farm Co., Ltd., in 1961 (Ashizawa, 1962, p. 320) and was operated for crushed rock for field roads and for concrete aggregate.

All the basalt quarries on Kauai are in the Koloa Volcanic Series, and resources of these rocks are virtually inexhaustible. All quarries operated on Kauai have been in the Koloa Series because these rocks are commonly harder and more massive than others, and because they occur in most of the less mountainous parts of the island where demands for construction materials are greatest. Adequate supplies of crushed basalt for Kauai's requirements can be obtained from existing quarries, and sites favorable for new quarries in the Koloa Series occur in several stream valleys. In addition to the extremely large resources of basalt in the Koloa Series, some local massive flows in the Waimea Canyon Volcanic Series might be suitable sources of crushed basalt.

RIVER SAND AND GRAVEL

Sand and gravel occur in stream beds and unconsolidated fills in most valleys. This material, which ranges in size from fine sand to large boulders, consists chiefly of stream-rounded fragments of basalt, but some deposits near the mouths of streams also contain shell and coral fragments. River sand and gravel is dug periodically and is used locally for construction of roadbeds, footings, and fill and for other purposes. Most of this material is used as dug from the deposits, but, occasionally, it is screened to obtain gravels of uniform size for concrete aggregate and road maintenance. Semiportable crushing and screening equipment is also used to make crushed rock from stream gravels, as was done in making concrete aggregate from deposits in the Kalihiwai River valley in 1963 (Ashizawa, 1964, p. 328). Deposits of river sand and gravel are adequate to fulfill local needs in most populated areas of Kauai. In addition to that from the Kalihiwai Valley, this material has been dug mainly from the Hanapepe, and Waimea Valleys.

VOLCANIC CINDER

Volcanic cinder is used only in limited quantities for maintenance of sugarcane haul roads on Kauai. The principal reason cinder is not used so extensively as on other islands in Hawaii is that most deposits are so weathered that the cinder breaks down when subjected to traffic and is unsatisfactory for road metal. However, the use of weathered cinder for road metal has been attempted, and fresh cinder, which is more satisfactory for roads, occurs at a few places. Several years ago weathered cinder was dug from Hanahanapuni cinder cone, about 5 miles northwest of Lihue. Comparatively fresh cinder is dug by the Grove Farm Co., Ltd., from Puu Hunihuni cinder cone, 2 miles southeast of Koloa, and the McBryde Sugar Co., Ltd., obtains cinder from Kapeka Hill. Cinder from both localities is used for road maintenance, and some from the Kapeka Hill locality is also used for concrete aggregate (Ashizawa, 1964, p. 329). Ashizawa, in this same reference, also notes that the Olokele Sugar Co., Ltd., at Kaumakani located and stripped a deposit of coarse cinder suitable for road maintenance in 1963.

GYPSUM

The presence of gypsum in lagoonal deposits on the Mana Plain along the southwestern coast of Kauai was noted by Macdonald, Davis, and Cox (1960, p. 86). Additional information on these deposits and associated sedimentary rocks was obtained during a study of samples from a few holes augered in the vicinity of the village of Mana. Some of the gypsum occurs as small selenite crystals, but most is extremely fine grained and is mixed with bluish-gray and gray unconsolidated marl and clay, which locally contain abundant rotted shells. At places the gypsiferous beds are overlain by only a thin layer of soil, and at others they occur below lagoonal deposits at depths of 10–30 feet. East of the village of Mana, both the gypsiferous and other lagoonal deposits are overlain by deeply weathered deltaic deposits, which are thickest near the escarpment along the east edge of the plain. The deposits richest in gypsum were penetrated by a hole augered about 1 mile south of Mana village; one sample taken from an interval 10–20 feet below the surface is about 20 percent gypsum, and another sample from depths of 20–30 feet is about 60 percent gypsum. Halloysite, a material amorphous to X-rays, and skeletal remains of marine animals are the principal materials other than gypsum in these deposits. The rock penetrated below the gypsiferous beds in this hole is brown unconsolidated feldspathic siltstone.

The gypsum in the sediments underlying the Mana Plain apparently was precipitated when sea water evaporated in a lagoonal basin. The rocks associated with gypsum consist chiefly of feldspar and clay transported from the Kauai landmass by streams and of marine animal remains.

Although the total gypsum in lagoonal sediments on the Mana Plain may amount to hundreds of thousands of tons, it probably has little value as a mineral resource. Most, if not all, of the gypsum is too impure to be suitable for use in construction materials. Some may be suitable for use as agricultural gypsum, but its value for this purpose may be less than that of the soil now cultivated above it.

The shape and size of the Mana Plain is remarkably similar to that of a shoal area lying just offshore to the north. The shape of this shoal, indicated by the 10-fathom isobath (pl. 11), suggests that it may have been a lagoon when sea level was 60 feet lower than at present (Stearns, 1966, p. 190). If this shoal was once a lagoon, it may also contain gypsum deposits.

IRON

Fe_2O_3 makes up more of the ferruginous bauxite on Kauai than does Al_2O_3 (table 12); therefore, iron would be a potential coproduct, if the bauxite were ever processed. The 110 million tons of bauxite on Kauai contains 39.4 percent Fe_2O_3, or about 44 million tons of Fe_2O_3; also, 500 million tons of aluminous saprolite that contains 27 percent Fe_2O_3 is associated with the bauxite. Other large accumulations of iron-rich weathered rock on Kauai were not investigated, and they are mentioned here only to note that the total material on Kauai rich in iron oxide is very large. Probably most of this material contains 25–35 percent Fe_2O_3, but some thin Humic Ferruginous Latosols contain as much as 80 percent Fe_2O_3 (Sherman, 1954, p. 17).

PLASTIC CLAY

SURFICIAL DEPOSITS

OCCURRENCE

Plastic clay deposits occur in swamp areas at several localities on Kauai, and deposits in five areas were investigated (pls. 1, 3–5). The deposits are of the underclay type and occur only below peat layers and muds rich in organic matter. The swamps containing the clay are at altitudes ranging from 400 to 4,000 feet and in belts that receive 100–200 inches of rainfall a year (fig. 10). The clay in Alakai swamp (pl. 5) is on rocks of the Waimea Canyon Volcanic Series, and the deposits at the other four localities are on Koloa Volcanic Series. Alakai Swamp and the swamp along the powerline south of Princeville Ranch are of the upland type that have been called summit swamps (Wentworth and others, 1940, p. 8); they occur on narrow ridges surrounded by deep steep-walled valleys. The swamps in the other three areas are in gently sloping areas adjacent to highlands. Rainfall is the only water now reaching the swamps on the ridges. The preservation of swamps under such conditions is partly due to the slow rate of evaporation caused by extended periods of rainfall and dense fog. Ground-water seepage probably contributes to the swamps in flat areas adjacent to highlands. The Alakai (pl. 5) and Kanaele Swamps (pl. 4) support only low-growing vegetation that consists, in part, of dwarfed forms of species that grow as large trees in the surrounding dense forest. The vegetation in the swamp south of Princeville Ranch (pl. 1) is only partly dwarfed, but it consists of distinctly smaller forms than those that grow in the forest. The endemic vegetation in the other two swamps has been replaced by introduced species, and whether vegetation was originally stunted cannot be determined.

DESCRIPTION

The plastic clays are light-colored nonbedded irregular lenticular deposits covered by a layer of peat or organic-rich mud. The clays and overlying organic layers are thickest in the central parts of the swamps and thin sharply toward the edges (fig. 11). Both commonly wedge out in the zone where the stunted swamp vegetation changes to normal forest growth. Several holes augered by hand in the central parts of swamps failed to penetrate the base of the clay at depths of 20 feet. One power-auger hole in the swamp south of Princeville Ranch penetrated 24 feet of clay. Deeper holes were not successful because of poor sample recovery, but a few cuttings from greater depths indicate that maximum thicknesses exceed 30 feet. All the clay in the swamps is very plastic, and some water-logged deposits are almost fluid, as shown by the fact that a 2-inch-diameter hand auger weighing about 30 pounds sank under its own weight at several localities in the Kanaele and Alakai Swamps (pls. 4, 5).

Most of the clay is light gray; but some is darker shades of gray, and parts of deposits in contact with the overlying peaty layers are ordinarily so rich in organic matter that they are almost black (logs of auger holes, p. 47). Lower margins of deposits are commonly tan or brown and are richer in iron than middle and upper parts. Relict masses of brown and gray saprolite are common near the base of deposits, and large residual boulders of nepheline basalt are scattered through parts of the clay along the powerline south of Princeville Ranch. The cores of these boulders are dark hard rock, but their outer rims, about an inch in thickness, are lighter colored and softer than the cores. Much of the iron has been leached from the boulder rims, and nepheline has been altered to clay minerals.

The clay in all the swamps investigated grades downward through saprolite from which much of the iron has been leached into iron-rich saprolite, which is the parent material of most of the clay. This saprolite is similar to the saprolite at depth in well-drained areas, except that it contains much more goethite in the form of veins and vesicle and vug fillings.

The clay is generally structureless and nonbedded, but one 4- to 8-inch-thick layer of light-gray clay within peat that overlies the underclay extends over part of Kanaele Swamp. This is the only evidence

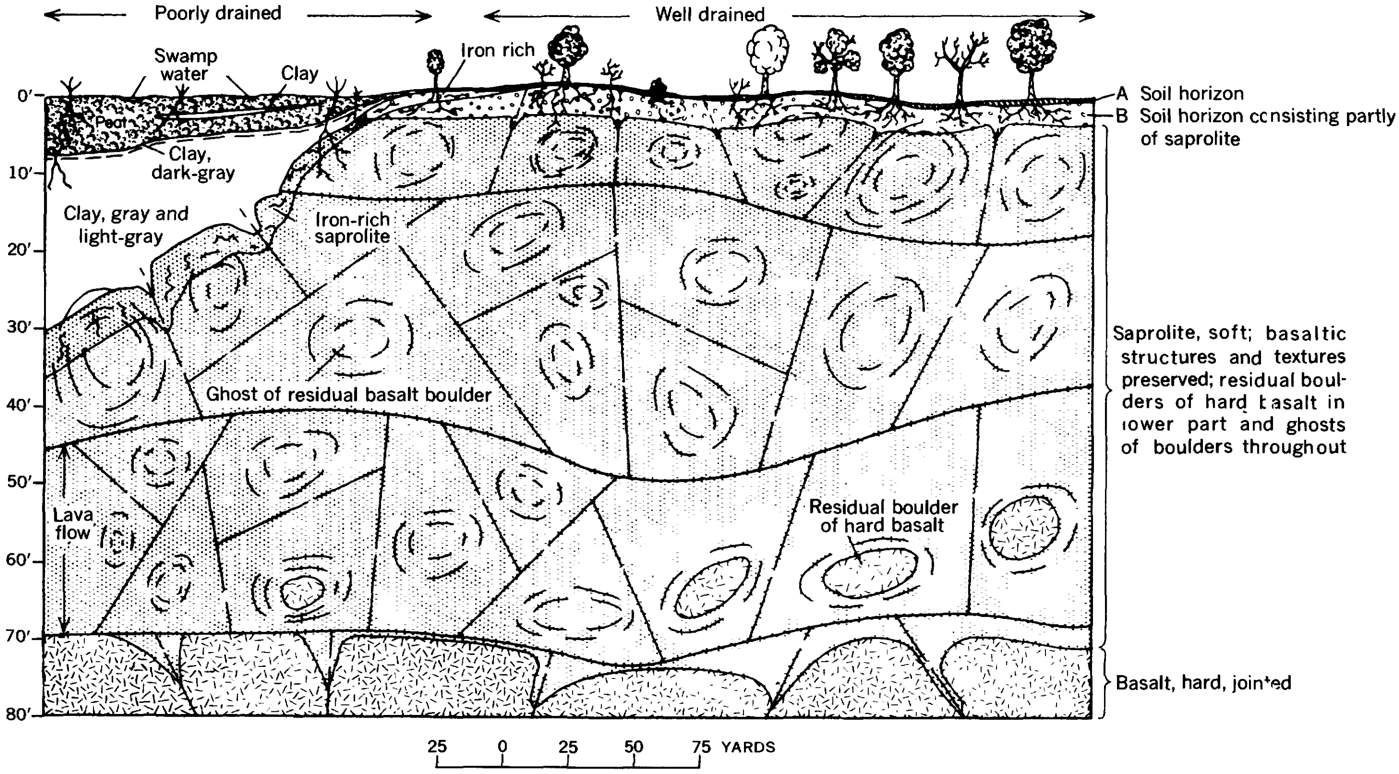

FIGURE 11.—Diagrammatic section illustrating the occurrence and nature of plastic clay deposits. Modified from Patterson (1964, p. 157).

of clay bedding and peat and clay interbedding found in the surficial deposits.

The pH of water in peat and clay, and of open-swamp water, was measured in the field; all are acid. One sample of swamp water had a pH of 3.5. Water from peat at five localities ranged in pH from 3.5 to 4.5; however, pH's as low as 3.2 have been recorded for water in this peat, and the water was described as "extremely acid" (Cline and others, 1955, p. 573). Water from clay at four localities along the powerline trail, which had been partly drained by ditching, ranged from 4.5 to 5.5.

The following logs of holes augered in surficial plastic clay deposits and associated peat and muds are given to document text references and to describe analyzed samples (table 14). Additional logs are listed in a preliminary report of these investigations (Patterson, 1962, app.).

Log of plastic clay penetrated by hole PR–46, south of Princeville Ranch (pl. 1) [1]

Depth (feet)	*Unit thickness (feet)*	*Description*
0.3	0.3	Swamp muck, darker than dark-brown (7.5*YR* 3/2).
5	4.7	Clay, pale-brown (10*YR* 6/3), plastic; contains abundant carbonaceous root remains.
15	9.3	Clay, light-gray (10*YR* 6/2), very plastic.
20	5	do

[1] Chemical analysis of clay from depth interval 0.3–10 ft is given in table 14.

Log of plastic clay penetrated by hole GF–2 (pl. 3) [1]

Depth (feet)	*Unit thickness (feet)*	*Description*
0.3	0.3	Swamp muck rich in organic matter
1	.7	Clay, dark-grayish-brown (10*YR* 4/2), plastic.
5	4	Clay, light-gray (10*YR* 6/1), very plastic.
10	5	Clay, light-gray (10*YR* 6/1); mixed with minor amounts of lighter colored clay; very plastic.
18	8	Clay, gray (2.5*Y* *N*5), very plastic.
18	..	Hard rock; a ferruginous vein deposit(?).

[1] Chemical analysis of clay from depth interval 0.3–10 ft is given in table 14.

Log of plastic clay and peat penetrated by hole 8, Kanaele Swamp (pl. 4)

Depth (feet)	*Unit thickness (feet)*	*Description*
0.3	0.3	Peat and muck, very dark brown.
.7	.4	Clay, gray (2.5*Y* *N*6).
11	10.3	Clay and peat mixed.
21	10	Clay, gray (2.5*Y* *N*6).

Log of plastic clay and peat penetrated by hole 4, Alakai Swamp (pl. 5), and partial chemical analyses of clay from selected intervals

[Partial chemical analyses by X-ray fluorescence methods; R. M. Bromery, analyst]

Depth (feet)	*Unit thickness (feet)*	*Description*	Major oxides			
			SiO_2	Al_2O_3	Fe_2O_3	TiO_2
5	5	Peat, dark-brown (7.5*YR* 3/2)	---	---	---	---
5.5	.5	Clay, very dark brown, plastic	---	---	---	---
10	4.5	Clay, light-gray (10*YR* 6/1) in upper part, gray (2.5*Y* *N*6) in lower part; plastic; contains a few small white gibbsite nodules	27.7	27.2	4.3	13.9
14	4	Clay, light-gray (2.5*Y* 7/2) and gray (2.5*Y* *N*6), mixed, plastic	33.0	34.7	3.0	6.0
20	6	Saprolite, upper part reddish brown (2.5*YR* 4/4) and dark brown (7.5*YR* 3/2) mixed; lower part dark brown 7.5*YR* 3/2) and dark grayish brown (10*YR* 4/2) mixed; plastic, partly granular	31.2	33.7	8.5	5.1

Log of plastic clay penetrated by hole 6, Alakai Swamp (pl. 5)[1]

Depth (feet)	Unit thickness (feet)	Description
0.7	0.7	Peat, very dark brown.
5	4.3	Clay, light-gray (2.5*Y* *N*7); upper 1 in. very dark brown; very plastic.
15	10	Clay, light-gray (2.5*Y* *N*7), very plastic; contains a few small nodules.
20	5	Clay, gray (2.5*Y* *N*5 and 2.5*Y* *N*4 mixed), very plastic; contains traces of saprolite near base.

[1] Chemical analysis of clay from depth interval 0.7–15 ft is given in table 14.

Log of plastic clay and peat penetrated by hole 10, Alakai Swamp (pl. 5) [1]

Depth (feet)	Unit thickness (feet)	description
4	4	Peat, dark-brown (7.5*YR* 3/2).
8	4	Peat, very dark brown.
20	12	Clay, gray (10*YR* 5/1), plastic.

[1] Chemical analysis of sample from depth interval 8–15 ft is given in table 14, and X-ray diffraction traces are shown on pl. 10*D*.

MINERAL COMPOSITION

The plastic clay consists chiefly of halloysite, gibbsite, illite, quartz, and anatase, and it contains traces of ilmenite and magnetite. Much of the clay probably also contains appreciable quantities of amorphous inorganic matter. The estimated ranges in abundance of these minerals and amorphous matter, expressed in parts of ten and trace, follow:

Halloysite	5 to 8
Illite	0 to 3
Quartz	0 to 2
Gibbsite	0 to 3
Goethite	Trace
Magnetite	Trace
Ilmenite	Trace to 1
Anatase	Trace to 2
Amorphous matter	0 to 4(?)

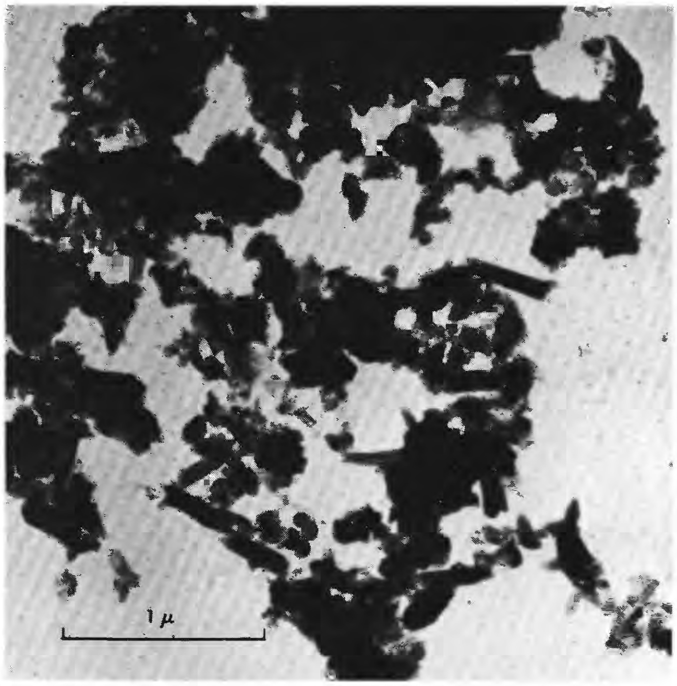

FIGURE 12.—Electron micrograph of light-gray plastic clay penetrated at a depth of 10 feet in auger hole PR-46 (pl. 1). Electron micrograph by J. C. Hathaway.

Halloysite is the most abundant mineral in the plastic clay, and in some samples it is the only one identifiable by X-ray methods (pl. 10*Da*). Halloysite is identified by its prominent 10 A reflection from the 001 planes, while the natural moisture is still present (pl. 10*Da*), and the collapse of this spacing to about 7 A after the mineral converts to the less hydrous form (pl. 10*Db*). Electron micrographs of the plastic clay (fig. 12) show the presence of tubular structures characteristic of metahalloysite, the halloysite having dehydrated during sample preparation or exposure required to obtain the micrograph.

Illite is generally not an abundant mineral in the plastic clay, but it makes up as much as 20 percent of parts of some deposits. It is uncommonly abundant in a layer 7 feet thick below the thickest peat penetrated in augering in Alakai Swamp (log, p. 47; pl. 5) and in a thin bed interlayered with peat and mixed peat and clay in Kanaele Swamp (log, p. 47; pl. 4). Illite was identified by its 10 A reflection in samples that had been dried to collapse the 10 A halloysite reflection (pl. 10*Dd–f*). Illite probably contains nearly all the K_2O in the plastic clay, inasmuch as the sample richest in this oxide (table 14, sample 2; pl. 10*De*) also contains considerable illite and no other K_2O-bearing minerals were identifiable in this clay.

Quartz occurs in sufficient quantities in much of the plastic clay to produce prominent X-ray reflections (pl. 10*Dc–f*). Most is extremely fine grained, similar to that found in the clay of the Koolau Volcanic Series on Oahu by Wentworth, Wells, and Allen (1940, p. 25).

Gibbsite occurs as irregularly rounded impure nodules, ranging from silt size (<1/16 mm diameter) to more than 6 inches in longest dimension, scattered throughout most of the clay. However, in some zones gibbsite is absent, and in other zones small nodules are so abundant that the clay has a granular texture and is difficult to auger by hand.

Anatase is the principal titanium mineral in the plastic clay, and it is most abundant in the $<2\mu$ fraction, but some is also present in the largest gibbsite nodules. Anatase is identified by its strongest X-ray reflection at 3.52 A (pl. 10*Dd, f*). Heat treatment to destroy the halloysite structure is required for this identification, because the reflection from the (002) halloysite plane masks the strongest anatase peak. The purest anatase found was sand-sized grayish-blue nodules that were concentrated in the heavy-mineral fraction separated by heavy liquid from a clay sample taken southwest of Kilohana Crater (pl. 3). These blue nodules contain approximately 47 percent TiO_2, and they consist chiefly of anatase, though trace amounts of ilmenite may be present.

Ilmenite is rare in most of the plastic clay, but a few zones contain as much as 10 percent. Most ilmenite is in the fine-silt fraction, but a few grains are as large as grains of fine sand.

Traces of goethite and magnetite were found in the silt and sand fractions separated from the clay. Neither mineral was sufficiently abundant in whole samples to be identified by X-ray methods.

Amorphous inorganic material is probably present in some of the clay because intensities of X-ray reflections from minerals in many samples are low, and estimated amounts of identifiable minerals are inadequate to account for the composition of whole samples. Also, the electron micrograph of the clay (fig. 12) shows much very finely dispersed material that is probably amorphous.

CHEMICAL COMPOSITION

The plastic clays consist chiefly of Al_2O_3, SiO_2, TiO_2, and H_2O (table 14); they are uncommonly low in Fe_2O_3 but rich in alkalies and several minor elements. The abundant SiO_2 in surficial plastic clay deposits, which ranges from 29.5 to 34.0 percent in

TABLE 14.—*Chemical analyses, in percent, of plastic clay and a titanium-rich soil, Kauai*

[Analyzed by rapid chemical methods described by Shapiro and Brannock (1956). Analysts: Paul Elmore, Ivan Barlow, Samuel Botts, Gillison Chloe, Lowell Artis, and H. Smith]

Sample No. Laboratory No.	1 160700	2 160701	3 160702	4 160702	5 156945	6 156946
SiO_2	34.0	33.1	29.5	29.7	38.1	31.5
Al_2O_3	34.8	26.7	34.6	32.7	33.1	9.6
Fe_2O_3	2.2	2.2	1.8	.72	5.2	18.6
FeO	.67	1.5	.68	.44	----	----
MgO	.06	.54	.10	.00	----	----
CaO	.00	.00	.00	.00	----	----
Na_2O	.08	.22	.08	.07	.03	.15
K_2O	.21	1.7	.28	.09	.21	1.4
H_2O-	6.8	6.1	10.8	15.0	----	----
H_2O+	13.5	9.3	12.6	11.9	17.4	5.3
TiO_2	7.5	17.5	8.9	7.6	6.2	30.6
P_2O_5	.41	.31	.31	.98	.05	.14
MnO	.08	.16	.08	.08	.06	.60
CO_2	$<.05$	$<.05$	$<.05$	$<.05$	----	----
Total	100	99	100	99	100	98

1. Surficial light-gray clay 14.3 ft thick (pl. 5, hole 6; log, p. 47).
2. Surficial gray clay 7 ft thick (pl. 5, hole 10; log, p. 47).
3. Surficial gray clay 9.7 ft thick (pl. 3, hole GF–2; log, p. 47).
4. Surficial light-gray and light-brown clay 9.3 ft thick (pl. 1; hole PR–46; log, p. 47).
5. Buried clay, channel sample of upper 5 ft of a thicker deposit exposed northeast of road junction in Knudsens Gap (pl. 3; p. 54).
6. Surficial gray titanium-rich clay soil 1 ft thick, near Kaneha Reservoirs (pl. 2, p. 55).

the samples analyzed (table 14, samples 1–4), contrasts sharply with the very low SiO_2 contents of saprolite near the surface in well-drained areas (table 3). Iron oxide is present in very small quantities in the clay and is the most abundant component of most saprolite in well-drained areas. Titania is even more abundant in plastic clay than in the saprolite; TiO_2 forms as much as 17.5 percent of the plastic clay (table 14, sample 2).

The alkali and alkaline-earth contents of the plastic clays vary considerably, but these elements tend to be more abundant in the clay than in saprolite in well-drained areas. A comparison of the semiquantitative spectrographic analyses of plastic clays and saprolite from depths of less than 20 feet (table 10; fig. 9) shows that Mg, Na, K, and Co all tend to be significantly more abundant in plastic clays in swamps than in saprolite in well-drained areas. The analyses by rapid chemical methods (tables 2, 14), however, show that K_2O is concentrated locally in the clay; that MgO and Na_2O tend to have approximately the same concentration in both clay and saprolite; and that CaO is not present in the clay, but this method of analysis is unreliable for small quantities of calcium oxide. The local concentration of K_2O is as great as 1.7 percent (table 14, sample 2) in clay formed on the Waimea Canyon Volcanic Series. This percentage of K_2O, though small, represents a considerable concentration, inasmuch as the nine rocks in the Waimea Canyon Volcanic Series that have been analyzed (Macdonald, 1960, p. 112) range from 0.22 to 0.47 percent K_2O, and the average is only 0.32 percent.

Two samples of plastic clay on the Koloa Volcanic Series and two on the Waimea Canyon Volcanic Series were analyzed for minor elements by semiquantitative spectrographic methods (table 10; fig. 9). The analyses suggest some differences in the behavior of minor elements during weathering in a swamp environment from that in typical well-drained areas. The minor elements concentrated in the clay are Sc, Ga, Nb, and V. Ce was found in all samples, and Ge was found in one sample of clay on the Waimea Canyon Series. As neither element was found in any hard or weathered rock in well-drained areas, both may be concentrated by weathering under swamp conditions. Minor elements that are leached, but at a much slower rate than in well-drained areas, are Na, Mg, Ca, Co, Ni, Cu, Sr, Y, Zr, Ba, La, and Pb.

ORIGIN

The plastic clay deposits and associated saprolite both formed chiefly from parent rocks of similar composition and age. The plastic clay deposits are restricted to swamps having peat or organic-rich layers, indicating that their origin is related to poor drainage conditions and decaying organic matter. Saprolite, which formed in well-drained areas, has very different mineral content and texture from the clay. Halloysite, illite, quartz, and anatase are much more abundant—and gibbsite, goethite, hematite, and magnetite are less abundant—in the clay than in the saprolite. Textures of the parent rocks have been destroyed in the clay but are well preserved in the saprolite.

Plastic clay has formed from both saprolite and hard basalt. Clay formation from saprolite is indicated by the downward and lateral gradation of clay into saprolite and residual lumps of saprolite in the lower parts of clay deposits. The residual nepheline basalt boulders in one swamp having outer rims in intermediate stages of alteration to clay indicate that the clay does form from the aluminous minerals in the parent rock. Weathering of basalt probably began shortly after the lavas cooled, as has been suggested for the rocks in well-drained areas. Probably some swamps in which the clay formed have always been areas of poor drainage, resulting from flow damming at the time the parent rocks accumulated. Reversed magnetic properties in the residual nepheline basalt boulders in one clay deposit on the

Koloa Volcanic Series indicate that the parent rock of this clay is older than 0.7 million year (p. 8). The Waimea Canyon Volcanic Series is much older than the Koloa Series, and weathering that resulted in the formation of clays on this older series (pl. 5) may have proceeded much longer. The thickness of the peat indicates that the swamps have existed for a long time, and the absence of evidence for any significant change in the swamp environment leads to the conclusion that both clay and peat are still forming today. The earliest date that can now be established for the beginning of clay formation is the close of the last glacial period. This date is based on analysis of pollen (Selling, 1948, p. 118) from near the base of the thickest peat that overlies clay on the Waimea Canyon Volcanic Series (pl. 5).

Part of the halloysite in the plastic clay probably formed in the swamps, and part has been preserved from a saprolite already rich in this mineral. Some of this clay formed in place and is probably still forming, as indicated by the several stages of replacement of nepheline by halloysite in the altered rims of residual boulders in the swamp south of Princeville Ranch. Formation of part of the clay by preservation of the halloysite already present in the parent saprolite is indicated by the isolated masses in the lower parts of clay bodies and by the gradation of clay downward into saprolite. The preservation of the clay is due to the influence of the low-pH swamp environment; under these conditions silica removal is impeded, but iron is leached efficiently.

The varying amounts of quartz in the plastic clay and its absence in the saprolite reflect the differences in the effectiveness of silica leaching under the two conditions of drainage. The restriction of quartz to clay would seem to indicate that it forms in a swamp environment. However, it occurs as very small angular grains, and any quartz having such an origin would probably occur in some other form. Recent investigations by Jackson and others (1968) and Rex and others (1969) have established that the quartz in the plastic clay was introduced from a distant source by atmospheric transport.

The origin of the potassium-bearing illite in the plastic clay deposits is difficult to explain, because the traces of biotite in the volcanic rock on Kauai are inadequate to supply sufficient micaceous parent material, and the saprolite on which some of the clay formed must have already been leached of potassium. The problem is further complicated by the fact that one concentration of illite is under the thickest peat (p. 47), whereas clay in the same stratigraphic position under thin peat in this swamp contains little or no illite. The relationship between abundance of illite and thickness of peat suggested to the author (Patterson, 1964, p. 170–171) that the origins of the two matrials are related, and illite may form in a swamp environment. Such an origin of illite under surface conditions would be similar to the one suggested for mica in several Hawaiian soils by Swindale and Uehara (1966, p. 726) and Juang and Uehara (1968, p. 35). Another concentration of illite occurs in a thin bed interlayered with peat and mixed clay and peat in Kanaele Swamp (log, p. 47), where the source of potassium may have been partly from decaying plant material. However, clays at both locations where illite is concentrated also contain angular quartz and a few euhedral microscopic grains of other minerals. The occurrences of these minerals suggest that an ash fall might have been the original rock of the bedded clay; therefore, an air-transported volcanic material, anomalously rich in mica and from an unknown source, might have been the parent of the illite.

Information leading to an explanation of the amorphous material in the plastic clays could not be obtained, inasmuch as these materials cannot be isolated for study. However, the high alumina-silica content of the clay suggests that the amorphous materials are probably similar to the alumina-silica gel and allophane on Maui. The amorphous materials in underclays may be an intermediate stage between the restruction of the silicate mineral in the parent rocks and the formation of clay minerals, or they may form during the gradual desilication of the clay minerals and formation of gibbsite.

RESOURCES

Five areas in which the largest plastic clay deposits occur were investigated and resources were estimated. These areas are as follows: (1) Along the powerline trail south of Princeville Ranch (pl. 1); (2) southeast of Kalihiwai Reservoir on Kilauea Sugar Co., Ltd., land (pl. 1); (3) the swamp west of Kilohana Crater on Grove Farm Co., Ltd., land (pl. 3); (4) Kanaele Swamp on McBryde Sugar Co., Ltd., land (pl. 4); and (5) State-owned land in the northwestern part of Alakai Swamp (pl. 5). The resources in these five areas (table 15) are estimated to be 5 million dry tons. These estimates are based on the volume of the clay times an assumed dry-weight factor of 50 pounds per cubic foot of clay. Other plastic clay deposits are probably present in scattered inaccessible areas in the southeastern part of Alakai Swamp, as indicated by areas of dwarfed vegetation on aerial photographs. Because of their location,

TABLE 15.—*Estimated tonnages of plastic clay on Kauai, Hawaii*

[Chemical analyses are averages of only a few samples from each area]

Area	Plate	Landowner	Short dry tons	Partial chemical analyses (percent)			
				SiO_2	Al_2O_3	Fe_2O_3	TiO_2
Princeville Ranch.	1	American Factors Co., Ltd. (forest reserve land).	1,100,000	31.5	37.8	1.1	7.8
Kilauea Sugar Co., Ltd., land.	1	C. Brewer Co., Ltd. (land leased to Gay and Robinson).	70,000	27.4	39.9	2.5	6.5
Swamp west of Kilohana Crater.	3	Grove Farm Co., Ltd.	1,500,000	31.3	37.3	2.2	5.4
Kanaele Swamp.	4	McBryde Sugar Co., Ltd.	900,000	30.8	33.8	5.6	5.7
Northwestern part of Alkai Swamp.	5	State of Hawaii.	800,000	30.2	32.4	6.2	7.4
Total			5,000,000	--	--	--	--

however, these inferred deposits have little value and were not investigated.

FIRING TESTS AND APPRAISAL

Firing tests were made on 20 samples of plastic clay, using a procedure similar to that described by Klinefelter and Hamlin (1957, p. 30–34). Deionized water was added to the raw clay until the proper plasticity was attained. The clay was then tempered overnight in air-tight containers, and test bricks were made. The bricks were air dried for 2 days at room temperature and for 24 hours at 110°C; they were then fired at 600°, 1,000°, and 1,200° C. Water of plasticity was determined by drying parts of the clays taken at the time the test bricks were made. Shrinkage was determined on a linear basis by measuring the distance between marks on freshly made brick and after each drying and firing step.

Most samples tested (table 16) were high in water of plasticity ranging from 30.9 to 52.7 percent, and the average was 37.5 percent) and shrank and cracked excessively during drying and firing. Although all test bricks shrank considerably during drying, shapes were retained satisfactorily in all but one sample, which warped. Shrinkage was particularly great in the 1,000°–1,200° C temperature range. All test bricks were weak after firing to 1,000° C and could be broken easily, but bricks fired at 1,200° C were dense and had strengths that were adequate for most ceramic purposes. Most test bricks were pale shades of yellow and yellowish brown after firing at 1,200° C.

The shrinkage and cracking are to be related directly to the mineral content of the clay. Halloysite-metahalloysite, the principal clay mineral present, tends to be highly hydrated. Large amounts of water are needed for plasticity because of this clay mineral, and water is probably the chief cause for the excessive shrinkage, at least during drying and at low firing temperatures. Although some cracking is from differential shrinkage, much is caused by the gibbistic nodules in the clay. The nodules either expand with heat or shrink much less than the clay, and cracks form as a result. Some of the unfavorable firing characteristics could be improved by grinding the clay before use, which would tend to thoroughly mix the gibbsitic material with the clay.

The mineralogy of one fired sample, from depth interval 1–19 feet in hole GF–4 (pl. 3), was investigated by X-ray methods. After firing at 1,000° C, the brick consisted chiefly of noncrystalline material, minor amounts of anatase, and traces of rutile (TiO_2). After firing at 1,200° C, the brick consisted chiefly of mullite ($3Al_2O_3 \cdot 2SiO_2$), minor amounts of cristobalite (SiO_2) and rutile, and traces of anatase. Probably most shrinkage and cracking at high temperatures is caused by the volume change involved in converting noncrystalline material into the more dense mineral forms.

The possibility of improving the ceramic properties of the plastic clay by double firing was investigated in tests of four samples (table 16). Clay samples previously fired at 600°C were ground to fine-sand size. Three parts of this ground material were mixed with one part ground unfired clay to obtain the required bond strength and plasticity. Water was then added and test bricks made. This double-firing method greatly improved the undesirable cracking properties of the single-fired clay; however, shrinkage was still excessive in test brick at 1,200°C. All test pieces retained their shapes well at all stages of drying and firing. All pieces were weak through the 1,000°C-temperature range, but they were dense and had adequate strengths for most ceramic products after firing at 1,200°C.

The raw plastic clays on Kauai are not suitable for large-scale use in ceramic products, according to the firing tests made during this investigation and to other tests by Arthur D. Little, Inc. (Little, 1957, p. 45–47). The unfavorable cracking properties might be controlled sufficiently for ceramic purposes by grinding the clay and calcining or double firing and remixing with small quantities of raw clay for bonding; however, shrinkage would be very difficult to control (table 16). Grinding and double firing would be costly and would make it more difficult to use the clay profitably. The dark color of much of the plastic clay and the abundance of mineral and organic impurities greatly reduce the possibilities of

TABLE 16.—*Firing tests of plastic clays from Kauai*

[Tests done by method similar to that described by Klinefelter and Hamlin (1957, p. 30–34); tested by S. H. Patterson]

Location	Auger hole	Sample depth interval (feet)	Water of plasticity (percent)	Air-dry properties			Properties after firing at 600°C			Properties after firing at 1,000°C			Properties after firing at 1,200°C		
				Color	Shrinkage (percent)	Firing characteristics	Color	Shrinkage (percent)	Firing characteristics	Color	Shrinkage (percent)	Firing characteristics	Color	Shrinkage (percent)	Firing characteristics
							Single-firing tests								
Alakai Swamp (pl. 5).	A1 3	2–19	35.0	Light brownish gray (2.5*Y* 6/2).	8	Slight cracking.	Yellowish red (5*YR* 5/8).	10	Moderate cracking.	Very pale brown (10*YR* 8/4).	14	Severe cracking.	Light yellowish brown (2.5*Y* 6/4).	24	Severe cracking.
	A1 4	5–20	34.4	Light gray (10*YR* 6/1).	8	Severe cracking.	do	9	Severe cracking.	Very pale brown (10*YR* 8/3).	12	Severe cracking and warping.	do	22	Do.
	A1 6	0.7–15	35.0	White (2.5 *N*8).	8	Good	White (10*YR* 8/1)	10	Good	Pinkish white (7.5*YR* 8/2).	12	Slight cracking.	Pale yellow (2.5*Y* 7/4).	18	Moderate cracking.
	A1 6	15–20	33.4	Gray (2.5 *N*7).	8	do	Light gray (10*YR* 7/1).	12	do	Light gray (5*YR* 6/1).	12	Good	Pale brown (10*YR* 6/3).	18	Severe cracking.
Kanaele Swamp (pl. 4).	B 1	1–21	42.0	Grayish brown (2.5*Y* 5/2).	10	Slight cracking.	Light reddish brown (5*YR* 6/1).	14	Slight cracking.	Very pale brown (10*YR* 7/3).	16	Slight cracking.	Light yellowish brown (2.5*Y* 6/4).	24	Do.
	B 2	1–17	40.0	do	10	Good	Reddish brown (5*YR* 5/4).	14	Good	Light brown (7.5*YR* 6/4).	18	do	do	22	Do.
	B 10	0.2–21	40.4	do	10	Slight cracking.	Light reddish brown (5*YR* 6/4).	12	Slight cracking.	Pink (7.5*YR* 7/4).	16	Slight cracking and warping.	do	24	Do.
	B 11	.9–21	44.7	Dark gray (5*Y* 4/1)	10	Severe cracking.	do	12	Severe cracking.						
	G 14	1–21	39.0	Gray (2.5*Y* *N*5)	8	Good	Pinkish gray (5*YR* 6/2).	9	Slight cracking.	Pink (7.5*YR* 7/4).	10	Slight cracking.	Light yellowish brown (2.5*Y* 6/4).	26	Severe cracking.
	B 15	1–15	52.7	Dark gray (2.5*Y* *N*4)	15	Moderate warping.	Light reddish brown (5*YR* 6/4).	17	Severe distortion.						
Grove Farm Co. land (pl. 3).	GF–3	0.3–24	34.3	Light gray (2.5*Y* 6/2)	6	Good	Very pale brown (10*YR* 7/4).	8	Good	Pinkish white (7.5*YR* 8/2).	12	Slight cracking.	Pale yellow (2.5*Y* 7/4).	22	Very slight cracking.
	GF–4	1–19	33.6	White (5*Y* 7/1)	8	do	Very pale brown (10*YR* 7/3).	9	do	do	10	do	do	18	Do.
	GF–4	19–24	37.2	White (5*Y* 7/2)	10	Slight cracking.	Very pale brown (10*YR* 7/4).	12		Very pale brown (10*YR* 7/3).	16	Severe cracking.			
	GF–5	0.8–15	32.0	White (2.5*Y* 7/2)	6	Good	do	8	Good	Pinkish white (7.5*YR* 3/2).	10	Slight cracking.	Pale yellow (2.5*Y* 7/4).	18	Slight cracking.
	GF–16	.7–5	30.9	White (5*Y* 7/2)	12	do	Yellowish red (7.5*Y* 6/2).	14	do	Pink (7.5*YR* 7/4).	16	do			
	GF–19	3–7	36.8	Light yellowish brown (2.5*Y* 6/4).	13	Moderate cracking.	Red (2.5*YR* 4/8)	16	Severe cracking.	Red (2.5*YR* 5/6).	18	Severe cracking.			
Princeville Ranch land (pl. 1).	PR–16	0.3–20	35.2	Light gray (2.5*Y* 7/2)	8	Good	White (10*YR* 8/2)	10	Good	White (10*YR* 8/2).	12	Moderate cracking.	Pale yellow (2.5*Y* 7/4).	21	Moderate cracking.
	(1)	0–8	39.4	White (10*YR* 8/2)	10	do	Yellow (10*YR* 7/6)	14	do	Very pale brown (10*YR* 8/3).	17	Very slight cracking.	do	26	Slight cracking.
Kilauea Sugar Co. land (pl. 1).	K–27	8–20	38.9	do	8	do	Reddish yellow (5*YR* 6/8).	10	do	Reddish yellow (7.5*YR* 7/6).	15	do			
	K–36	1–10	37.6	Light gray (5*Y* 7/2)	10	do	Reddish brown (2.5*YR* 4/6).	13	do	Light reddish brown (5*Y* 6/4).	10	Slight cracking.			
							Double-firing tests								
	A1 4 [2]	5–20	31.5	Light yellowish brown (10*YR* 6/4).	3	Good	Reddish yellow (5*YR* 6/6).	6	Good	Very pale brown (10*YR* 6/3).	8	Good	Pale yellow (2.5*YR* 7/4).	21	Good.
	GF–3	0.3–24	29.7	Light brownish gray (2.5*Y* 6/2).	2	do	Very pale brown (10*YR* 7/4).	4	do	Very pale brown (10*YR* 8/3).	8	do	Pale yellow (2.5*YR* 8/4).	18	Do.
	GF–4	1–19	31.0	Light gray (10*YR* 7/2)	2	do	do	5	do	White (2.5*YR* 8/2).	10	do	do	16	Do.
	GF–5	.8–15	28.7	do	1	do	do	3	do	Very pale brown (10*YR* 7/3).	9	do	do	17	Do.

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[1] Very light gray clay from an auger hole in a small clay body near pole 44 on powerline, 1 mile south of southernmost boundary of pl. 1.

[2] Sample from Alakai Swamp.

using the clay as petroleum catalyst or for other purposes for which halloysitic clays are in demand.

BURIED DEPOSITS

Plastic clay deposits buried by weathered younger rocks associated with, and formed chiefly from, the Koloa Volcanic Series were found at three localities. The upper parts of two deposits are exposed, and the third was penetrated at depth by augering. One exposure is on the north side of Highway 50 near Knudsen Gap (auger hole Kn–16, p. 54; pl. 3). The other exposure is in a field roadcut near the boundary between Grove Farm Co., Ltd., and Knudsen Estate lands (auger hole GF–29, p. 53; pl. 3). The unexposed deposit was penetrated by auger hole GF–22 (p. 53; pl. 3) on Grove Farm Co., Ltd. land.

The unexposed plastic clay (auger hole GF–22) is in the center of a deeply weathered cone-shaped vent that has been cut and drained on the south side by the headward erosion of a small stream. This deposit is overlain by a bed of peat 9 feet thick, and another bed of peat is interbedded with the clay. The rocks above the peat are similar to saprolite in chemical composition but are so weathered that their original character could not be determined from auger cuttings. They probably contain weathered alluvium and slope wash transported from higher parts of the cone. The deposit is small and probably lenticular, as indicated by the limited extent of the vent (pl. 3) and by the absence of peat and clay in rocks penetrated by hole GF–23 nearer the present internal edge of the vent.

Log and partial chemical analyses, in percent, of materials from auger hole GF–22 (pl. 3)

[Analyzed by R. M. Bromery using X-ray fluorescence methods]

Depth (feet)	Unit thickness (feet)	Description	Major oxides			
			SiO_2	Al_2O_3	Fe_2O_3	TiO_2
0.5	0.5	Soil				
4	3.5	Clay, yellowish-red (5*YR* 5/6), plastic	5.7	24.5	34.2	8.8
10	6	Clay, reddish-yellow (7.5*YR* 6/8), plastic; nodules common in lower part	6.5	26.5	28.5	9.3
19	9	Peat, black				
20	1	Clay, very dark gray (7.5*YR N*3), very plastic	26.5	39.0	2.0	6.7
22	2	Peat, black				
24	2	Clay, gray (2.5*YR N*5), very plastic	30.2	28.7	4.1	6.9
34	10	Clay, gray (2.5*YR N*5); auger cuttings are fluid mud				
44	10	Clay, mostly brownish-yellow (10*YR* 6/8); auger cuttings are fluid mud, poor recovery				

Massive chunky gray clay is exposed near auger hole GF–29 (pl. 3). Very plastic dark-gray clay containing a layer of peat and clay underlies the exposed deposit. Materials overlying the clay consist of weathered saprolite or alluvium. The contact of the overlying rocks with the clay is inclined gently to the east. The exposed clay ranges in thickness from 10–12 feet, and auger hole GF–29 at the base of the exposure passed through 26 feet of clay and peat (log of hole GF–29, p. 53). The clay at the base of the exposure is dark gray (10 4/1), and most of the upper part is dark gray (7.5 *YR N*4). Irregular masses of light-gray clay and gibbsite nodules are abundant in the upper part of the exposed clay.

The clay deposit is small and lens shaped, as indicated by augering in nearby areas (Patterson, 1962, holes GF–28, 30; app., p. 183–184). Hole GF–28, 175 yards northwest of hole GF–29, passed through 7 feet of gray clay containing minor quantities of black organic matter. Hole GF–30, 200 yards southeast of GF–29, passed through very plastic gray clay at depths of 19–24 feet, and a 10-foot interval of lost cuttings below this clay may also have been clay. No clay or peat was penetrated by several other holes augered nearby.

Log of auger hole GF–29 (pl. 3)

[Hole is in roadcut at base of gray clay exposure described above]

Depth (feet)	Unit thickness (feet)	Description
4	4	Clay, grayish-brown (10*YR* 5/2), stiff plastic.
10	6	Clay, dark-gray (10*YR* 4/1), plastic; contains specks and lumps of light-gray gibbsite(?) and vein deposits of red (7.5*R* 4/8) ferruginous material.
16	6	Peat, black; contains a few thin beds of clay.
22	6	Clay, very dark gray (2.5*YR N*3); cuttings are gellike.
26	4	Clay, gray (7.5*YR N*5) and grayish-brown (10*YR* 5/2); cuttings are fluid mud.
29	3	Saprolite, dark-reddish-brown (5*YR* 3/4), stiff plastic; nodules abundant.

NOTE.—Partial chemical analysis of clay from depth of 0–10 ft is as follows: SiO_2, 36.1 percent; Al_2O_3, 32.4 percent; Fe_2O_3, 9.1 percent; and TiO_2, 6.4 percent. Analyzed by R. M. Bromery using X-ray fluorescence methods. The pH of the water that seeped into the hole was 4.4.

Gray (5*Y* 5/1) chunky clay, about 5 feet thick, is exposed in the roadcut north of the Knudsens Gap (pl. 3). An auger hole about 50 yards south of the exposure penetrated 5 1/2 feet of chunky clay (log of hole Kn–16, p. 54), then 29½ feet of plastic brown, gray, black, and red clay, and bottomed on hard rock. A black clay layer, 28 feet below the top of the clay deposit, is rich in organic matter and contains small pieces of wood. The material overlying the clay is typical saprolite that contains residual boulders of hard rock as much as 10 inches in diameter. The clay deposit is not extensive because several deep holes within a half-mile radius of the exposure failed to penetrate clay.

Log of auger hole Kn–16 and estimates of the principal minerals present

[Mineral estimates are based on the results of differential thermal analysis with portable equipment, and content is expressed in parts of 10 and trace]

Depth (feet)	Unit thickness (feet)	Description	Gibbsite and goethite (undifferentiated)	Halloysite-metahalloysite
2	2	Saprolite, yellowish-red (5*YR* 5/8)	6	2
7.5	5.5	Clay, gray (5*Y* 5/1) chunky (same as exposed in roadcut)	3	5
9	1.5	Clay or saprolite, dark-grayish-brown (10*YR* 4/2), crumbly; gibbsitic nodules common	3	5
12	3	Clay, gray (5*Y* 5/1), plastic	5	3
16	4	Clay, dark-red (7.5*R* 3/6), plastic	1	7
19	3	Clay, dark-gray (2.5*YR* *N*4), stiff plastic	Trace	8
23	4	Clay, dark-brown (7.5 *YR* 3/2) and very dusky red (7.5*R* 2/4) mixed, plastic	2	6
29	6	Clay, dark-gray (2.5*YR* *N*4); contains a small amount of dark-red (10*R* 3/6) mixed plastic clay	0	8
30	1	Clay, black, very plastic; contains organic matter and wood	0	5
37	7	Clay, dark-gray (2.5*YR* *N*4) plastic	0	9
37		Hard rock, basalt(?)	--	--

The few samples of buried clay investigated by X-ray and differential thermal analysis methods consist chiefly of halloysite-metahalloysite and contain minor quantities of anatase and gibbsite. The anatase is very fine grained, and the gibbsite occurs chiefly as corallike nodules of varying dimensions scattered throughout the clay. Gibbsite also occurs with ferruginous materials as veinlets along joints.

The buried clay (table 14, sample 5; logs of holes GF–22 and GF–29) is similar in composition to the surficial clay (table 14, samples 1–4). Both types of clay are much higher in silica and alumina and lower in iron oxide than typical saprolite (table 2).

The buried plastic clay deposits formed, like the surficial clays, under conditions of poor drainage in the presence of abundant decaying organic matter and were later covered by younger materials. One buried deposit (hole GF–22) lies under a thick bed of peat in the center of a cone-shaped vent and must have been poorly drained until the cone was breached by stream erosion. The other two deposits are interbedded with peat or organic-rich layers, and peat that may have overlain both deposits was eroded before burial, a possibility suggested by the inclined upper surface of the deposit at hole GF–29. The materials overlying these deposits are younger than the clay, as indicated by their superimposed positions and their less weathered condition. The saprolite overlying the clay in the vicinity of Knudsen Gap still contains residual boulders of hard basalt. The buried and surficial clay deposits are related in origin, as indicated by their similar characteristics and their shared differences from the typical weathered rock in areas of good subsurface drainage. The two types of clay deposits are similar in that (1) both are small and irregularly lenticular in shape; (2) textures and structures of the parent rock have been destroyed, but both types grade downward into saprolite; (3) both consist chiefly of halloysite; and (4) both are uncommonly low in iron oxide and iron-bearing minerals. In the typical saprolite in well-drained areas, lenticular units are rare, except in cross section of preserved lava flows; textures and structures of the parent rock are preserved; and iron-bearing minerals are abundant and commonly make up more of the rock than does halloysite.

In addition to the absence of the overlying organic layer, the two exposed buried deposits differ from the surficial deposits in being more dense. The higher density of the exposed buried clay is due to the compacting effect of the overlying rocks and to the fact that they were partly drained when cut by the present land surface. The subsurface parts of both of these buried clay deposits are more like the surficial ones in being extremely plastic. Clay flowed into one hole (Kn–16) when it was augered, and the cuttings that came from this hole were approximately four times the quantity taken from a hole of equivalent depth in well-drained saprolite. Both exposed buried deposits also are cut by joints along which gibbsite and (or) iron oxide-bearing minerals have accumulated. Much of these accumulations probably formed from material transported downward during the weathering of overlying rocks.

No tests or evaluations of the buried plastic clays were made; they probably have little value because of their limited extent, the presence of overburden, and their occurrence on valuable lands that are now under cultivation or in pasture. Furthermore, one sample of gray clay from the Knudsen Gap locality tested by Arthur D. Little, Inc. (Little, 1957, p. 47), shrank excessively when dried and fired, however, this clay formed well when plastic.

PEAT

SURFICIAL DEPOSITS

Layers of peat overlie plastic clay deposits in the five swamps investigated on Kauai. The peat is thickest in the central parts of swamps and grades into black muck toward the edges. The thickest peat is on State-owned land in Alakai Swamp, where deposits 4–8 feet thick were penetrated in augering (p. 47; pl. 5, holes 5, 9, 10). Peat is 3–4 feet thick in part of Kanaele Swamp (pl. 4, holes 3, 4), on land owned by the McBryde Sugar Co., Ltd.; however, the average thickness in this swamp is little more than 1 foot. The peat in the other three swamps is, with few exceptions, less than 1 foot thick, and much of it is mixed with clay and muck.

All peat has formed under poor drainage conditions. The origin of the deposits is related to the origin of the plastic clays that underlie them (p. 49). The only available evidence on the age of the peat is based on pollen analyses of samples from Alakai Swamp and from swamps on other islands in Hawaii. According to these pollen studies (Selling, 1948, p. 139), peat formation began in Hawaii about the end of the last glacial period. The pollen record reveals (1) a depressed vegetation phase that correlates with the weak glaciation on Mauna Kea on the island of Hawaii, the highest mountain in Oceania; (2) a warm phase that resulted in rapid accumulation of peat; and (3) a cooler phase related to the climatic deterioration known from the northern and southern hemispheres, which presumably resulted in a second period of depression in the rate of peat accumulation.

A few thousand cubic yards of peat are present in the Alakai and Kanaele Swamps. The deposits in Alakai Swamp are of little value because of their remote locations, but small supplies for local use might be dug from the Kanaele Swamp.

BURIED PEAT

Peat deposits now buried by deeply weathered alluvium or saprolite were penetrated in two holes augered on Grove Farm Co., Ltd., land. Both peats overlie clays that are described under the discussion of buried plastic clays. One peat (pl. 3, hole GF–22; p. 53) is 12 feet thick but contains a layer of clay 1 foot thick. This deposit is overlain by overburden 10 feet thick. The second deposit (pl. 3, hole GF–29, p. 53) is 6 feet thick, but it contains thin layers of clay. The overburden where this hole was augered is also 10 feet thick; but the hole was near the bottom of a small valley, and the overburden thickened appreciably within a short distance of the hole. Both deposits of buried peat are probably small, and their value is decreased by the overburden.

SALT

Small quantities of salt were obtained in past years by solar evaporation of sea water in a shallow pond near Salt Pond Park southwest of Hanapepe. Although salt concentrated here was of particular value locally for the preparation of certain Hawaiian and oriental foods, no production has been reported in recent years. The rock salt now commonly used as a substitute for "Hawaiian salt" is imported.

TITANIUM

The soils and weathered rock in Hawaii have long been known to contain uncommonly large proportions of titanium. Large masses of these materials on Kauai could be considered potential titanium reresources, including the following: (1) ferruginous bauxite resources of 110 million tons containing an average of 6.7 percent TiO_2 (table 12); aluminous saprolite resources of 500 million tons (p. 42) containing an average of 5 percent TiO_2; and (3) plastic clay resources of 5 million tons (table 15) that range from 7.5 to 17.5 percent TiO_2 (table 14). Much titanium in the bauxite and aluminous saprolite is in fine-grained magnetite and ilmenite, and some may occur in anatase and other secondary minerals. Titanium in plastic clay is chiefly in clay-sized anatase.

The richest concentrations of titanium are in thin clayey soil in the vicinity of the Kaneha Reservoirs (pl. 2). This soil extends over about 40 acres and was mapped as part of the Haiku soil family (Cline and others, 1955, p. 446–457, Kauai-eastern sheet). The titaniferous soil is gray and dark gray, chunky, and clayey. Its maximum thickness is about 12 inches, and over much of its extent it is little more than half this thick. In most places where the base of the soil can be observed in shallow cuts along field roads, it rests with sharp contact on the underlying saprolite and subsoil. One analyzed sample of this soil (table 14, sample 6) contains 30.6 percent TiO_2, and Cline and others (1955, p. 446) reported 12–20 percent TiO_2 for Haiku soils from other localities. The principal minerals in this soil as identified by X-ray techniques are anatase, goethite, and halloysite-metahalloysite; minor quantities of gibbsite and quartz are also present. The quantity of anatase present is probably not adequate to account for the total titanium, which suggests that some titanium may be contained in amorphous matter, a possibility also suggested by Arthur D. Little, Inc. (Little, 1957, p. 22). This soil has little value as a possible resource of titanium because the deposit is small, and over much of its extent the soil has been mixed during plowing with the underlying saprolite that is much lower in titanium.

The titanium soil in the vicinity of the Kaneha Reservoirs may be a drained swamp clay; this possibility is suggested by both the titanium and quartz contents, which are more like those of swamp clays than of soils in well-drained areas. The sharp basal contact of the soil does not seem to conform with the swamp clay theory, but a similar contact is present where a layer of swamp clay no more than 1 foot thick occurs in the vicinity of holes 1 and 2 on plate 5.

Although the total titanium on Kauai is large, and the thin soil near the Kaneha Reservoirs is one of the richest titanium-bearing naturally occurring materials, little hope exists for profitable mining of titanium on Kauai. The chief reason is the fine-grained disseminated occurrence of the titanium minerals, which would require costly processes for extraction. This conclusion is in agreement with one reached by Arthur D. Little, Inc., who evaluated the possibilities for producing titanium in behalf of the Hawaiian Economic Planning and Coordination Authority. The conclusions of Arthur D. Little, Inc. (Little, 1957, p. 2), are as follows:

> According to preliminary field reconnaissance, the occurrences of titanium minerals are too thin and scattered to warrant commercial development in the near future. The titanium minerals are so finely and evenly distributed throughout the soil that separation by known physical methods appears impractical. Chemical beneficiation of the titanium content would be possible, although preliminary cost estimates indicate that it would be considerably more expensive to process Hawaiian soils than to produce high-grade TiO_2 from commercially available ilmenite, which is readily available from other sources.

RECONNAISSANCE OF FERRUGINOUS BAUXITE DEPOSITS ON MAUI

Maui, the second largest island in Hawaii, has a maximum length of about 48 miles, a maximum width of about 26 miles, and an area of 728 square miles. The island consists of two large mountainous shield-shaped domes joined by a narrow lowland. Because of its physiographic form, the island is divided into East and West Maui, well-established geographic terms.

Low-grade ferruginous bauxite deposits occur in the northern parts of West (fig. 13; pl. 6) and East Maui (fig. 13; pl. 7). Most bauxite occurs near the surface in weathered lava flows, but one type in West Maui crops out only in hill slopes where it forms ledges (fig. 14) that have been described as wind-cut benches (Stearns and Macdonald, 1942, pl. 31*A*, *B*). This type appears to extend under, and to have been buried by, younger rocks. It is referred to (p. 62) as ledge-forming bauxite, and is quite different from deposits on Kauai.

WEST MAUI

VOLCANIC ROCKS ASSOCIATED WITH BAUXITE

Two volcanic series, the Wailuku and Honolua, were mapped and described by Stearns and Macdonald (1942, pl. 1, p. 312–331) in that part of West Maui containing the bauxite deposits. The lavas forming the Wailuku, the older series, are mainly olivine basalts, but they range from basalt poor in olivine to basalt in which this mineral is very abundant. In addition to olivine phenocrysts, many of these basalts contain small feldspar and augite phenocrysts, and only a few are nonporphyritic. Wailuku lavas are low-silica basalts (table 17, samples 1–3), similar in composition to the basalts in the Koloa Volcanic Series on Kauai (table 7). The Honolua Volcanic Series, the younger one, consists of dense massive aphanitic andesites and soda trachytes characterized by platy jointing and abundant clinker beds. Honolua lavas are much richer in SiO_2 and Na_2O and poorer in MgO (table 17) than most other rocks in Hawaii. They are richer in alumina than the parent rocks of the extensive ferruginous bauxites on Kauai (table 7, sample 1). Honolua lavas contain less iron than most other rocks associated with bauxite, and some are uncommonly poor in titania, which accounts for the low contents of titania in weathered rock at some localities (pl. 6).

Major differences in the saprolite formed on the Honolua and Wailuku Volcanic Series results from compositional differences of the parent rocks, as noted by Bates (1960, p. 4). Because of their high alumina and silica and low iron content, Honolua lavas weather to light-gray saprolite that consists chiefly of halloysite-metahalloysite. Wailuku flows that are rich in iron and magnesia weather to dark-brown, gray, red, and purplish-red saprolite that is rich in iron. Soil on the Honolua Series is generally light brown or reddish brown and distinctly lighter than the dark-brown and reddish-brown soil on the older series. With few exceptions, the weathered rock and soil on the Honolua Series contain more gibbsite than those on the Wailuku Series, and the differences in the abundance of gibbsite in the weathered rocks are related directly to differences in the alumina contents in the two series (table 17).

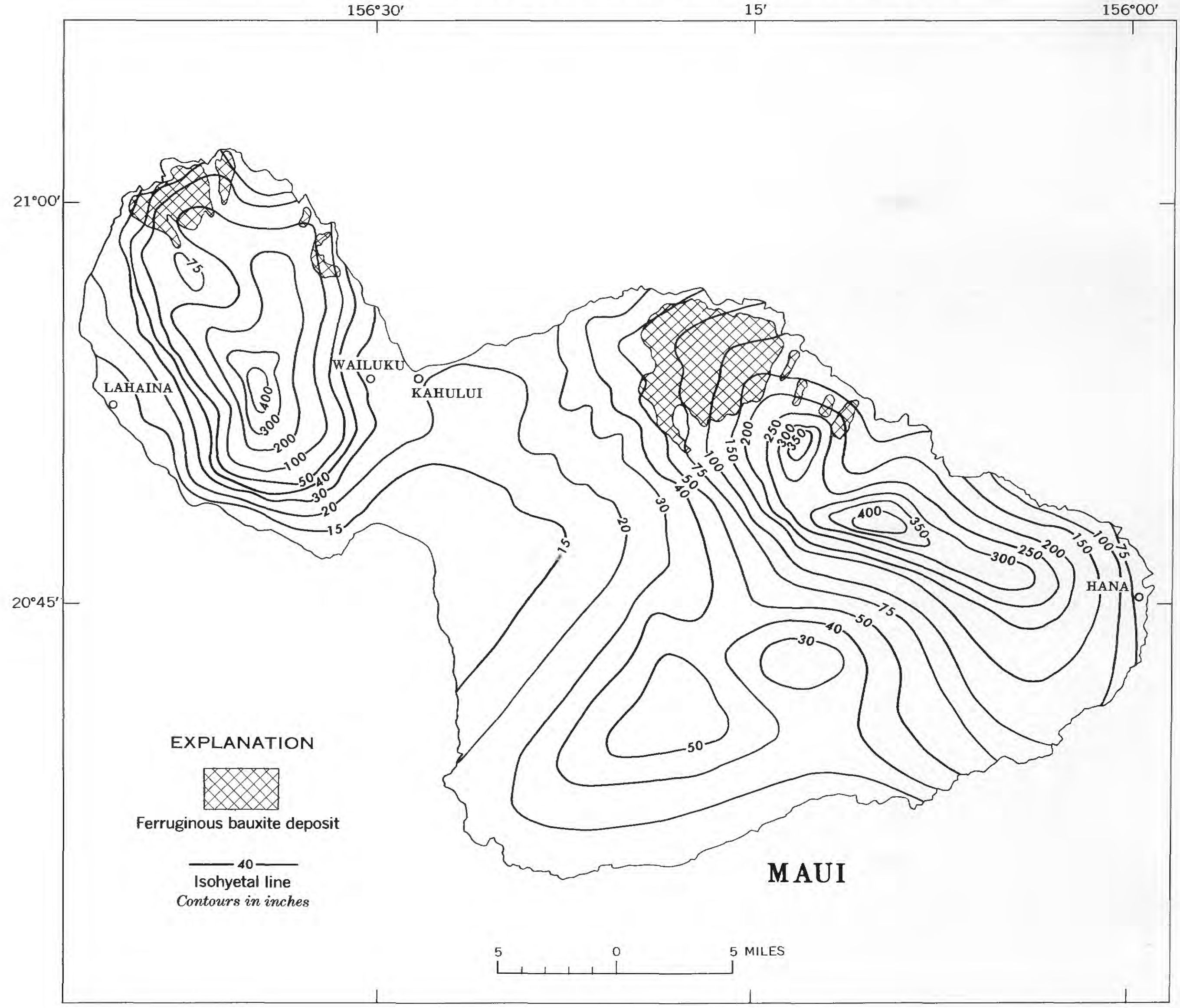

FIGURE 13.—Location of ferruginous bauxite deposits on Maui. Distribution of annual rainfall shown by isohyetal lines. Compiled from U.S. Weather Bureau maps.

Differences in composition and texture between the Wailuku and Honolua Volcanic Series also result in differential resistance to erosion. The abundance of olivine and the rather coarse texture of the Wailuku rocks make them much more susceptible to weathering and less resistant to erosion than the fine-grained massive flows of the Honolua Series. As a result, outcrops of the Wailuku Series are restricted to the valleys, and the Honolua Series forms a protective caprock above them in the uplands of the northern part of West Maui. The resistant Honolua Series also underlies most of the interstream planezes.

The saprolites of the Wailuku and Honolua Volcanic Series contain halloysite-metahalloysite, gibbsite, secondary iron minerals, minor amounts of titanium minerals, unaltered iron minerals, and probably abundant amorphous material. Halloysite-metahalloysite is the most abundant mineral in saprolite of both series (see stratigraphic sections at locs. 1–3, 5; pl. 6, auger holes 1–22). Thin vein deposits of porcelainlike halloysite-metahalloysite occur in the Honolua saprolite; but most of this mineral in both the Honolua and Wailuku Series is disseminated throughout the saprolite, and much presumably is pseudomorphic replacements of feldspars

FIGURE 14.—Ledge supported by gibbsite-cemented saprolite West Maui (pl. 6, loc. 2).

TABLE 17.—*Chemical analyses, in percent, of volcanic rock associated with ferruginous bauxite on Maui*

[From Macdonald (1942, p. 309, 334); N.d., not determined]

	1	2	3	4	5	6	7	8
SiO_2	47.06	47.72	48.53	59.74	61.69	41.89	47.03	48.04
Al_2O_3	10.26	15.44	14.26	18.86	17.33	14.41	15.57	17.95
Fe_2O_3	2.14	.23	2.84	1.94	5.30	7.32	3.22	4.28
FeO	6.60	9.52	9.10	3.75	.07	8.26	8.68	7.21
MgO	17.76	11.31	5.01	.90	.16	6.73	4.29	2.79
CaO	8.62	10.23	11.62	3.00	1.05	11.69	8.67	7.52
Na_2O	2.80	2.31	2.60	7.33	7.47	2.68	4.88	5.55
K_2O	.84	.63	.66	2.89	3.47	.94	1.84	1.91
H_2O+	.63	.46	1.09	.12	1.93	.47	.67	.14
H_2O-	.65	.05	.07	.26	.42	.09	.11	.08
TiO_2	2.26	1.81	3.72	1.02	.67	4.68	4.60	3.27
ZrO_2	N.d.	N.d.	N.d.	N.d.	.16	N.d.	N.d.	N.d.
P_2O_5	.50	.15	Trace	.26	.05	.15	.42	.88
MnO	.16	.16	.11	.13	.21	.16	.18	.39
BaO	N.d.	N.d.	N.d.	N.d.	.07	N.d.	N.d.	N.d.
S	N.d.	N.d.	N.d.	N.d.	.02	N.d.	N.d.	N.d.
Total	100.64	100.02	99.61	100.20	100.07	99.47	100.16	100.01

1. Wailuku Volcanic Series, olivine basalt, transitional to picrite basalt; flow at junction of Amalu and Honokowai streams; S. Iwashita, analyst.
2. Wailuku Volcanic Series, olivine basalt; stream boulder, Iao Valley; M. G. Keyes, analyst.
3. Wailuku Volcanic Series, olivine-free basalt; stream boulder, Iao Valley; M. G. Keyes, analyst.
4. Honolua Volcanic Series, oligoclase andesite; stream boulder, Iao Valley; M. G. Keyes, analyst.
5. Honolua Volcanic Series, soda trachyte; Launiupoko Hill; G. Steiger, analyst.
6. Kula Volcanic Series, basalt; at Haleakala rest house, rim of summit depression; M. G. Keyes, analyst.
7. Kula Volcanic Series, basaltic andesite; 2 miles above Olinda, north slope of Haleakala; M. G. Keyes, analyst.
8. Kula Volcanic Series, andesite; at Haleakala rest house, rim of summit depression; M. G. Keyes, analyst.

and other original minerals of the basalt and trachyte. Gibbsite is concentrated in various nearly pure and very impure forms, and it also occurs in fine grains disseminated throughout the saprolite. The iron minerals have not been thoroughly investigated, but the iron content of much Honolua saprolite is distinctly lower than that in saprolite of the Wailuku Series. Goethite is recognizable in Wailuku saprolite where it occurs as light-yellowish-brown or brass-colored open-textured pseudomorphs after olivine. Some goethite is probably also present in nearly all the fine-grained Honolua saprolite. Unaltered magnetite and ilmenite were present in all the few samples of Honolua saprolite examined by X-ray diffraction, and they probably occur throughout the saprolites in West Maui. Trace amounts of black secondary manganese minerals that may include lithiophorite are present locally at depth and in rocks that are in intermediate stages of weathering. The presence of amorphous materials in the saprolite of the Honolua Series has been noted by Bates (1960, p. 6), and much of the alumina in this saprolite may be in noncrystalline form. Several units in the sections from locations 1–6 (pl. 6), for which no or very little gibbsite or halloysite-metahalloysite was identified by differential thermal analysis methods, may contain appreciable quantities of amorphous materials.

A distinctive red-weathered soil formed on Wailuku basalt and buried by Honolua rocks extends along the northern coast of West Maui. This soil, which ranges in thickness from a few inches to about 4 feet, is a useful marker for separating the rocks of the two series in the field. Samples of this soil from three localities (sections at loc. 1, bed 10, p. 59; loc. 2, bed 4, p. 60; loc. 5, bed 2, p. 61) consist chiefly of halloysite-metahalloysite and contain very little gibbsite.

SECTIONS AND PARTIAL MINERAL-CONTENT ESTIMATES OF WEATHERED PARTS OF THE WAILUKU AND HONOLUA VOLCANIC SERIES

The following descriptions of parts of the Wailuku and Honolua Volcanic Series exposed in outcrops and a roadcut are given to outline the types and principal mineral constituents of the weathered rocks in West Maui. Estimates of partial mineral content are based on differential thermal analyses made with portable apparatus.

Section and partial mineral estimates of parts of the Wailuku and Honolua Volcanic Series at location 1 on plate 6

[1.5 miles southeast of Lipoa Point, West Maui]

Description	Thickness (feet)	Estimated mineral content (in parts of 10)	
		Gibbsite and goethite	Halloysite-metahalloysite
Honolua Volcanic Series:			
1. Soil, dusky-red (10*R* 3/4), crumbly	0.5	-------	-------
2. Clay and soil, dusky-red (7.5*R* 3/4), slightly purplish, titaniferous(?)	.9	-------	-------

Section and partial mineral estimates of parts of the Wailuku and Honolua Volcanic Series at location 1 on plate 6—Continued

Description	Thickness (feet)	Estimated mineral content (in parts of 10)	
		Gibbsite and goethite	Halloysite-metahalloysite
Honolua Volcanic Series—Continued			
3. Clay and soil, red (10*R* 4/8). Contains a few scattered gibbsite nodules	3±	--------	--------
4. Saprolite, light-gray, brecciated, mostly clay; contains some feldspar, magnetite, and ilmenite. Probably weathered clinker	6+	0	0
5. Saprolite, light-gray, mostly clay. Poorly exposed	28	6	Trace
6. Partly weathered rock and saprolite, light-gray (*N*7); stained yellow (2.5*Y* 8/6) and brownish yellow (10*YR* 6/8), mostly brecciated. White halloysite(?) veinlets as much as 2 in. thick are common. Probably weathered clinker. Poorly exposed	4–6	--------	--------
Brecciated saprolite		0	0
White halloysite(?) veins		5	3
7. Saprolite, poorly exposed; has several zones that contain fresh gray trachyte or andesite	30±	--------	--------
8. Clay, light-gray (*N*7), hard	35	--------	--------
9. Saprolite, light-gray (5*Y* 7/1). Contains many relict weathered boulders from joint-block weathering, many of which are white and some are very hard	38	--------	--------
Saprolite		Trace	3
Hard weathered boulders		0	5
Wailuku Volcanic Series:			
10. Clay, red (7.5*R* 4/8). Contains many saprolite chunks that are as much as 10 in. in diameter and are weak red (10*R* 4/4). Buried soil zone	2–3	--------	--------
Red clay		Trace	8
Saprolite chunks		0	7
11. Saprolite, dark-brown. Contains abundant replaced phenocrysts	15±	--------	--------
12. Basalt, porphyritic, hard. Contains abundant weathered olivine crystals	40	--------	--------

Section, partial mineral estimates, and chemical analyses of beds 2 and 3, of the Wailuku and Honolua Volcanic Series at location 2 on plate 6

[0.3 mile west-southwest of light at Nakalele Point, West Maui]
Chemical analyses by Paul Elmore, Samuel Botts, and Gillison Chloe; analyzed by rapid chemical methods described by Shapiro and Brannock (1956).

Description	Thickness (feet)	Estimated mineral content (in parts of 10)	
		Gibbsite and goethite	Halloysite-metahalloysite
Honolua Volcanic Series:			
1. Saprolite, dark-brown (7.5*YR* 3/2), very fine grained. Contains abundant root remains. Possibly weathered ash. The basal zone, 3 ft thick, is much harder than other parts and appears to be bedded	20+	3	5
2. Saprolite(?), mostly light-gray (*N*7); brecciated appearance.			

Section, partial mineral estimates, and chemical analyses of beds 2 and 3, of the Wailuku and Honolua Volcanic Series at location 2 on plate 6—Continued

Section, partial mineral estimates, and chemical analyses of beds 2 and 3, of the Wailuku and Honolua Volcanic Series at location 2 on plate 6—Continued

Description	Thickness (feet)	Estimated mineral content (in parts of 10)	
		Gibbsite and goethite	Halloysite-metahalloysite
Honolua Volcanic Series—Continued			
Probably weathered clinker. Contains abundant white gibbsite as vein deposits, lenses, and irregular masses 2–4 ft thick. Upper part locally stained dark brown from overlying material. Forms prominent ledge	2–4	....	....
3. Saprolite, pinkish-gray (7.5*YR* 7/2), fine textured; after trachyte. White halloysite(?) veins in lower part. Abundant gibbsite along joints in upper part	6–12	....	....
Wailuku Volcanic Series:			
4. Clay, red (2.5*YR* 4/6). Buried soil	0–2	Trace	8
5. Saprolite, mostly strong brown (7.5*YR* 5/8). Contains abundant goethite as replacements of olivine phenocrysts	14	3	5
6. Saprolite, mostly strong brown (7.5*YR* 5/6); vertical and horizontal joints of original rock(?) preserved; coarse textured with abundant goethite as replacements of olivine phenocrysts	2–4	5	3
7. Saprolite, mostly pale-red (7.5*YR* 6/4 to 2.5*YR* 5/2), coarse textured. Contains abundant goethite as replacements of olivine phenocrysts, Manganese stains along joints	21±	Trace	8
8. Incompletely weathered, porphyritic basalt, mostly light-gray (2.5*Y* 7/2). Contains partially and completely weathered olivine phenocrysts as much as one-quarter inch in diameter. Spheroidal weathering common	4–10	Trace	6
9. Saprolite, lower 2/3 poorly exposed, upper part reddish-brown (2.5*YR* 2/4). Contains many vesicles filled with white halloysite(?) and abundant goethite replacements of olivine phenocrysts. Manganese mineral stains and open-textured vug-fill deposits common	60	4	4

Partial chemical analysis of samples from beds 2 and 3

Bed	SiO_2	Al_2O_3	Fe_2O_3	FeO	TiO_2	Loss on ignition (1,000°C)
2	9.6	44.9	9.8	1.8	3.0	28.5
3	26.8	26.1	16.8	3.3	5.2	19.1

Section and partial mineral estimates of parts of Wailuku and Honolua Volcanic Series (?) at location 3 on plate 6

[Near Papanalahoa Point, Maui]

Description	Thickness (feet)	Estimated mineral content (in parts of 10)	
		Gibbsite and goethite	Halloysite-metahalloysite
Honolua Volcanic Series(?)			
1. Saprolite, mostly dark-brown (7.5*YR* 3/2), soft, wind-eroded. Contains abundant root remains. Basal part 2–3 ft thick, strong brown (7.5*YR* 5/8), more resistant than upper part. Contains a few light-bluish-gray nodules as much as 2–3 in. long	25	--------	--------
Upper part	--------	2	6
Basal part	--------	6	1
Wailuku Volcanic Series:			
2. Saprolite, strong brown (7.5*YR* 5/8), hard; forms prominent ledge. A few gibbsite nodules along joints. Breaks into large talus blocks	4–5	7	Trace
3. Saprolite, mostly strong brown (7.5*YR* 5/8). Contains abundant goethite as phenocryst replacements, softer than 2	6–8	5	3
4. Covered, like unit 3(?)	60+	--------	--------

NOTE.—Bed 1 is of uncertain age, but it presumably is the same as bed 1 of the section at location 2, which was assigned to the Honolua Volcanic Series.

Section and partial mineral estimates of parts of Wailuku and Honolua Volcanic Series (?) at location 5 on plate 6

[0.3 mile south of Kahakuloa Head, Maui]

Description	Thickness (feet)	Estimated mineral content (in parts of 10)	
		Gibbsite and goethite	Halloysite-metahalloysite
Honolua Volcanic Series:			
1. Trachyte or andesite, light-gray (10*YR* 7/1), aphanitic; weathers white; mostly hard rock	20+	0	Trace
Wailuku Volcanic Series:			
2. Saprolite and clay, red (2.5*R* 4/8) in lower part, light-red (2.5*YR* 6/8) in upper part. Contains irregular nodules, light-gray (10*YR* 6/2), having small vesicles filled with white clay. Buried soil	0.5–4	0	8
3. Saprolite, dark-gray (5*Y* 4/1); after porphyritic basalt. Contains abundant goethite as replacements after olivine; some manganese mineral films lining vesicles; most weathered parts are grayish brown (10*YR* 3/2)	50+	0	6

Although most saprolite formed on the Honolua Volcanic Series is for the most part uniform and of the character outlined in the preceding sections and discussion, some in the northeastern part of West Maui is very irregular and variable in composition. Some of these weathered rocks are exposed in roadcuts (fig. 15) south of Kahakuloa Head. These saprolites are not sufficiently well exposed, however, to determine the reasons for their irregularities, but they probably result chiefly from differences in composition and texture of the parent rock. Their complex relation may be due to irregular flow contacts, a certain amount of remelting, interlayering of pyroclastic materials, and minor structural disturbances.

ECONOMIC GEOLOGY

The bauxite deposits on West Maui are in a belt, extending inland about 2 miles, along the north coast from Lipoa Point eastward nearly to Waihee Point (pl. 6). The deposits are at altitudes ranging from 200 to about 1,000 feet. The topography in both the eastern and western parts of the bauxite area is

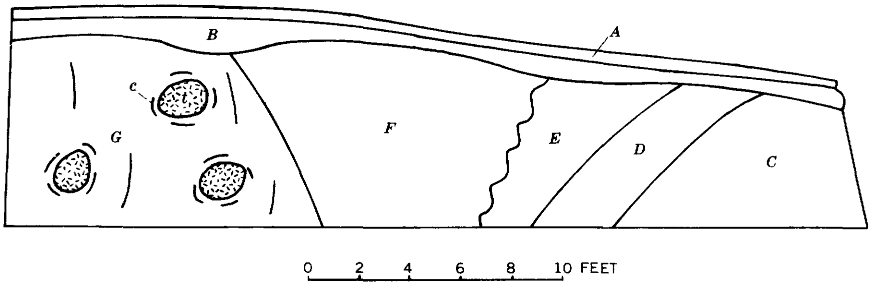

FIGURE 15.—Weathered rocks of the Honolua Volcanic Series exposed in a roadcut, West Maui (pl. 6, loc. 6). Partial mineral content estimates are based on differential thermal analyses made with portable apparatus.

A, Soil (A horizon), dark-brownish-gray (7.5*YR* 3/2).

B, Soil (B horizon), strong brown (7.5*YR* 5/6); contains scattered white gibbsite nodules. Rock is approximately 1/2 gibbsite and 3/10 halloysite-metahalloysite.

C, Saprolite, mostly strong brown (10*YR* 8/4); contains irregular hard joint deposits. Rock is approximately 3/5 gibbsite and 1/5 halloysite-metahalloysite.

D, Clay, light-gray (10*YR* 6/1), hard, jointed. Rock is approximately 3/5 gibbsite.

E, Saprolite, strong brown (10*YR* 8/4); contains abundant irregular hard joint deposits. Rock is approximately 3/5 gibbsite and 1/5 halloysite-metahalloysite.

F, Saprolite, mostly light-yellowish-brown (10*YR* 6/4) with lighter and darker banding; abundant gibbsite nodules alined along banding. Rock is approximately 7/10 gibbsite and 1/5 halloysite-metahalloysite.

G, Saprolite; contains incompletely weathered trachyte boulders (t) enclosed by concentric crusts of gibbsitic saprolite (c) of intermediate hardness; contains scattered small gibbsitic nodules along joints, and white powdery halloysite-metahalloysite(?) is present in small veins. The fresher trachyte is gray (10*YR* 5/1), and most of the rock is light gray (10*YR* 6/1).

characterized by planezes separated by deep stream valleys. The central part of the area, which is underlain by the Wailuku Volcanic Series, is very thoroughly eroded, and only small remnants of interstream uplands remain. The yearly rainfall in the area ranges from 40 to more than 100 inches (fig. 13). The uplands in the western third of the area are cultivated for pineapple. The remaining parts of the area are chiefly pasturelands and wastelands.

The low-grade ferruginous bauxite is in (1) upland deposits that consist of thin surficial layers of saprolite and soil underlying planezes and (2) ledge-forming zones that crop out in steep hillsides.

UPLAND DEPOSITS

All upland deposits in West Maui are in areas mapped by Stearns and Macdonald (1942, pl. 1) as the Honolua Volcanic Series; however, younger pyroclastic materials may have been present in the parent rock of some of the bauxite. The possibility that younger rocks were present is suggested by the dark colors and texture of some saprolite, which is quite different from the typical saprolite of the Honolua Series. This darker saprolite is shades of red and brown, and the gibbsite in it occurs in ferruginous nodules, veinlets, crusts, and disseminated grains; whereas the typical Honolua saprolite is light gray, and most gibbsite in it occurs as pseudomorphic replacements of feldspar and as small nodules along joints.

The best quality deposits occur in the eastern part of the West Maui bauxite belt (pl. 6), where ferruginous bauxite 10 feet or more thick extends over about 100 acres. One of the better areas is in the vicinity of hole 21 (pl. 6), which penetrated 24 feet of bauxite that has an alumina content of 36 percent. Bauxite greater than 10 feet thick was also penetrated by holes 19 and 20, as inferred from the very low content of the silica-bearing halloysite-metahalloysite in samples from these holes (Patterson, 1962, app., p. 239).

Most deposits in the western part of the West Maui belt are small, thin, and scattered. Some of the better deposits in this area were penetrated by auger holes 4, 7, 10, 11, 13 and (pl. 6) and sampled in the outcrop measured at location 1 (pl. 6; p. 59). Probably none of these deposits contains significant tonnages of low-silica bauxite.

LEDGE-FORMING BAUXITE DEPOSITS

Ledge-forming bauxitic zones are present in both the Wailuku and Honolua volcanic rocks and are overlain by a distinctive unit of massive brown saprolite that appears to be of Honolua or younger age. The ledge deposits crop out in steep hillsides inland between Kanounou Point and Kahakuloa in an area mapped by Stearns and Macdonald (1942, pl. 1) as Wailuku rocks. However, in outcrops on the flanks of the broad upland southwest of Nakalele Point (section at loc. 2, beds 2, 3), the bauxite ledge is at the top of a thin unit of rocks having the lithologic and weathering characteristics of the Honolua Series. Moreover, the thin red ancient soil between the rocks of the two series is present at this locality. At location 2, the ledge containing bauxite is overlain by a thick distinctive layer of soft brown saprolite which contains abundant root remains and has a prominent basal zone about 3 feet thick, which is harder than the rest of the saprolite and appears to be bedded (fig. 14). This brown saprolite unit has the same distinctive characteristics where it rests on a gibbsite-rich zone in Wailuku rocks at location 3 and in areas to the south and east of locations 3 and 4 (pl. 6). The brown saprolite is interpreted as resting unconformably on Wailuku rocks, and it is probably post-Honolua in age. A genetic relation between the brown saprolite and the ledge containing bauxite is strongly suggested by the position of the ledge below the saprolite in both series, and because the ledge in the Wailuku is virtually the only bauxite deposit in that series. Probably the brown saprolite has weathered from volcanic ash or other pyroclastic material, and it may be much more extensive than shown on the map of West Maui (pl. 6). The extent of this saprolite probably is approximately the same as that of a soil unit mapped as the Nakalele silty clay, gently sloping phase (Cline and others, 1955, p. 301, Maui sheet 1).

The bauxite ledge cropping out in Honolua rocks at location 2 (pl. 6) consists of irregular masses of gibbsite-rich saprolite ranging in thickness from 2 to 4 feet. This material is light gray and light brown, but the upper part is stained dark brown from the overlying saprolite. Much of this unit has a brecciated appearance, and it probably formed by the weathering and replacement of clinker. White gibbsite nodules are common along joints, and fine-grained gibbsite is also abundant throughout the saprolite. The ledge at location 3 (pl. 6; section at loc. 3) is 4–5 feet thick. This saprolite is dark brown and contains common pseudomorphic replacements of goethite after olivine phenocrysts; it is clearly derived from Wailuku rocks.

The ledge-forming bauxite is fairly good grade and is among the best in Hawaii. A channel sample of the ledge at location 2 (bed 2) contained 44.9 percent Al_2O_3 and 9.6 percent SiO_2, and differential thermal analysis of samples from the ledge at location 3 (bed 2) indicated the presence of much gibbsite. The basal part of the overlying brown saprolite also contains appreciable gibbsite. Locally, the ledge forms a narrow belt from which the overburden has been naturally stripped. The overburden thickens uphill from the inland edge of the ledge, however, and could be removed by stripping methods only in narrow zones along the outcrop. The bauxite ledges have never been tested at depth, and their existence under thick overburden is purely speculative. Auger hole 11, in an area that should have been underlain by the zone at about 40 feet, was put down to a depth of 55 feet, and the ledge was not penetrated.

EAST MAUI

GENERAL GEOLOGY

Low-grade ferruginous bauxite deposits in East Maui occur in weathered parts of a group of flows that originated from scattered vents on the north slope of Haleakala Volcano mapped by Stearns and Macdonald (1942, pl. 1) as the Kula Volcanic Series. The name "Kula," Hawaiian for a broad flat upland slope, is particularly appropriate because the topography on this series is characterized by broad slopes separated by deeply incised valleys. The unweathered rocks of the Kula Series consist chiefly of aphanitic dense gray to steel-blue andesitic-type aa flows with thick clinker beds and interstratified soils (Stearns and Macdonald, 1942, p. 75). The fresh rock in the Kula Volcanic Series contains 14–18 percent Al_2O_3 (table 17), which is similar to that in the volcanic rock in West Maui and distinctly higher than in the parent basalt of the extensive bauxite deposits on Kauai.

The ferruginous bauxite occurs in an area where most of the soils are assigned to the Haiku family (Cline and others, 1955, p. 446–457, Maui sheets 2, 3). The soils of this family are Humic Ferruginous Latosols that have been thoroughly leached.

ECONOMIC GEOLOGY

The general area of thoroughly weathered rocks favorable for bauxite formation is at altitudes of 400–2,000 feet, between Haiku and Honomanu Bay in the northern part of East Maui (pl. 7). The saprolite mantle is thick in many areas west of Haiku, but the gibbsite content of these rocks is so low that this area is not shown on plate 7. East of Honomanu Bay, most of the rocks at the surface are only partially decomposed, and the area is generally unfavorable for bauxite. Some small areas of thoroughly weathered rock are present above 2,000 feet altitude, but in most places the saprolite becomes progressively thinner above this altitude; above 3,000 feet altitude, hard rock is covered only by a very thin soil. About a third of the bauxite land is forest reserve, a third is under cultivation, and a third is pastureland. The average rainfall in the area ranges from 50 to 250 inches a year (fig. 13).

The low-grade bauxite deposits are in saprolite underlying planezes. Depth and intensities of weathering vary considerably, and distribution of the saprolite is irregular, apparently because of appreciable differences in ages of the flows in the Kula Series. At many places essentially fresh rock occurs under a very shallow soil, and in nearby areas the depth to hard rock may exceed 60 feet. In other areas, the flows are in intermediate stages of weathering, and as much as 50 percent of the weathered rock consists of hard spheroidal boulders. As on Kauai, the most favorable bauxite deposits are in soil and thoroughly weathered saprolite near the surface. The deposits are less than 15 feet thick at most places. Some zones associated with buried soils are richer in gibbsite than are the overlying rocks; however, no low-silica deposits were found at depth.

Part of the bauxite mineral, gibbsite, occurs in relatively pure nodules; most is impure, however, and is finely disseminated and intermixed with silica-, iron-, and titania-bearing minerals throughout the saprolite. The detailed mineralogy of the deposits in East Maui has not been investigated; but the minerals and their distribution are similar to those described for Kauai. Differential thermal analysis and hand-specimen observations show that halloysite-metahalloysite and fine-grained iron minerals are closely associated with the gibbsite. Halloysite-metahalloysite was identified in two samples by X-ray examination (Cathcart, 1958, table 7). Spheroidal bauxite nodules formed by precipitation in vesicles were noted near Haiku by Cathcart (1958, p. 45). These vesicle fillings were investigated by Uehara, Ikawa, and Sherman (1966), who found that they range in composition from virtually pure halloysite-metahalloysite to gibbsite containing trace amounts of metahalloysite, but no pure gibbsite spheroids were found. Both the relatively pure and part of the impure gibbsite occur as nodules, veinlets, agglutinated aggregates, crusts, and vesicle-fill deposits that are harder than most of the weathered rock. The purer forms of gibbsite are light gray, white, and yellow, and the iron-rich forms are mostly shades of brown and red. Gellike materials were found near the surface at some localities, and amorphous iron, alumina, and probably silica most likely are present in much of the bauxite.

SECTIONS AND PARTIAL MINERAL-CONTENT ESTIMATES OF WEATHERED PARTS OF THE KULA VOLCANIC SERIES

The following descriptions of parts of the Kula Volcanic Series are given to outline the types and principal mineral constituents of weathered rocks in East Maui. Partial mineral content estimates are based on differential thermal analyses made with portable apparatus.

Section at location 1 on plate 7

[1 mile south of Pilale Bay, East Maui]

Description	Thickness (feet)	Estimated mineral content (in parts of 10)	
		Gibbsite and goethite	Halloysite-metahalloysite
Kula Volcanic Series:			
1. Soil and gravel	5+	--------	--------
2. Saprolite, brown (7.5*YR* 4/4). Contains abundant veinlets of gibbsite as much as one-sixteenth inch thick	9	8	0
3. Clay, red (7.5*R* 3/8). Contains a few gibbsite nodules; dips northward. Buried soil	.5–1	2	6
4. Saprolite, dark-brown (7.5*YR* 3/2) and dark-gray (*N* 4). Contains abundant nodules of gibbsite as much as half an inch long and scattered spongelike masses of gibbsitic(?) material as much as 1 ft in diameter. Unit thickens to the south	5	7	1

Section at location 8 on plate 7

[1.7 miles northwest of Makawao, East Maui]

Description	Thickness (feet)	Estimated mineral content (in parts of 10)	
		Gibbsite and goethite	Halloysite-metahalloysite
Kula Volcanic Series:			
1. Soil, dark-brown (7.5*YR* 3/2)	1	--------	--- ---
2. Soil (B horizon), light-gray (2.5*Y* 7/2), hard chunky. Contains a few small gibbsitic nodules	3.5	8	0

Description	Thickness (feet)	Estimated mineral content (parts of 10)	
		Gibbsite and	Halloysite-metahalloysite
Kula Volcanic Series—Continued			
3. Clay or saprolite, mostly light-brownish-gray (2.5Y 6/2), hard, chunky; yellow (2.5Y 8/6) stains along joints. Contains abundant small pockets of white dry halloysite	12	2	5

Section at location 9 on plate 7

[3.5 miles south of Kealii Point, East Maui]

Description	Thickness (feet)	Estimated mineral content (parts of 10)	
		Gibbsite and goethite	Halloysite-metahalloysite
Kula Volcanic Series:			
1. Soil, crumbly, dark-brown (7.5*YR* 3/2)	1	7	0
2. Saprolite, dark-reddish-brown (5*YR* 3/4). Contains abundant angular fragments of gibbsite as much as 1.5 in. long. Grades into underlying unit	4	7	1
3. Saprolite, mostly dark-brown (7.5*YR* 3/2) with dark-grayish-brown lumps. Contains abundant gibbsite fragments	10	5	3
4. Saprolite, dark-brown (7.5*YR* 4/4). Contains abundant light-colored grains of halloysite(?)	13	5	3
5. Covered	16	-----	-----
6. Clay, red (10*R* 4/6). Contains rounded masses of vesicular saprolite as much as 6 in. in diameter. Buried soil	19	5	3
7. Saprolite		-----	-----

ALUMINUM RESOURCES

FERRUGINOUS BAUXITE

WEST MAUI

Cathcart's estimate (1958, p. 55) of 9 million tons of potentially recoverable low-grade bauxite in West Maui is assumed to be correct. The deposits are so irregularly distributed that the more detailed reconnaissance during this investigation failed to provide adequate information for improving Cathcart's estimate. Clearly, the amount of gibbsite in surficial and ledge-forming bauxite deposits and in harder coarse particles throughout the high-silica saprolite and soil is at least 9 million tons. However, much of the gibbsite is so irregularly distributed, and the extent of the variable ledge-forming deposits under thick overburden is so uncertain, that accurate calculations of the size of bauxite deposits in West Maui would be very difficult and costly. Bulk densities of the bauxitic materials are extremely variable. The dry weights of five samples of surficial deposits in West Maui range from 65 to 123 pounds per cubic foot, and the average is about 80 pounds. The ledge-forming deposits are considerably more dense than the surficial deposits, and two samples of the ledge bauxite have an average dry weight of 120 pounds per cubic foot. The grade of the bauxite is also inadequately known; however, the average partial chemical analysis of samples from outcrops at location 2 and auger hole 21 (pl. 6) is 7 percent SiO_2, 38 percent Al_2O_3, 22 percent Fe_2O_3, and 4 percent TiO_2. The prospects for the development of an efficient process of upgrading the bauxite are poor, because hardness, magnetic properties, and bulk densities of the gibbsite-rich and gibbsite-poor materials are similar.

EAST MAUI

Information available on the ferruginous bauxite resources in East Maui consists of the analyses and mineral-content estimates of samples from 21 auger holes (pl. 7) and three outcrops measured (p. 64, 65) in this investigation; metallurgical studies of outcrop samples by Calhoun (1958, p. 22–23) and Calhoun and Hill (1962, p. 14–20); and analyses of hand specimens from outcrops (Cathcart, 1958, p. 44–53). Samples from 15 of the 21 holes augered in this investigation were chemically analyzed (pl. 7), and those from six holes were investigated by differential thermal analysis methods only. Ferruginous bauxite about 10 feet thick or more, and containing an average of less than 10 percent SiO_2, was penetrated in holes 30–33, 36–38, and 40–42; the material penetrated in the other five holes from which samples were analyzed averaged more than 10 percent SiO_2. Low-silica material is 22 feet thick at hole 38 and

19 feet thick at hole 37, but in most of the other holes it is 9–12 feet thick. Holes 27 and 29 penetrated low-silica bauxite about 10 feet thick, as indicated by the low halloysite-metahalloysite content in samples investigated by differential thermal analysis (Patterson, 1962, app., p. 213, 214); samples from the other four holes that were investigated by this method penetrated only material that is high in silica or less than 10 feet thick. The work by Calhoun and Hill involved investigations of methods of beneficiating the bauxite and extracting alumina from it. All their samples, containing less than 10 percent Al_2O_3, represented bauxite less than 10 feet thick (Calhoun, 1958, table 15; Calhoun and Hill, 1962, table 12). However, they indicate low-silica bauxite occurs where their samples 17, 19, 21, 22, and 25 were collected (see pl. 7, present report). Cathcart's work primarily outlined the general areas where bauxite occurs, and his analyses are chiefly of selected hand specimens.

On the basis of the sketchy available information, low-silica bauxite is present at scattered localities in the central and eastern parts of the East Maui district. The total area in the interstream uplands in the eastern two-thirds of the East Maui district is about 5,000 acres; about 25 percent of this area (1,250 acres) is believed to contain low-silica bauxite having an average thickness of 10 feet. The assumption that only 25 percent of the upland areas are underlain by bauxite, though two-thirds of the auger holes penetrated bauxite, is based on the fact that most holes were intentionally augered in the more favorable areas, and fresh or partially weathered rocks occur at or near the surface in much of the uplands. The amount of low-silica bauxite in East Maui is calculated on this basis to be 22 million tons. The approximate average partial composition of this bauxite, based on analyses of samples from holes which penetrated low-silica material 10 feet or more thick, is 7.8 percent SiO_2, 31.8 percent Al_2O_3, 32 percent Fe_2O_3, and 6.9 percent TiO_2.

The density factor used in calculating the tonnages in East Maui was 80 pounds dry weight per cubic foot. The figure is the approximate average of measurements of 24 samples of gibbsitic weathered rock at scattered locations. The dry densities of these 24 samples ranged from 62 to 111 pounds per cubic foot. Moisture contents of these samples ranged from 15 to 31 percent. However, these samples came from near the surface and were collected during the dry season. Both rock at depth and surficial materials are likely to contain appreciably more water during rainy periods than was present in the samples tested.

ALUMINOUS SAPROLITE

WEST MAUI

Resources of ferruginous gibbsitic saprolite in West Maui are at least 200 million tons. These resources are chiefly in surficial deposits formed by weathering of rocks of the Honolua Volcanic Series and occur under sloping interstream uplands. Deposits rich in alumina are located in the vicinity of holes 1–13 on Baldwin Packers Co., Ltd., land in the western part of the West Maui district (pl. 6). About 2,000 acres of interstream uplands under which rocks are weathered to an average depth of 40 feet are present in this area and in adjoining lands to the southwest (pl. 6). The tonnage of this resource is more than 150 million dry tons, and the average partial composition based on the chemical data (pl. 6) is about 20 percent SiO_2, 33 percent Al_2O_3, 22 percent Fe_2O_3, and 4 percent TiO_2. At least 50 million tons of aluminous saprolite is present in the vicinity of auger holes 14–18 east of Kahakuloa. This saprolite is similar in grade to that in the vicinity of holes 1–13, except that it is slightly lower in silica and higher in alumina. The distribution of gibbsite in this area is very irregular, and residual boulders of trachyte are very common in the saprolite (fig. 3). A dry weight factor of 80 pounds per cubic foot was used in calculating the tonnages.

EAST MAUI

Very large amounts of ferruginous gibbsite saprolite in East Maui are potential resources of alumina. The resource appraisal attempted here is based only on the partial chemical analyses and mineral content estimates of samples from the auger holes and outcrops (pl. 7; sections at locs. 8, 9; Patterson, 1962, app., p. 241–250) and on analytical data and descriptions of outcrops by Cathcart (1958, p. 44–53). Although many irregular areas in the interstream uplands in East Maui are underlain by nearly fresh rock, the average thickness of the saprolite over an area of 8,000 acres, exclusive of the areas estimated to contain bauxite, is at least 15 feet. Saprolite also occurs below the bauxite deposits. More than 200 million tons of ferruginous gibbsite saprolite is present in East Maui. The approximate partial composition of this saprolite is 15 percent SiO_2, 31 percent Al_2O_3, 27 percent Fe_2O_3, and 6 percent TiO_2.

As much as 20 percent of the saprolite in East Maui is coarse hard gibbsite and ferruginous gibbsitic nodules; part of this material could be concentrated by screening. The partial composition of the concentrate might be approximately the average of five samples of coarse fragments from these deposits listed by Cathcart (1958, table 7)—which is 42 percent Al_2O_3, 9.8 percent SiO_2, 14.0 percent Fe_2O_3, 3.5 percent TiO_2, and 24.6 percent loss on ignition at 1,050°C. Much of the coarse gibbsitic material is closely associated with abundant hard spheroidally weathered basalt boulders, which would make concentrating difficult and would increase the waste disposal problems, if the saprolite were mined. Also, hard rock would be near the surface in many areas after mining, and soil reclamation in such areas would be costly.

ECONOMIC CONSIDERATIONS REGARDING FERRUGINOUS BAUXITE ON KAUAI AND MAUI

Whether the low-grade ferruginous bauxite resources on Kauai and Maui can be used commercially depends on several economic considerations. Inasmuch as the resources are low grade, their possible use involves all the economic factors related to the mining of a low-grade mineral resource in competition with higher grade ore currently used by industry. In addition, most of the deposits are on highly valuable agricultural lands, and soil reclamation soon after mining would be necessary to control erosion. Even if never mined on a competitive basis, both the ferruginous bauxite and aluminous saprolite are valuable potential sources of aluminum, because the United States is deficient in bauxite. United States bauxite reserves of the grade currently used by industry are mainly in Arkansas; they are sufficient to last less than 4 years, if they were the only source of this raw material. The deposits in Hawaii are a large resource that might be mined if the more competitive foreign sources of bauxite were cut off.

Alumina can be extracted from the ferruginous bauxite by the Bayer process, but the recovery is not complete. Calhoun and Hill (1962, p. 1) found that 73.1–78.8 percent of the alumina in bauxite from Kauai and Maui was recovered using a Bayer-type digest, and the recovery was increased to 82.8–85.5 percent by modifying the process to include calcining and caustic desilication steps. In additional metallurgical testing, Calhoun and Hill (1967, p. 1, 36) were able to recover 95.4 percent of the alumina in ferruginous bauxite on Kauai by using a caustic-lime-bake-sinter-water-leach process, and 94.1 percent of the alumina in deposits on Maui by a caustic-lime-reduction-sinter-water-leach process. The recovery could also be improved by beneficating the bauxite before processing. The Al_2O_3 content of deposits on Kauai can be upgraded about 10 percent by washing out the fine-grained material (p. 41). Deposits on Maui probably could be upgraded even more because they are much higher in alumina. However, benefication by washing would permit the recovery of only a third or less of the total Al_2O_3 present, owing to the large percentage that occurs in fine sizes.

Although the potential resources of aluminous saprolite are very large, their value is decreased because Al_2O_3 would be more difficult to recover from the saprolite than from the lower SiO_2 ferruginous bauxite. Metallurgical tests by Calhoun and Hill (1967, p. 15–22, 37), using the caustic digestion, lime-soda-sinter, caustic-lime-bake-sinter-water-leach, and sulfation treatment methods for extracting alumina, failed to recover as much as 90 percent of the Al_2O_3 in samples of this saprolite.

POSSIBILITIES FOR THE RECOVERY OF IRON AND TITANIUM

The recovery of iron and titanium from Hawaii bauxite would seem to be attractive possibilities because deposits on Kauai contain nearly 40 percent Fe_2O_3 and those on Maui about 30 percent Fe_2O_3; the average TiO_2 content of most deposits is about 6 percent. However, most of the iron and all the titanium occur in fine-grained minerals and possibly amorphous materials that are disseminated throughout the soil and saprolite; also, the minerals containing these metals are so closely associated with aluminum- and silicon-bearing minerals that there is little possibility for concentrating them cheaply by mechanical or magnetic methods (Calhoun and Hill, 1962, p. 14, 19). If iron and titanium are ever recovered from the bauxite, they will most likely be coproducts of Al_2O_3. Recovery may require an intermediate step of virtually complete chemical digestion of the entire processed material. Further evidence that metallurgical problems would be encountered in recovery of iron from the bauxite lies in the results of additional metallurgical testing by Calhoun and Hill (1967, p. 1, 28, 29); they found that one magnetic concentrate from bauxite treated by a caustic-lime-reduction-sinter-leach process was 71.1 percent Fe, but this material still contained 4.0 percent TiO_2 and 3.2 percent SiO_2.

REQUIREMENTS FOR SOIL RECLAMATION

If the bauxite were mined, soil reclamation after mining would be essential, because (1) much of the bauxite occurs on valuable agricultural land that would have to be put back into production; (2) mined areas would be subject to severe erosion without a protective cover of plant growth; and (3) reestablishment of an attractive terrain would be required because of the importance of Hawaiian scenery to the tourist industry (Sherman and others, 1961, p. 2).

Soil reclamation in the event bauxite is mined has been investigated by the Hawaii Agricultural Experiment Station, University of Hawaii, under the supervision of Dr. G. D. Sherman. The investigations were carried out in the Wailua Game Reserve, Kauai, where a plot comparable to a mined-out area was prepared by bulldozing away the soil and shallow subsoil. The results of this work demonstrate that erosion of unprotected subsoil is as much as 9.2 tons per acre per year, but it can be controlled by a protective cover (Woudt, 1961). A soil even more productive than the original one can be reestablished by proper techniques (Younge, 1964; Takahashi and others, 1961; Plucknett, 1961). Soil can be reestablished because the saprolite below the bauxite on Kauai is rich in clay minerals that are more efficient in retaining fertilizer and moisture than the nodular aluminous and ferruginous minerals that form the principal components of the bauxite. Somewhat different problems might be encountered if soil reclamation were attempted in East Maui. In parts of this area the saprolite zone between the bauxite and the fresh rock might be too thin or contain too many residual boulders to serve as a suitable soil.

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