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CERAMIC CLAY IN HAWAII

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Contents

[1] Chemical analyses and discussion published with approval of the Director, U. S. Geological Survey.

INTRODUCTION

Purpose and Scope of Study

Exceptional interest, from the standpoint of the geologist, the student of soils, and the practical craft potter, attaches to the recent discovery of excellent ceramic clay in Hawaii. This clay was first found in 1935, in small deposits in restricted areas near the crest of the Koolau Range of eastern Oahu. A considerable amount of high-grade pottery has been made of clay from this area by members of the Hawaiian Potters' Guild during the past three years. It has been supposed that clay would be found in topographically similar situations on other islands and some samples had been sent to Honolulu. In the summer of 1938, Wentworth collected samples and made brief examinations of clay localities on East Molokai, West Maui and Kauai. In this paper the occurrence and geologic relations of the clay are described by Wentworth, the chemical analysis and discussion are by Wells and the petrography and mineralogy by Allen. In addition, in order to define more accurately the ceramic character of the Hawaiian clay, a few practical tests of physical properties have been made. These have been applied to the three clays used by the Hawaiian Potters' Guild, in order to refer to two clays known in the United States. They also furnish in the practical work of guild members, some rational explanation of the behavior of the clays, which is already familiar from practical experience.

Significance and History of Ceramic Materials in Hawaii

It is a well-established fact that there was no ceramic art among native Polynesian peoples in the central Pacific area, to which Hawaii belongs. This is an area of true oceanic islands, which are chiefly basaltic, or coral islands, and a region where continental types of rocks, such as coal, clay, plutonic rocks, ores of metals, and the like, are generally absent. It stands in contrast to the islands of probable continental affinities, which lie south and west from Fiji, (Fig. 1), in some of which pottery making was known to primitive races. This fact, and the underlying geologic and climatic basis, gives special interest to the clay here described.

Soft, gumbo-like soil material is by no means rare in Hawaii, but nearly all such material is either highly ferruginous or contains other constituents detrimental to ceramic use. Light-colored muds are found on parts of the coastal plain, but these have not shown ceramic quality and probably carry excessive amounts of calcium carbonate. Dark gray, nearly black alluvium, colloquially known as "taro-patch clay" is common on the flats of larger valley bottoms, but, so far as known, none of this material can be used successfully for making pottery. In places volcanic ash of basaltic composition, or such material altered to palagonite, has been further decomposed into a soft, unctuous mass, red or brown in color, having some physical features that resemble bentonite. Some of these materials have been used with other clays in developing

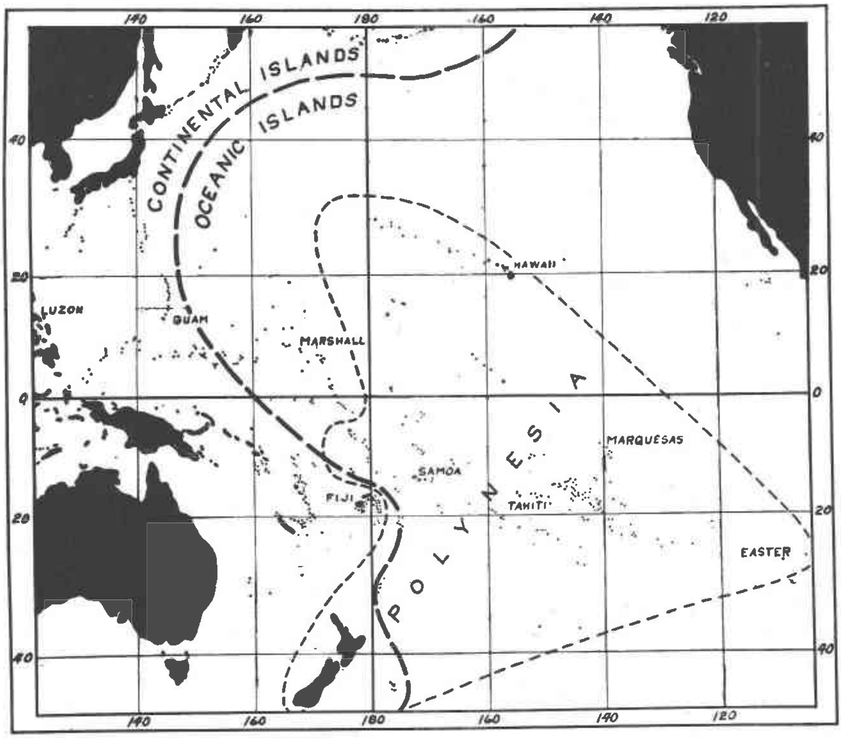


FIG. 1. Map of Pacific Ocean showing distribution of islands and boundary between islands having continental types of rocks, and those lacking such rocks and composed only of basic volcanic rocks, or of coral and related sediments.

distinctive colors in pottery, but these used alone are not suitable for ceramic use.

From the beginning of settlement of westerners in Hawaii there has been sporadic search for clay material either suitable for ceramic use, or usable as an aluminous constituent in the making of Portland cement. Ocean freight rates constitute a differential which would strongly favor the establishment of brick, tile or cement plants in Hawaii if raw materials reasonably suitable for these products could be found. Experiments have been made by several persons looking to local production, both of brick and cement, but with no substantial success to date. During the period 1917–1922, when the World War led to unfavorable ocean freight conditions, a hydraulic cement was made on the island of Maui. Soda trachyte from Launiopoko Hill near Lahaina was used as the source of silica and alumina, and the resulting cement was in most respects within the Portland cement standards. Certain differences necessitated more than usual care by workmen in practical use and the project was abandoned when freight conditions became normal.[2,3] Attempts have also been made to produce brick from red clays on Maui, but these, like similar projects tried on Oahu, according to report, were not successful.[3]

Frequently consulted as to suitability of clay-like materials, most students of Hawaiian geology, including the senior author of this paper, have been skeptical as to the likelihood of finding ceramic clays or rock of highly aluminous composition in this region. As is well known, the volcanic rocks of the group are largely of basaltic composition, dominantly plagioclase basalts, but subordinately nepheline, or nepheline-melilite basalts. A few trachyte or andesite flows are known. Weathering of such rocks, in an oceanic, tropical climate, generally produces detrital materials and soils high in iron and magnesium, and low in silica and alumina. As a consequence the soil materials are clay-like only in a partial sense. They may be sticky, somewhat plastic, and moderately suitable for use as impervious core-wall material in dams, but they are in general too ferruginous and too low in silica and alumina to dry or fire successfully in ceramic tests.

Clay is rare on all islands of the central Pacific (Polynesia) area, where igneous rocks are dominantly basic in composition. The absence of ceramic art among the Polynesian people in this area has been mentioned. It is suggested by some that use of pots in cooking is rendered unnecessary by the general practice of steam cooking of leaf-wrapped food in a ground oven (Hawaiian *imu*), but the possibility of a reciprocal development of such cooking as a result of the lack of pottery is worth consideration.

Discovery of Local Deposits of Clay

Under the auspices of the Honolulu Academy of Arts for several years past, and to a limited extent in certain schools, craft pottery has been taught. About 1931, Mrs. James A. Wilder started classes in craft pottery at the Honolulu Academy of Arts. More recently this work has been expanded under the supervision of Mrs. Nancy Andrew and has led to the formation of the Hawaiian Potters' Guild. Enthusiasts in the craft,

[2] Foster, J. P., Personal communication.

[3] Watkins, W. K., Letter dated August 23, 1937.

despite geological skepticism, have continued the search for ceramic clay on Oahu. In 1934, near the crest of the Koolau Range, a light-gray (in places almost white) clay was found, which gave very promising results on testing. The find was made by Lieut. Thomas Wells and Mr. Joseph Musser. Since that time additional sites have been found and in

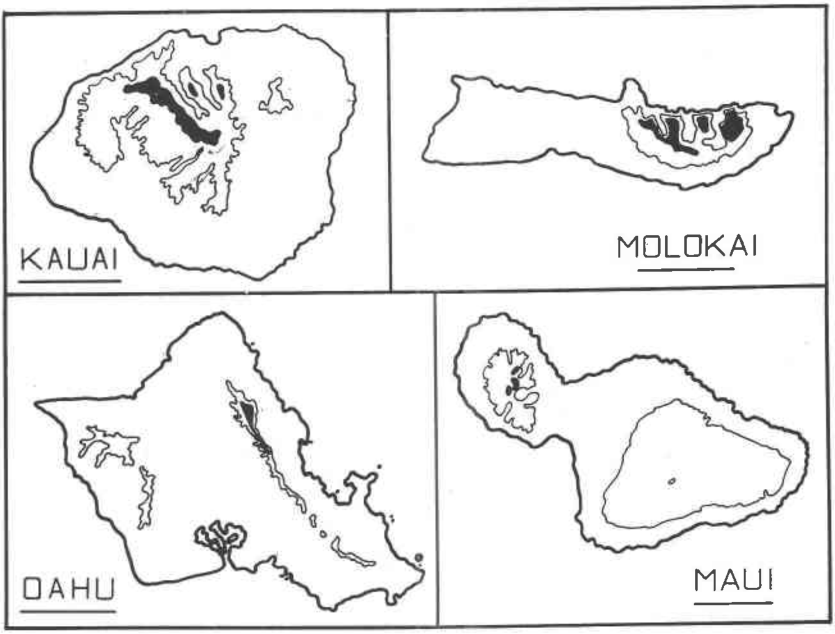


FIG. 2. Maps of islands showing summit swamp areas (solid black). On Kauai and East Molokai the areas shown are identical with the geomorphic provinces mapped elsewhere by one of the authors. On West Maui the areas shown approximate those mapped by Foster as peat-forming (Soil type VI). The area shown on Oahu is that roughly marked out by topographic conditions and known clay occurrence. These areas indicate according to present knowledge the probable limits of occurrence of ceramic clay, usable deposits being restricted to small pockets within the swamp region. On the basis of plant and bog conditions, some botanists feel that the area of clay occurrence may be somewhat larger on the higher area of West Maui, and smaller on the low summit swamp of Molokai, than shown here (St. John, personal communication).

the aggregate some three or four tons of clay have been packed out of the mountains and brought into Honolulu. Its ceramic and petrographic properties will be described in a later section.

During the summer of 1938, a one-day visit was made to clay localities on West Maui, a half day was spent in the area of clay occurrence on East Molokai and two days were spent in the Kokee area on Kauai, largely in examination of potential clay localities. Samples were collected and trials made which permit some general discussion of the clays and localities on these islands, though we have far less practical knowledge of these than of their counterpart on Oahu.

DESCRIPTION OF LOCALITIES

Oahu

All the Oahu localities from which good clay has been taken lie along the crest of the Koolau Range from the head of Waikane Valley northward to the vicinity of Puu Kainapuaa, a peak in Latitude 21°-36′ North (Fig. 2). In this distance of about seven miles the summit elevations range from 2,100 to 2,900 feet. On the east side the steep-walled heads of valleys form a nearly continuous cliff with declivity of 50 to 70 degrees. On the west, though the range slope for 4 or 5 miles is maturely dissected to very rugged and heavily-wooded country, the accordant interfluve ridges appear to stand in close approximation to the original constructional surface of the volcanic dome. Moreover, in a number of places in this area, small patches are shown by the topographic map to be but slightly dissected. It is probable that these few small areas are truly remnants of an old surface, which has for a very long period suffered neither degradation nor aggradation to a significant extent (Fig. 3).

The chief exposures of the clay have been revealed by the extensive trail-cutting operations carried on by the Civilian Conservation Corps in 1934 and 1935. They occur almost wholly in places where the trails cross fairly gentle slopes, and never where the trails are cut against steep banks below the gentler upper slope of the range. Where the trails are on the constructional surface, on the lee side of the crest, the clay bed is commonly found in the trail itself, or in a low bank on one side. On the other hand, on the windward or eastern side, where the mountain slope is a cut surface, no clay is found except in the few places immediately at the crest where the clay bed is exposed in section.

The plant cover in the Oahu localities consists of open swampy scrub, with conspicuous club mosses and ferns. In the more protected spots and along the slight depressions at the head of drainage are remnants of a forest, dominated by the ohia lehua (*Metrosideros*). The general aspect is that of a cover which was formerly more largely forest, broken by the open grassy areas which represent tension zones, where the forest has not maintained itself against the destructive effect of wild hogs and of man. In the strict botanical sense there is no plant complex which could be called a bog, comparable to that on the other islands.[4]

[4] This view has been expressed informally by Dr. H. St. John, Dr. Constance Hartt, Miss Marie Neal and Miss Lucy Cranwell, all botanists familiar with upland forest conditions in Hawaii.

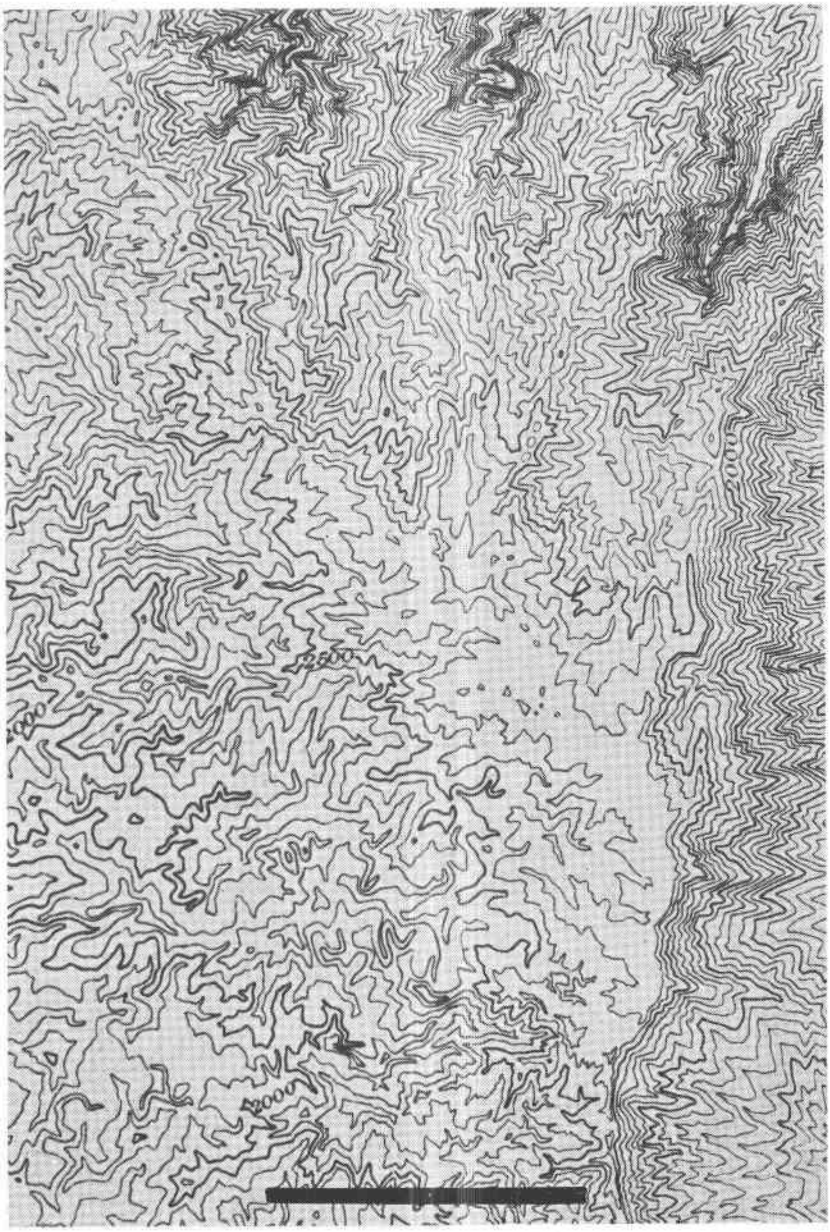


FIG. 3. Contour pattern of the summit of the Koolau Range at the northern end of the area of clay occurrence on Oahu, showing comparatively smooth, little-dissected, probable remnant of constructional surface. To the east is the steep, nearly continuous cliff formed by the heads of windward valleys. The heavy line is one mile long. Contour interval 100 feet. Photograph from the blue-and-brown U.S.G.S. sheet.

The largest deposits which have been found, though not prospected in detail, probably cover one or two acres and the total area is not known to exceed five acres. The typical stratigraphic section shows at the top a 6 to 9-inch mat of peaty material, in places almost wholly plant debris, of dark brown to black color. Below this layer and quite sharply marked off from it by its color and the scarcity of plant roots is the light gray clay. Commonly the clay is but one or two inches thick; locally, for a few feet it may reach 6 to 8 inches in thickness. Below, the clay grades in an inch or two to less pure clay, usually brown, buff or red in color and often lumpy or stony, showing original igneous rock structures. In this layer there may appear more roots than in the clay layer above. Such root stems as pass through the gray clay evidently do not branch effectively into the pure gray clay layer (Fig. 7).

Molokai

East Molokai, West Maui and Kauai have in common the fact that they are high volcanic domes which have been deeply dissected on one or more sides and display near their summits conspicuous tabular areas of sloping bog which represent remnants of original constructional surfaces. These surfaces have been reduced but little by weathering and slope wash. Moreover, on each of these islands, though in differing degree, the vegetation of these upland swamps is of distinctive bog type.

The Summit Swamp province[5] of East Molokai stretches for about 8 miles northwestward from Kamakou summit at 4,970 feet, past the steep-walled heads of Pelekunu and Waikolu valleys and with a branch between these valleys, to the elevation of about 2,500 feet at a point overlooking the Leper Settlement of Kalaupapa. Only the portion from Waikolu eastward is notably swampy. There are two other distinct sections of the Summit Swamp, one lying between elevations of 3,600 and 2,300 feet, east of Wailau Valley, and the other on the spur between Wailau and Pelekunu Valleys at 3,300 to 4,600 feet and entirely surrounded by the merged heads of these profound valleys. The total area of swamp mapped on the U.S.G.S. topographic sheet approximates six square miles (Fig. 4).

Clay was collected by one of us (C. K. W.) at two points on the trail west of the locality Pepeopae at the southwest rim of Pelekunu Valley, and was seen at various points in the vicinity. From present scanty knowledge of this little-visited country it may be presumed that clay occurs rather generally through the summit swamp area, and that, sporadically, patches of six inches to a foot or more thick may be found.[6]

[5] This name is applied to this area as one of the geomorphic divisions of Molokai. (Wentworth, C. K., *First Progress Report, Territorial Planning Board*, Plate 8, **1939**.)

[6] Presence of clay in this area had been noted by Mr. and Mrs. George P. Cooke, who pointed out localities and assisted in other material ways.

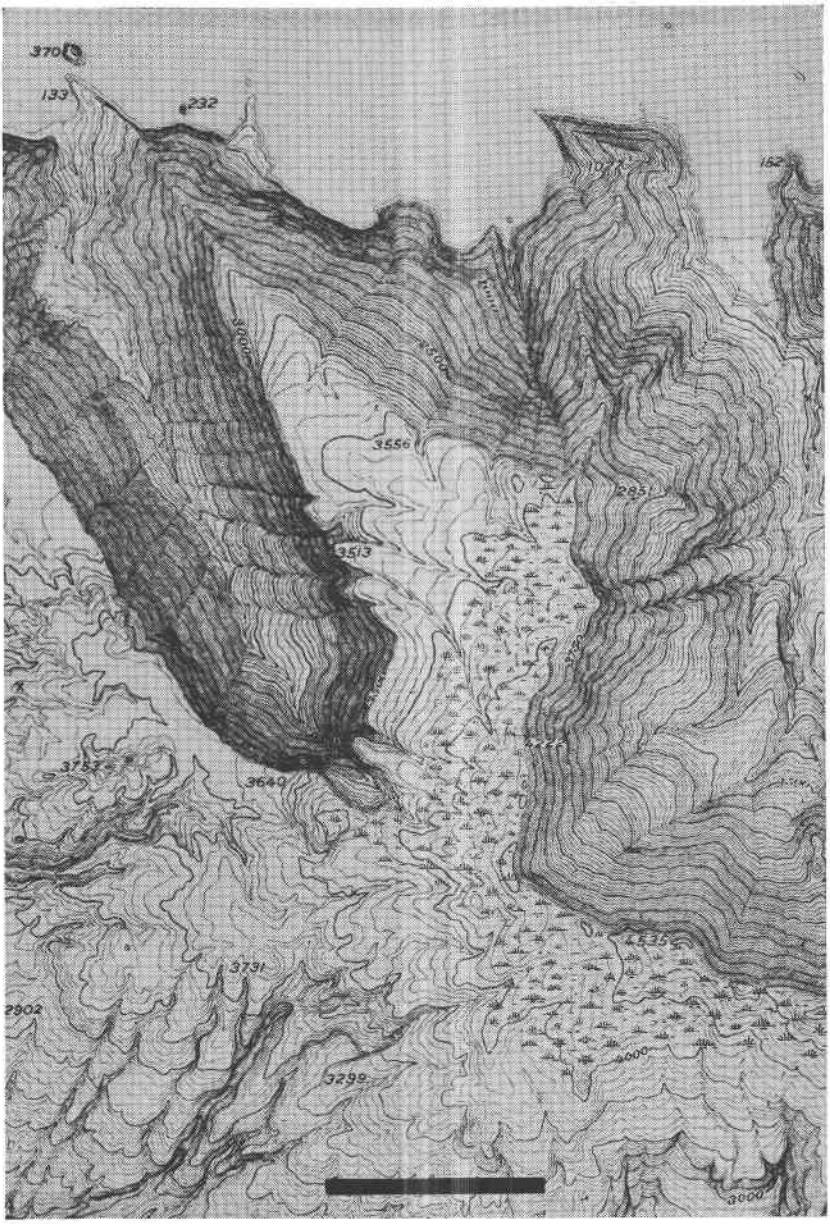


Fig. 4. Contour map of portion of the summit swamp of East Molokai, showing Waikolu Valley on the west side and part of Pelekunu Valley on the east. The heads of leeward, south-facing valleys are also shown; in the middle is the sloping remnant of the original dome surface in which clay occurs. The heavy line is one mile long. Contour interval 50 feet. Photograph from the blue-and-brown U.S.G.S. sheet.

Clay seen here was in general a little darker gray than that most seen on Oahu, though at one point a notably clean, very light cream to gray clay called "Molokai select" was found. The thickest clay beds seen were 12″ to 18″ thick and were found beneath a mat of 1 to 3 feet of fairly clean peat. Beneath the clay layer in many places was a marked limonitic layer two or three inches thick, with buff or grayish weathered rock beneath. The parts of the summit swamp traversed are marked by open areas of grass, sedges and diminutive ohias dwarfed from their usual tree-like habit, surrounded by larger trees and ferns at the margins of the flatter areas, where better drainage occurs. The vegetation is more shrubby and less a prostrate mat than on the bog areas of West Maui.

Maui

A one-day visit was made to the West Maui summit peak, Puu Kukui, elevation 5,788 feet, in company with Dr. H. A. Powers of the

Fig. 5. Detail of surface of West Maui bog at about 5,250 feet. Area shown is about 2 feet across. Very few plants are more than 6 inches high. Among the plants is the small tuft-like sedge, *Oreobolus fursatus*, the rosette-formed lobelia sp. and the diminutive ohia (*Metrosideros*), with oval leaves.

U. S. National Park Service. The chief summit swamp area of West Maui is the circular, filled bowl of Eke Crater, with several smaller areas lying down slope to the northeast and with two areas near the summit of Puu Kukui. The entire area mapped as swamp scarcely exceeds a square mile and lies at elevations from 2,600 to 5,700 feet. Only the small area lying north of the Puu Kukui summit was examined. Here, between 5,200 and 5,700 feet, there are several small areas covered with bog vegetation forming a striking, carpet-like surface and with but few plants rising over a foot from the ground (Fig. 5). As elsewhere the open bog areas are surrounded by a somewhat scrubby forest of taller bushes and trees at the margins of the tabular, ill-drained areas. Here the peat is a clean, compact mass of plant material of rufous color, found generally to be two to four feet thick. With considerable digging a few patches of rather dark clay, a few inches thick, were found, with a poorly marked layer showing limonitic accumulation below. It is quite possible that, in some parts of the summit swamp, thicker, lighter-colored clay, of presumptively better ceramic quality may be found; so far as limited observations to date indicate, the clay of West Maui is darker in color and less abundant than that of East Molokai, despite the more perfect development of bog vegetation.

KAUAI

On Kauai, as on other islands, known occurrences of clay passing ceramic tests are restricted to the summit swamp area. A sample of clay was collected at about 1,200 feet along the power transmission line which follows the ridge immediately east of Hanalei Valley, but this clay, like a number of other buff clays from moderate elevations on Oahu and elsewhere, has not proved satisfactory.[7]

The summit swamp of Kauai slopes for about 12 miles northwest from the highest point of the island (Waialeale, 5,080 and Kawaikini, 5,177) to a point at about 4,000 feet overlooking the precipitous northwest "napali" (the cliffs) coast of Kauai. Two small isolated remnants of the summit swamp (Alakai Swamp geomorphic province) mark the crests of interfluve ridges in the area to the north which is dissected by the three great rivers Hanalei, Nimahai and Wainiha of northern Kauai (see Fig. 2). The total area of the summit swamp province probably does not exceed 15 square miles.

Two days were devoted to a reconnaissance in the western end of the Alakai Swamp area, where several samples of clay were collected.[8] In so brief a time, it was only possible to traverse perhaps 8 or 10 miles of

[7] This locality was visited in company with Joel B. Cox, Engineer of McBride Plantation, and keenly interested in the geologic problems of Kauia, who conducted the author (C.K.W.) to many other points of interest.

[8] A part of the first day was spent in the company of Zera C. Foster, U. S. Bureau of Chemistry and Soils, who was engaged in completing a soil survey of the territory and who has made valuable contributions to understanding of soil-forming processes in Hawaii. The pit from which the largest and best-quality clay samples were collected was first opened by A. J. MacDonald, territorial forest ranger stationed at Kokee, who directed the writer (C.K.W.) to it.

trail, always returning by the same route, and to take clay from a few pits dug for the purpose. The Alakai Swamp as a whole is very little known, and but few persons have traversed any considerable part of it, and then only by definitely restricted routes.

The swamp is a sloping, upland bog, similar to those of Molokai and West Maui, whose open areas of grass and shrubs are surrounded by trees and more continuous forest around the margins and at the heads of invading drainage ways (Fig. 6). The features of the swamp, both its

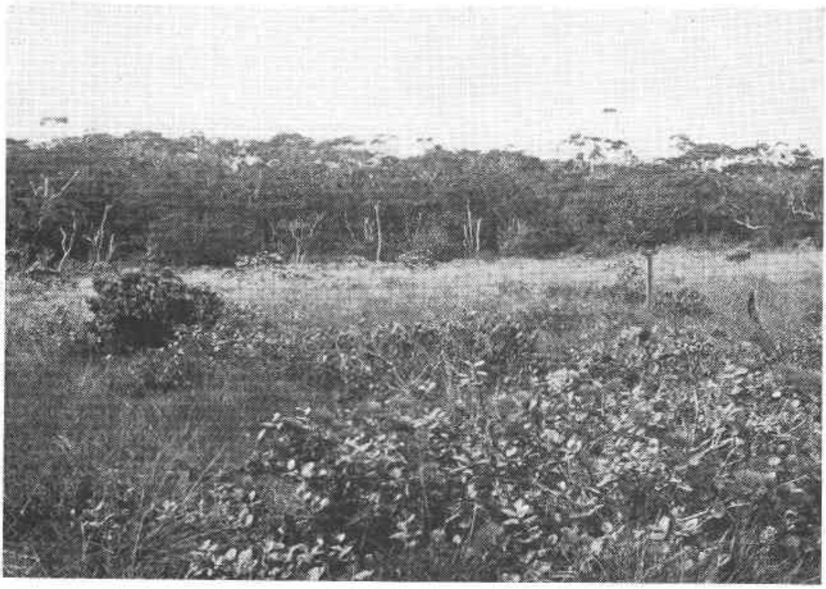


FIG. 6. Surface of bog in Alakai Swamp above Kokee, showing characteristic margin of the forest. Most of the plants in this area are 1 to 2 feet high with a few shrubs reaching 3 or 4 feet in height. They include grasses, shrubby ohias and the rare sundew, *Diosera longifolia.*

bog vegetation and its soil profile of peat, clay and limonitic sub-soil layer, are the results of the extremely imperfect soil drainage coupled with very high rainfall.

The Alakai area shows broader areas of bog than were seen on the part of East Molokai visited. In the Alakai area the clay was found underlying 6 inches to more than 2 feet of clean peat. In some sections, only 3 to 6 inches of rather dark clay, with numerous plant roots, was found. However, at the pit opened by A. J. MacDonald, the following section was measured. This pit is located in the fifth bog clearing and about 40 minutes walk beyond the crossing over a branch of Kawaiko Stream at B.M. 3698 and in the vicinity of spot elevation 4,024 ft.

Top	Grassy surface of bog	
	Clean peat, with little mineral debris	24″
	Dark gray clay, soft, with numerous plant roots	6″
	Light gray to cream-colored clay, with hard, secondary masses (lithomarge) in upper part Averages	15″
	Grades downward to stonier layers of buff color	
Base concealed		

This pit is in the midst of a rather uniform area of bog and the thickness of the clay suggests that workable thicknesses might be found beneath perhaps two feet of peat under one or two acres or more.

Hawaii

Small areas near the summit of the Kohala dome of Hawaii have been mapped by the Federal Soil Survey as peat-bearing areas in the same category as Alakai Swamp of Kauai. Clay has been reported as lacking, or of poor quality;[9] the area has not as yet been visited by us.

Summary of Occurrence

Certain generalizations seem justified by the preceding observations. Restriction to summit swamp areas is complete, if the Oahu locality can be regarded as such. The small size of the area and its lack of a markedly tabular aspect is opposed to such a classification. On the other hand, the topographic map, particularly the blue and brown printing, from which the culture and printed names are omitted, shows clearly a much less dissected and generally smooth topography at the summit of the range in the area where clay has been found, and the general conditions of drainage are very similar to those of the margins of several of the true bog areas (Fig. 3). From the standpoint of soil formation, this Oahu area may probably be regarded as marginal to the more typical and larger summit swamp areas of Kauai, Maui and Molokai.

The essential feature of the summit swamps is retarded drainage, enhanced by high rainfall. Rainfall in the Alakai Swamp of Kauai ranges from 450 down to 150 inches, the latter value being found near the west end where samples of clay were collected. Rainfall in the Puu Kukui area of West Maui is about 350 inches to somewhat over 150 inches. In the clay-yielding area of Oahu annual rainfall ranges from 250 to 300 inches. Apparently soil conditions suitable for clay formation may develop with a large range of annual rainfall, though all the areas receive high rainfall, and swampy conditions are general.

In all areas except that of Oahu, plant formations are of true bog character. These localities were studied during the summer of 1938 by a party

[9] Cranwell, Lucy, Personal communication.

of bog specialists headed by Dr. Carl Skottsberg. The results of their special studies have not yet been compiled or published. However, the distinctive nature of the plant cover of the bog areas is very apparent, even to a casual observer. Development of this special floral assemblage, with the stunting of certain plants which normally grow to larger size, and the accumulation of the peat is the result of a combination of causes and effects which include poor soil drainage, high soil acidity and reducing conditions which have led to the development of a relatively iron-free clay from a rock originally rather high in iron and comparatively low in silica.

With a few local variations there are three characteristic layers in the soil profile from the top downward, the peat or humus dark soil at the top, an intermediate layer of clay of varying quality and freedom from plant roots and at the bottom a more or less definite layer indicating accumulation of iron. Below this is weathered rock of various colors (Fig. 7). The soil conditions are succinctly epitomized by Foster as follows:

"VI ALAKAI-KAWELA-PUU KUKUI ASSOCIATION

Occupying gently rolling more or less flat-topped areas in high rainfall belt, best developed between altitudes of 4,000–5,000 feet but occurring at lower elevations of 2,500 feet in places, there are areas wet enough and cool enough to favor the accumulation of peat. Open areas of grasses, sedges and shrub ohia surrounded by taller ohia and ferns form a characteristic vegetation on poorly drained areas. Larger ohia and associated vegetation borders drainageways. The soils are in part peat and muck and in part gray mineral soils, with a shallow limonitic transition zone to gray soft rock. These areas have an economic value in their ability to absorb water and retard quick run-off."[10]

Production Methods

Except in the few places where the clay has been exposed in trails, prospecting consists of sinking a small spade into the turf mat of the perennially water-soaked surface of open, non-forested areas to determine the thickness of the light-colored clay layer. On Oahu only two or three places have been found where a thickness of 8 inches is maintained over an area as much as ten feet square. Under such conditions digging the clay is a laborious operation, involving the stripping of the humus layer from the top and hampered by rain, water-soaked ground and the extreme toughness of the clay.

The first few hundred pounds of clay dug were carried out by C.C.C. workers, camped in the mountains for trail work and willing to pack it out at a stipulated rate per pound, on their week-end holiday trips to

[10] Foster, Zera C., Soils of Hawaii: *Territorial Planning Board, First Progress Report*, 63, **1939**.

FIG. 7. Exposure of Koolau clay at Kawailoa-Summit Trail junction. The dark area near the top is a mat of low-grade peat. Below it is the light gray clay with a few plant roots and carbonaceous remnants in it, and near the bottom the clay grades into a stonier, more ferruginous layer. Thickness of whole section about 30 inches.

town. Several efforts were made to use horses or mules as pack animals, but extremely muddy trail conditions, increasing damage to trails from landslides and occasional loss of animals off trails made this an unsatisfactory method. Late in 1937, nearly two tons of clay was packed out to the Forest Reserve boundary by four Filipino laborers on a contract rate and was further transported by pack horses to the paved highway.

From the deposit one can collect by hand nearly pure balls of clay which might go directly into a ceramic article, but in process of digging by shovel a considerable quantity of twigs and lumpy material is incorporated. In preparing the clay for use, the lumps from the pit are crushed after drying and put to slack in barrels of water. Some impurities settle out and twigs, leaves and the like are in part floated off. The slip is strained and used directly in mold work or further dried out in plaster boxes for wheel and coil work.

CERAMIC PROPERTIES

General Appearance

In the discussion that follows, the Oahu or Koolau clay, which alone has been used and tested in substantial amounts, must be regarded as the type Hawaiian ceramic clay, as compared with the Molokai, Maui and Kauai clays, respectively. It should be recognized, that all these clays are variable, and that each type in any particular discussion is in reality the particular sample of a few pounds or production lot of one or two tons; subsequent lots, while similar, may be appreciably different in appearance and ceramic behavior.

The Koolau clay when dry is light gray in color (pale to light olive gray, (23′′′′′ e).[11] In the outcrop, when wet, the commonest color is a light to medium neutral gray; in a few places it is lighter gray or almost white. The damp clay is extremely tenacious and tough; when slightly more water is worked in, it becomes a highly plastic mass. To the feel and when tested between the teeth it is very fine grained and almost entirely free of grit.

The common Molokai clay is slightly darker and less pearly gray than the Koolau clay; a less common variant called "Molokai select" is a light cream color. The sample of Maui clay collected is much darker gray than most of the Koolau clay discovered and used. Some of the samples of common Kauai clay are darker, somewhat buff, and less neutral gray than the Koolau; the lower layer in the MacDonald pit is a light, pearly gray clay as fine-textured as any of the Koolau clay. This clay, in particular, when it sets from slip on plaster takes on an extraor-

[11] Color terms and symbols are those of Robert Ridgway, *Color Standards and Color Nomenclature*, Washington, 1912.

dinarily smooth, satiny appearance which approaches a polish. All the varieties of Hawaiian clay can be given a semi-polish by burnishing when dry and pieces so finished fire in the kiln to an extremely attractive saddle-leather aspect.

The California clay used by the Hawaiian Potters' Guild is produced by the Bauer Pottery Company and is understood to be a blended clay containing fractions from the Ione formation and from other Eocene formations.[12,13] This clay is tan in color (21'''f) and is much more gritty. It is less tenacious and hence more satisfactory for work on the potter's wheel. On the other hand, the Koolau clay in the form of slip is distinctly superior to either the Ione clay or the Monmouth clay in the making of molded pieces. This is because, from slip of the same consistency, a piece becomes set and dried sufficiently to clear the mold very much more quickly with Koolau slip than with either of the others used.

A commercial variety known as Monmouth clay is also used in Honolulu and this is reported to be produced in the Colchester district of Illinois. Both this clay and its counterpart formerly produced at Monmouth, Illinois, are from the Cheltenham group of Pennsylvanian clays.[14]

In most respects the Monmouth clay is intermediate in properties between the Ione and the Koolau clay. It is slightly darker in color than the Koolau clay, nearer a smoke gray (21''''f). Other properties are indicated in the tests reported below.

Mechanical Composition

Methods of determining particle-size distribution in clays are numerous and far from standardized. There is no occasion in this paper to add to deflocculation procedures or forms of subsidence apparatus. The most practical approach suggested a hydraulic classification of particles in the electrolytic condition obtaining in the practical operations of the pottery workshop. Therefore the tests have been carried out with tap water from the artesian system of Honolulu. This water, in parts per million at Beretania station contains the following: calcium, 6.7; magnesium, 6.4; sodium, 36; potassium, 1.6; chloride (Cl), 40; sulphate (SO_4), 6; bicarbonate (HCO_3), 76.[15]

The general distribution of particle sizes was determined for the Koolau, Ione and Monmouth clays by the plummet method,[16] in which the

[12] Sutherland, J. Clark, Letter dated February 26, 1938, addressed to Dr. J. P. Buwalda.

[13] Allen, V. T., The Ione formation of California: *Univ. of California, Bull. Dept. Geol. Sci.*, **18,** No. 14, 347-448 (1929).

[14] Leighton, M. M., Chief, Illinois Geological Survey, Letter dated April 21, 1938.

[15] Bryson, L. T., *Board of Water Supply, 7th Biennial Report*, 41, **1939.**

[16] Schurecht, H. G., *Jour. Am. Ceramic Soc.*, **4,** 816 (1921).

decreasing density of a clay suspension is measured by weighing a cylindrical plummet in the upper half of the suspension. The buoyant effect of the suspension on the plummet at a given time is exactly complementary to the weight retained at the same time on a pan at the bottom of the same column in the Odén subsidence method. The weight of the suspension was determined by a pycnometer, the mixture was then placed in a jar and shaken, and weighings of the plummet taken. The method has the superiority that the end points, both of the full suspension and the clear water, are known, and plotting and interpretation are thus better controlled. Moreover, weighing the plummet in several

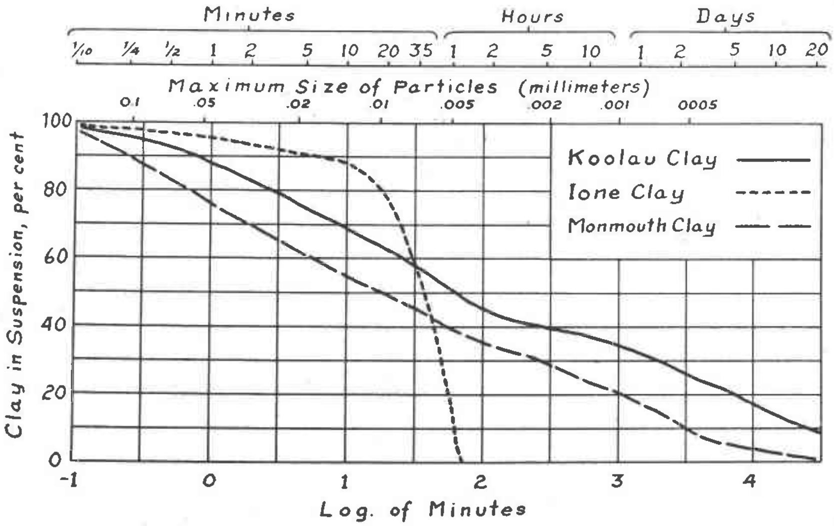


FIG. 8. Graph showing rates of subsidence of Koolau, Ione and Monmouth clays, as used in ceramic workshop at Honolulu. Determinations by the Schurecht plummet method, as described in the text.

samples, in a balance not continuously at the disposal of the operator, is more practical than when working with an Odén setup. Each set of weighings included a weighing of the plummet in a control jar of clear water which furnished a control correction for slight changes of temperature in the laboratory. The mechanical composition was derived from the subsidence curve by the tangent-intercept method.[17]

The results are shown in Fig. 8. The Ione clay was notable in the rapidity with which the settling was completed, the subsidence being nearly complete in about 1 hour. The amount of material settling slower than 1 mm. per minute, and thus under about .005 mm. in size is negligible

[17] Calbeck, J. H., and Harner, H. R., *Industrial and Eng. Chem.*, **19**, 58 (1927).

in the Ione clay. On the other hand, about 31 per cent of the Koolau clay remained in suspension after one day, and 10 per cent after 11 days. In this respect, the Monmouth clay is intermediate, as shown in Fig. 8.[18]

Specific Gravity

Specific gravities of plastic clay, air-dried clay, fired biscuit and of the clay substance were determined. That of the latter was determined by a pycnometer; the remaining determinations were made by weighing the clay in air and immersed in mercury by means of a saddle and stirrup arrangement. The resulting values are tabulated below.

Table of Specific Gravities of Clays in Different Conditions[1]

Condition	Koolau Clay	Ione Clay	Monmouth Clay
Clay substance (By pycnometer)	2.65	2.53	2.56
Plastic clay wedged for use	1.87	1.81	1.92
Air-dried clay	1.67	1.78	1.88
Fired biscuit	1.62	1.62	1.75

[1] All values are averages of from 2 to 8 determinations.

Porosity

Simple saturation tests of porosity were made of the several fired test pieces by boiling in water. Results of these tests and porosities computed by several methods are given in the following table:

Table of Percentages of Porosity[1]

	Koolau	Ione	Monmouth
Total porosity of wet clay, by computation from grain specific gravity	47.6	45.5	41.1
Total porosity of wet clay, by computation from water loss	48.0	43.0	40.3
Total porosity of dry clay by computation from grain specific gravity	36.9	29.4	26.7
Open porosity of fired biscuit	35.13	33.75	26.16

[1] Averages from determinations on three samples.

Plastic Tensile Strength

Comparative measurements on the three clays were made by determining the lengths extruded from a die before self-rupturing took place.

[18] The Ione clay and possibly the Monmouth clay are not simple, raw clays but have undergone some blending and grinding.

For all the tests herein described, standard pieces were made by forcing the wedged clay through a square die attached to a large-size, hand-driven food chopper. This device, using a round die, is used for producing clay coil material in quantity for making large coiled pottery pieces. In making the tests, the die was faced downward from a point of sufficient height and the clay forced out slowly and as uniformly as possible, until the extended clay broke from its own weight. As shown in the following table the Koolau has a much higher plastic strength than the Ione clay, and the Monmouth clay shows intermediate strength.

TABLE OF PLASTIC TENSILE STRENGTH[1]

Clay	Length at Rupture (Inches)			Average Breaking Strength	
	Trial 1	Trial 2	Trial 3	Grams per sq. cm.	Pounds per sq. inch
Koolau	63	78	72	332	4.72
Ione	46	43	40	195	2.76
Monmouth	57	55	57	270	3.83

[1] The clay was tempered and wedged to the consistency commonly used; there was no rigorous control to insure optimum strength.

LIQUIDITY AND DENSITY OF SLIP

In preparation for mold clearance tests, slips were mixed from each of the three clays to a standard consistency approximating that used in mold work. This consistency was measured by timing the draining of a funnel through a cylindrical opening drilled in a metal piece at the bottom. The slips prepared drained from the funnel in 50 seconds, as compared to 35 seconds for water. The densities were: Koolau clay, 1.410; Ione clay, 1.245; Monmouth clay, 1.359. The far higher density of the Koolau slip having the same liquidity as a Ione slip is striking, though the explanation is somewhat complex. In fact, such a slip, because of its greater density, passes through the funnel with such rapidity as to appear less viscous than it really is. In reality, the viscosities of any of several slips having a standard rate of draining from the funnel are directly proportional to their densities. In practice this means that slips mixed so as to appear of equal liquidity in pouring, or in passage through the funnel, the Koolau slip contains nearly 70 per cent more clay substance per unit of liquid measure. Presumably this is in part the explanation of the more rapid settling and greater firmness of molded pieces made from Koolau than from Ione clay. As in other respects the Monmouth clay occupies an intermediate position.

Moisture Loss and Shrinkage

Standard test pieces, 1″ by 1″ by 2½″, were made by cutting square extrusion pieces to a standard length in a simple jig. The following table shows the progressive loss of moisture and the shrinkage on drying and firing.

Table of Volume and Moisture Changes[1]

	Koolau			Ione			Monmouth		
	Volume (cc.)	Per cent loss[2]		Volume (cc.)	Per cent loss[2]		Volume (cc.)	Per cent loss[2]	
		Volume	H_2O[3]		Volume	H_2O[3]		Volume	H_2O[3]
Plastic condition	41.90	—	—	41.12	—	—	41.50	—	—
Air dried	34.80	20.4	34.6	31.75	29.5	31.6	33.00	25.8	25.8
Fired	32.30	7.2	9.4	30.70	3.3	12.0	31.95	3.2	10.7

[1] Values are averages from three or more determinations.
[2] Percentages referred to air dry volume and weight as base.
[3] Moisture loss is per cent by weight of water lost to total air dry weight of test piece.

Slacking Test

Marked differences in slacking behavior were noted, partly direct and partly caused by differences in structure set up in passing through the extrusion die. The Koolau clay placed under water with the linear axis of extrusion vertical, showed immediate opening of tangential cracks all around the square margin of the transverse exposed face and sloughing off of thin laminae progressively all around the vertical sides of the column. The mass typically reduced to a pile of soft, thin flakes. The Ione clay slacked most rapidly with a spalling off of larger flakes from edges, without displaying marked relationship to the axis of extrusion. Later the whole block was split parallel to this axis into three or four columns which toppled over. The Monmouth clay yielded very slowly to slacking action and in all early stages showed a compact, unpenetrated core.

Mold Clearance

Practical consequences of several of the physical peculiarities shown by the above tests are found in the exceptional adaptability of the natural Koolau clay to the process of pouring and setting in plaster molds. It has been consistently found that pieces cast from Koolau slip become sufficiently dry to clear the mold, and sufficiently tough to be handled, in one-fourth to one-sixth the time required by pieces cast from the

Ione clay. With a thoroughly dry mold, small, compact articles of Koolau clay will often clear the mold within less than an hour after commencing the pouring, and even with larger shapes, several pieces can often be taken from a single mold in a single day, a feat quite impossible with the Ione clay. In this respect the Monmouth clay is again intermediate.

It is notable, also, that the Koolau clay when blended with other clays greatly improves their setting up and mold-clearing qualities. In general, so small a proportion as 1/5 to 1/10 of the Koolau clay with Ione or similar clays will reduce to one-third or less the time required for clearing of molds. We have no rigorous physical or chemical explanation of this striking property of Koolau clay, but it appears to be related to (*a*) the density of the clay substance, (*b*) the large amount of material in the colloidal state and (*c*) the large amount of clay substance per unit of volume of slip of a given appearance of liquidity (hence smaller amount of water necessary to be removed to leave a specified amount of residue).

Fusibility

The Koolau clay has a somewhat lower fusion point than the Ione clay, as well as a shorter firing range. Best results are obtained by firing the Koolau clay to cone 07, which at the heating rate used is probably about 980° C. Care has to be taken not to place articles made of Koolau clay in parts of the kiln where temperatures more than one cone higher are reached, equivalent to about 1010° C., whereas articles made of Ione clay can safely go to considerably higher temperatures. The lower fusion point of the Koolau clay is probably caused by its high content of titania.[19]

Properties of Molokai, Maui and Kauai Clays

Generically, the clays from other islands are found to be similar to the Koolau clay of Oahu in their behavior in casting and drying. However, some differences are noted, greater than those between production lots of the Koolau clay used to date. The Molokai clay as collected is most similar to the Koolau clay; probably the "Molokai select" is equal to the best Koolau and the "Molokai common," or gray Molokai clay, is somewhat darker in color and forms a somewhat less firm body. The Maui clay is a much darker gray and appears more susceptible to cracking as it dries. It is probable that a careful search would reveal better grades than were found during the brief visit made. The Kauai clay collected from several points along the Alakai Swamp trail was gray to slightly buff in color and of poorer quality than the standard Koolau

[19] Ries, H., *Clays; Occurrence, Properties and Uses*, New York, 144–148 **(1927)**.

clay. That from the MacDonald pit, however, is light pearly gray and is exceptionally fine grained. Indeed it appears to be so rich in colloidal clay substance that it has a detrimentally high shrinkage and also offers difficulty in casting. Whereas thin castings made of this clay set very rapidly to an extremely tough condition, with a fine, satiny surface and clear the mold quickly, it is somewhat difficult to get thicker pieces from this slip owing to the tendency for the piece to start shrinking and separation from the mold while the mold is still filled with slip. It is quite likely that less extreme types of this clay will be found in the Alakai Swamp area, and also that such clay can be successfully blended with other types less rich in colloidal material.

COMPOSITION OF THE CLAY

Chemical Analysis

The clays as received for analysis in Washington were well sealed in glass jars and still very moist, 40, 14, 34 and 35 per cent, respectively, of water above the air-dried weight. They were dried in air of about 40 per cent humidity for analysis. A few minor constituents were determined in some of them but, as these did not seem significant, the main attention was given to the major constituents, of which titanium was conspicuous. This was separated from aluminum by means of cupferron, after removing iron as sulphide in a tartrate solution. A colorimetric check showed the titanium to be of the order found gravimetrically. Organic matter was determined by dissolving the silica and most of the alumina in a mixture of hydrofluoric and hydrochloric acids, filtering off the crude organic matter and determining it by means of concentrated hydrogen peroxide. The loss on ignition was then corrected for H_2O- and for organic matter. The other constituents were determined by usual methods.

All the iron is reported as Fe_2O_3. Ferrous iron could not be determined accurately on account of the presence of organic matter. The apparent figures for FeO were 1.47, 1.47, 3.57 and 0.77 per cent, respectively, in the four clays but these figures are not entitled to much weight. It seems clear, however, that most of the iron in clays 1, 2 and 7 is in the ferric condition.

Comparison of the analyses of the three clay samples shows a marked variation in some oxides. Samples 1 and 2 were field duplicates and are similar though by no means identical. Sample 7 was a notably white clay from a point where the marshy conditions might be a little more extreme. The SiO_2 is more than 20 per cent higher, and the TiO_2 about 10 per cent less than in samples 1 and 2; alumina and iron oxide are

TABLE NO. 1

ANALYSES OF HAWAIIAN CLAYS, BASALT AND SOIL

	1	2	5	7	A	B
SiO_2	33.88	39.72	23.24	57.00	49.88	42.13*
Al_2O_3	25.69	25.12	9.16	21.93	13.79	10.41
Fe_2O_3	8.61	7.38	3.97	3.23	12.26	25.12
MgO	0.92	0.61	0.44	0.86	6.12	0.39
CaO	0.06	0.05	0.13	0.03	9.59	0.44
K_2O	2.76	3.01	1.23	4.18	0.17	0.60
Na_2O	0.25	0.21	0.11	0.40	3.30	0.19
Li_2O	0.04	—	—	0.03	—	—
H_2O-	2.08	1.40	7.25	1.84	—	3.80
H_2O+	8.20	8.70	17.34	6.27	—	
TiO_2	15.28	14.06	3.88	4.33	3.97	3.40
P_2O_5	0.06	—	—	—	0.26	0.12
ZrO_2	0.04	—	—	0.02	—	—
BaO	—	—	—	0.04	—	—
CO_2, MnO, SO_3, Cl, N, Rare Earths	None	None	None	None	0.67	0.58†
Organic matter	0.91	0.66	32.29	0.43	—	13.20‡
Total	98.78	100.92	99.30	100.61	100.26	100.38

1. Clay from crest of Koolau Range, at junction of Kawailoa and Summit Trails, Latitude 21°36′, Oahu. (Acidity, pH=4.65; determined by L. T. Bryson.) Analysis by R. C. Wells.
2. Same locality as (1) above. (Acidity, pH=4.80; L.T.B.) Wells, analyst.
5. Peaty, humus layer above clay, same locality. (Acidity, pH=4.75; L.T.B.) Wells, analyst.
7. Lighter clay from head of small gully about 400 feet southwest of above locality. Wells, analyst.

A. Basalt, Koolau Mountains. Analysis by A. B. Lyons. (Cross, W., *U.S.G.S., Prof. Paper* **88,** Analysis No. 19, p. 52, 1915).

B. Soil, red, Wahiawa district. (Kelley, W. P., McGeorge, Wm., and Thompson, Alice R., The soils of the Hawaiian Islands: *Hawaii Agricultural Expt. Station, Bull. No.* **40,** Soil No. 5, p. 27, 1915.)

* Insoluble residue.

† Includes Nitrogen, 0.24; SO_3, 0.08; and manganese oxide, 0.26.

‡ Volatile matter.

about 4 and 5 per cent lower, respectively. There is no doubt that samples collected generally from different places in the clay districts of the several islands would show similar wide ranges of composition, while in general showing high enough silica plus alumina, and low enough iron, to possess ceramic utility.

The more normal gray clay is extraordinarily high in titanium; casual inspection of washed lag as well as mineralogical examination suggests that much of the clay is high in ilmenite or leucoxene, and hence of comparable richness in titanium oxide, though the composition of the whiter sample 7 shows that a markedly smaller percentage of titania is found in some varieties. Although the clay is in general regarded as residual, washings of fine black rill silt, largely ilmenite, seen in the clay areas suggest that some local removal or concentration of ilmenite by mechanical transport may explain the variation in amounts of titania. Elements that might be associated with titanium, such as zirconium and rare earths, are absent. The percentage of titanium does not seem to run parallel with that of any other element, except possibly iron. They are high-titanium clays and seem to tend toward silica-alumina ratios higher than that of kaolinite.

Mineral Composition

In thin sections the Koolau clay[20] appears to be a mixture of illite with small amounts of kaolinite, plagioclase and a black opaque mineral resembling magnetite or ilmenite. Certain areas of the clay minerals are brown in thin section and have higher refringence and birefringence than others. Measurements in oils on the fine colloidal fraction separated by sedimentation methods indicate that the refractive indices of different parts vary. Some have optical properties that suggest kaolinite, and others fall within the range recently reported for illite,[21] in which the refractive indices increase with the ferric oxide. The highest value determined for gamma was 1.608 and for gamma minus alpha about .03. These values are close to those found by Grim for a sample of illite with 10.73% ferric oxide. An *x*-ray pattern of a sample of the Koolau clay was made through the courtesy of the State Geological Survey of Illinois. Dr. W. F. Bradley[22] reports that this pattern indicates that the clay is composed of illite, some kaolinite and extremely fine quartz. The presence of quartz in the sample could not be established by optical examination. The chemical analyses of the Koolau clay (Table No. 1, Samples 1, 2 and 7) suggest that the potash, silica, alumina and part of the iron and water could be accounted for mainly by mixtures of illite and kaolinite. Grim, Bray and Bradley[23] consider that the composition of illite can be expressed by the formula $2K_2O \cdot 3MO \cdot 8R_2O_3 \cdot 24SiO_2 \cdot 12H_2O$, in which MO represents the divalent oxides of calcium and magnesium and ferrous oxide, and R_2O_3 the trivalent oxides alumina and ferric oxide.

[20] Samples 1 and 2, Table No. 1.

[21] Grim, R. E., Bray, R. H., and Bradley, W. F., The mica in argillaceous sediments: *Am. Mineral.*, **22**, 813–829 (1937).

[22] Written communication.

[23] *Loc. cit.*, p. 823.

The unusual feature of the chemical analyses of the Koolau clay is the presence of over 15 per cent of titania, which far exceeds the 8 or 9 per cent of titania previously reported in the soils of Oahu.[24] In more than 200 analyses of Hawaiian soils and sub-soils only about 10 per cent show more than 5% of titania, nearly all being in samples from the Hamakuapoko district of Maui. Nearly as many samples show less than one per cent, the median being 2.55 per cent.[25] The black opaque mineral in the clay was concentrated by elutriation and by the use of heavy solutions and gave a qualitative test for titanium. It is only weakly magnetic and is probably ilmenite. The black opaque mineral in Hawaiian lavas is usually termed magnetite, but Cross[26] found that the powder isolated with a magnet from a nephelite-melilite basalt on Oahu contained 13.4 per cent TiO_2. A fair representation of the average content of the black mineral in the Koolau clay is indicated in the photomicrograph of Fig. 9. The amount present seems too small to explain the 15 per cent titania in the clay. The only other abundant titanium mineral in the heavy separation was leucoxene, the gray opaque alteration product of ilmenite. Two grains of anatase and one that possibly was rutile were observed among several hundred grains of ilmenite and leucoxene. W. F. Bradley of the State Geological Survey of Illinois compared the x-ray pattern of the Koolau clay with several titanium minerals and found the six strongest lines of anatase represented by weak lines suggesting the possible presence of some anatase.[27] He, however, did not compare it with the x-ray pattern of leucoxene. McCartney[28] found that small samples of leucoxene gave no x-ray pattern. Paul F. Kerr[29] reported that samples of leucoxene prepared by the writer (Allen) gave x-ray patterns too indistinct to recognize in a mixture of clay minerals. The composition of leucoxene is uncertain. According to Coil,[30] the leucoxene in the Permian sandstones of Oklahoma is an amorphous hydrous titanium oxide. Tyler and Marsden more recently have concluded that leucoxene is a microcrystalline form of rutile, anatase and perhaps brookite and recommend

[24] Lyons, A. B., Chemical composition of Hawaiian soils and the lavas from which they have been derived: *Am. Jour. Sci.*, **2**, 421, 29 (1896).

[25] Kelley, W. P., McGeorge, W., and Thompson, Alice R., The soils of the Hawaiian Islands: *Hawaii Agricultural Experiment Station, Bull.*, **40** (1915).

[26] Cross, Whitman, Lavas of Hawaii and their relations: *U.S.G.S. Prof. Paper* **88,** 22 (1915).

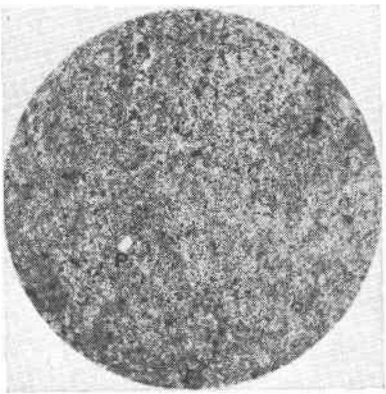
[27] Written communication.

[28] McCartney, G. C., A petrographic study of the Chester sandstone of Indiana: *Jour. Sed. Petrology*, **1**, 82–90 (1932).

[29] Kerr, Paul F., Written communication.

[30] Coil, Fay, Chemical composition of leucoxene in the Permian of Oklahoma: *Am. Mineral.*, **18**, 62–65 (1933).

retention of the name leucoxene for this material since it is not a mineral species.[31] Because finely divided leucoxene mixed in a clay could escape detection by optical and x-ray methods which would reveal such minerals as rutile, titanite and anatase, it seems probable that the titania of



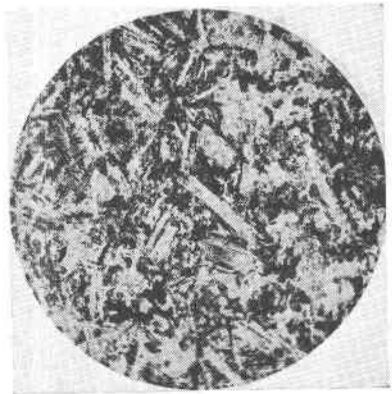


FIG. 9. (left). Koolau clay showing illite (I), kaolinite, ilmenite (solid black specks) and plagioclase (white rectangle above P). (×54)
FIG. 10. (right). Nodule showing ilmenite (solid black) and plagioclase altered to kaolinite. (×31)

the Koolau clay, which is not in the form of ilmenite, is present as leucoxene. A similar conclusion was reached by the writer (Allen) regarding the titanium in separations from Missouri diaspore clay which analyzed over 24 per cent titania[32] and contained leucoxene but did not give the x-ray pattern of any titanium mineral.

PETROGRAPHY OF PARENT ROCKS

The occurrence in the summit areas of Mauna Kea and Kohala on Hawaii, West Maui and Haleakala on Maui, and perhaps elsewhere, of intermediate lava flows of trachytic or andesitic composition has been known in a general way for many years. This fact suggests the possibility that the clays of some of the summit deposits may not be wholly, or largely derived from such intermediate rocks, by weathering entailing less pronounced removal of iron and increase of silica and alumina.

Hard rock specimens are difficult to obtain in the near vicinity of the clay deposits and insufficient work has been done to give a comprehen-

[31] Tyler, S. A., and Marsden, R. W., The nature of leucoxene: *Jour. Sed. Petrology*, **8**, No. 2, 55–58 (1938).

[32] Allen, Victor T., Mineral composition and origin of Missouri flint and diapsore clays: *Missouri Geol. Survey, 58th Biennial Report*, App. **IV**, 11–13 (1935).

sive view of the succession of original lava flows. However, some specimens have been examined in thin section with the following results:[33]

Four specimens collected at different points along the crest of the Koolau Range within the area of clay occurrence are olivine basalt, or olivine-basalt porphyry, with textures either typical of the fundamental Koolau basalt, or well within its range of textures. Olivine is abundant, also magnetite, and pyroxene. The feldspar is in the labradorite range. These specimens afford no evidence of late, summit lava flows on the Koolau Range of composition significantly less basic than the Koolau series generally.

No rock specimens were collected from the clay area on Molokai, nor on West Maui. Late capping lava flows of trachytic composition are known to occur on West Maui dome, but the specific relation of these to the clay deposits is unknown. As the West Maui clay seen in the field is uncommonly dark and appears to contain much dark mineral, thought to be ilmenite, it seems at least plausible that the clay may be derived in part from basalt.

In the vicinity of Kokee, Kauai, below the west end of Alakai Swamp, numerous road-cuts lead to the tentative field conclusion that both basaltic flows and intermediate flows occur on that part of the dome. Both are deeply weathered, but show rather contrasting features. The basalt is commonly dark red or purple in color, spheroidal in weathered structure, and shows clear vesicular texture. The supposed trachyte has less spheroidal structure, or none at all, is commonly light lavender to chalky white in color and not significantly vesicular. In places, slabby, light gray blocks of the "trachyte" lie imbedded in a buff, or tan-colored, slope-washed soil. Six specimens from this area were examined in thin section. Three of these are classified as olivine basalt or porphyry, showing moderate to much weathering. A fourth is described as "Clay, pseudomorphous after basalt or closely related rock. The preserved texture strongly suggests a common ophitic or intergranular Hawaiian basalt, rather than any marked differentiate. The secondary minerals are extremely fine grained and were identified tentatively as clay minerals."[34]

Two specimens (H1935 and H1941) appear to be somewhat more acid than basalt. A certain parallelism of the feldspar laths was noted and the plagioclase is more abundant than in most basalts. Orthoclase was tentatively identified in one of the specimens. On the other hand, olivine, magnetite and pyroxene are present. In the Alakai area the clay may

[33] Winchell, Horace, Manuscript report based on microscopic examination of specimens collected by one of us, in comparison with extensive series of specimens of Koolau basalt of Oahu, and limited number of specimens from elsewhere in Hawaii.

[34] Winchell, Horace, *Op. cit.*

in part be derived from intermediate rocks, though basalts are present and appear to have constituted much of the parent material. It is concluded that the clay has been derived from basalt, perhaps exclusively so on the Koolau Range of Oahu, and to an important degree elsewhere. Despite the likelihood that much clay has also been derived from rocks of less basic composition, there seems no basis for concluding that such intermediate parent rocks are essential.

ORIGIN OF THE KOOLAU CLAY

Petrographic study of the Koolau clay suggests that the clay was derived from the weathering of basaltic lavas. It contains tiny grains of plagioclase altered to kaolinite at the edges but with the central cores of some grains sufficiently fresh that albite twinning can be distinguished between crossed nicols. Some of these were collected by washing large samples of clay, and their refractive indices indicated basic labradorite or acid bytownite.

Figure 10 shows a photomicrograph of a nodule of weathered rock collected from the same locality as the Koolau clay. The phenocrysts, probably originally plagioclase, are altered to clear white kaolinite, as shown by the interference colors of these areas which are first order gray (birefringence .005). Moreover, powders representing parts of them tested in oil have the refractive indices of kaolinite, and there is also a suggestion of the worm-like structure often assumed by kaolinite. The groundmass, which originally was probably composed of feldspar grains and ferromagnesian minerals, is now altered to a clay mineral having the properties of illite. The solid black is ilmenite or titaniferous magnetite. Titanium is present in the augite of some Hawaiian lavas and gives it a purple color in thin section. The ferromagnesian minerals of these nodules are too markedly altered to show their original nature. Thus, the relict plagioclase feldspars in the Koolau clay indicate that minerals of basaltic lava contributed to the formation of the clay, and altered nodules reveal that weathering in this area could furnish the clay minerals of which the Koolau clay is composed. Study of other specimens of rock in various stages of weathering, collected from the crest of the Koolau Range and the Alakai Swamp area, as reported above, also points to the same conclusion.

Further indication of the derivation of this clay from basaltic lava is afforded by the chemical analyses. Comparison with a representative analysis of basalt of the supposed parent rock (Analysis *A*), indicates that silica in the gray clays is decreased, while it has increased by nearly 10 per cent in the lighter clay. Alumina generally is considerably higher, as it remains while other oxides are removed. In the gray clays, titania is present nearly four times the percentage found in the rock and iron is reduced by $\frac{1}{3}$ to $\frac{2}{3}$ of its original amount. There is great loss of lime, magnesia and soda, but marked increase in potash. That common changes incurred in lower level weathering are suggested by analysis *B*, though any series of analyses of soils will show much variation. However, in the soils, under laterization, iron oxides increase, commonly to twice the amount in the original rock, and alumina is slightly reduced in amount. Titania varies from much less than that in the rocks to somewhat more, in soils in which concentration appears to have taken place.

Since Deville's observation[35] of titania in bauxite, it has been regarded as a concentration of the insoluble material of the original rock. The titania apparently increases directly as the alumina is concentrated[36,37] by weathering and decreases as the alumina is removed under other conditions.[38] In the 14 analyses of Hawaiian lavas given by Cross,[39] not including those of trachytes, the range for TiO_2 is from 1.48 to 4.05 per cent, with an average of 2.44 per cent. The average TiO_2 of 56 analyses of Hawaiian lavas listed by Washington is 2.84 per cent.[40] Maxwell[41] reports that the average TiO_2 of ten lavas is 3.5 per cent and that it is the most insoluble constituent in Hawaiian soils, where its increase is proportional to the decrease in silica. A dark red soil with 31.45 per cent silica is stated to contain 7.62 per cent titanic acid. McGeorge[42] lists the chemical compositions of several lavas and the disintegration products derived from them. All show an increase in titania, alumina and iron and a decrease in silica during weathering of the lavas. From these observations the presence of titania in Hawaiian lavas and its concentration during weathering may be considered an established fact. But, to account for the 14 or 15 per cent of titania in the Koolau clay, either the parent rock was unusually high in titania or, what is thought more likely, there may have been some local placer concentration of the heavy mineral ilmenite.

Another feature of the weathering process that formed the Koolau

[35] Deville, H. Sainte-Claire, *Annales Chim. phys., 3rd series*, **61,** 309 (1861).

[36] Coghill, William F., Titanium in bauxite ores and sludges: *Report of Investigation of U. S. Bureau of Mines*, No. **2867,** Rolla, Mo. (1928).

[37] Allen, Victor T., *Loc. cit.*, **1935.**

[38] Allen, Victor T., A study of Missouri glauconite, *Am. Mineral.*, **22,** 1181 (1937).

[39] *Loc. cit.*, 51 (1915).

[40] Washington, H. S., and Keyes, M. G., Petrology of the Hawaiian Islands, V. The Leeward Islands: *Am. Jour. Sci.*, **12,** 351 (1926).

[41] Maxwell, Walter, Lavas and soils of the Hawaiian Islands: *Hawaiian Gazette Co.*, Honolulu, 80 (1898).

[42] McGeorge, W. T., Composition of Hawaiian soil particles: *Hawaii Ag. Exper. St., Bull.* **42,** 6 (1917).

clay is the behavior of potash. In the papers of Maxwell[43] and McGeorge[44] a decrease in K_2O is shown in the soils over that present in the parent material. The samples of Koolau clay with over 14 per cent titania have about 3 per cent potash. The average of the 56 analyses of Hawaiian lavas by Washington[45] contains 1.02 per cent potash. Either the parent rock of the Koolau clay had a higher content of potash than the average of the Hawaiian lavas, or its being stored during the formation of illite prevented the usual loss that takes place during the formation of lateritic soil. Though trachytes[46] with over 5 per cent potash are known in the Hawaiian Islands, there does not appear to be good evidence that the clays have been formed from such less common rocks, especially since such trachytes have less than 1 per cent titania and this substitution would merely increase the difficulty of explaining the high titanium and the basic plagioclase in the Koolau clay. The conclusion appears justifiable that the chemical and mineralogical composition of the Koolau clay can be best explained by weathering of a basaltic lava within the range of those already known in the Hawaiian Islands.

The more important changes in the formation of clays in general, of these clays in particular, and of soils commonly formed at low levels in Hawaii, are shown graphically in Fig. 11. A clay may be defined as a residue, leached of oxides of calcium, magnesium, potassium and sodium, and consisting of those oxides which possess ceramic qualities, silica and alumina, and with iron oxides largely removed. In these clays an important amount of titania must be included with the silica and alumina as the ceramic residue. In the diagram, ceramic clays fall near the top. The igneous rocks, ranging from acid to basic compositions, fall in a nearly vertical zone left of the center line. Change from the composition of a granite to a clay involves a comparatively slight relative loss of alkali and alkaline earth oxides, a slight increase and change in the proportions of silica and alumina, and usually some increase of iron. Basalt, as a producer of ceramic clay, starts with the handicap of containing much less silica and alumina, several times as much iron and twice the percentage of alkali and alkaline earth oxides as an ordinary granite. Furthermore, basalt is a fine-grained rock; there is no segregation of its feldspars or other favorable clay sources, as in some pegmatites of granitic composition. And finally, in the ordinary lowland climatic zones of Hawaii, weathering forms lateritic types of soils which contain far too

[43] *Loc. cit.*, 421–429 (1898).

[44] *Loc. cit.*, 6 (1917).

[45] *Loc. cit.*, 351 (1926).

[46] Washington, H. S., Petrology of the Hawaiian Islands, II. Hualalai and Mauna Loa: *Am. Jour. Sci.*, **6**, 108 (1923).

much iron to have any ceramic value. Production of a ceramic clay with a content of silica, alumina and titania quite within the clay range on the diagram of Fig. 11 evidently represents a type of weathering differing strongly from the common laterization and a somewhat extreme degree of such weathering. The crucial difference between this weathering and laterization is in the removal of iron, as distinguished from its accumulation.

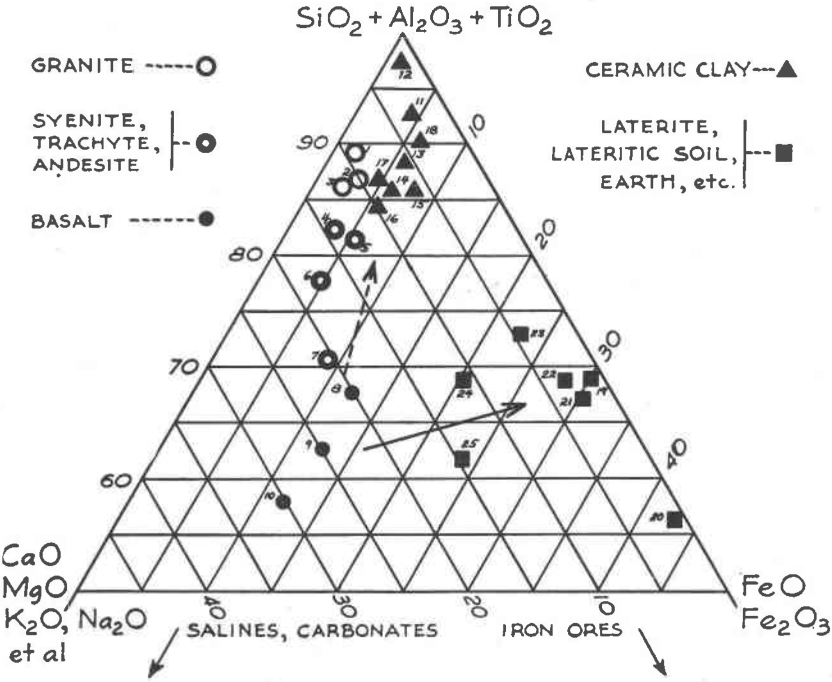


FIG. 11. Three-component diagram showing chemical composition of various igneous rocks, of Hawaiian and other clays, and of Hawaiian rocks and their more common soil derivatives. The solid arrow indicates the direction of lateritic weathering and the dashed arrow shows the contrasted direction of weathering by which the Koolau and other Hawaiian ceramic clays must have been formed. Source data are tabulated below.

1—Granite, Pikes Peak (Clarke, p. 441, B)
2—Granite, Minnesota (Clarke, p. 441, E)
3—Granite, Vermont (Clarke, p. 441, D)
4—Trachyte, Yellowstone (Clarke, p. 443, C)
5—Trachyte, West Maui, Hawaiian Islands (Cross, p. 47, 1)
6—Syenite, Montana (Clarke, p. 443, K)
7—Andesite, Yellowstone, (Clarke, p. 458, C)
8—Basalt, Koolau Range, Oahu, Hawaiian Islands (Cross, p. 48, 19) (See Table No. 1, A)
9—Basalt, Kauai, Hawaiian Islands (Cross, p. 48, 26)

10—Basalt, Puna, Hawaii Island (Cross, p. 48, 41)
11—Crude kaolin, Virginia (Ries, p. 321, VIII)
12—Fire clay, Alabama (Ries, p. 336, I)
13—Stoneware clay, West Virginia (Ries, p. 342, VII)
14—Sewer-pipe clay, Ohio (Ries, p. 346, I)
15—Bentonite, Alberta (Ries, p. 369, IV)
16—Crude clay, Oahu, Hawaiian Islands (Wells, this paper, 1)
17—Crude clay, Oahu, Hawaiian Islands (Wells, this paper, 2)
18—Crude clay, Oahu, Hawaiian Islands (Wells, this paper, 7)
19—Primary laterite, British Guiana (Harrison, p. 13)
20—Ferruginous bauxite, British Guiana (Harrison, p. 17, III)
21—Red lateritic soil, Oahu (Kelley *et al.*, p. 27, 5) (See Table No. 1, B)
22—Brown lateritic soil, Maui (Kelley *et al.*, p. 23, 547)
23—Black soil, Oahu (Kelley *et al.*, p. 27, 11)
24—Brown soil, Oahu (Kelley *et al.*, p. 28, 398)
25—Red soil, Oahu (Kelley *et al.*, p. 29, 331)

Clarke, F. W., Data of Geochemistry: *U. S. Geol. Survey, Bull.* **770** (1924).

Cross, W., Lavas of Hawaii and their Relations: *U. S. Geol. Survey, Prof. Paper* **88** (1915).

Ries, H., Clays, John Wiley & Sons **(1927).**

Harrison, J. B., The katamorphism of igneous rocks under humid tropical conditions: *Imperial Bureau of Soil Science, Harpenden* **(1933).**

Kelley, W. P., McGeorge, Wm., and Thompson, Alice R., The soils of the Hawaiian Islands: *Hawaii Agricultural Experiment Station, Bull.* **40** (1915).