

HALLOYSITE AND GIBBSITE FORMATION IN HAWAII¹

by

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ABSTRACT

Desilication and removal of bases from the basaltic rocks of the Hawaiian Islands produces large amounts of halloysite and gibbsite, together with variable quantities of allophane and nontronite, iron and titanium oxides, and amorphous mineral and gel material.

The nature and relative abundance of intermediate and end products of weathering depend primarily upon the amount of rainfall, angle of slope, and texture of the rock. The formation of clay minerals is the common step in the transformation of primary silicates to oxides and hydroxides, but the amount and relative importance of the clay "stage" depend on the intensity of the weathering process.

Halloysite forms from plagioclase usually by alteration of first the core and subsequently the rim of the feldspar laths. No kaolinite was observed, its absence being attributed to the absence of fine-grained mica as an intermediate weathering product.

Gibbsite is produced by (1) removal of silica from halloysite, (2) dehydration of Al-gel, and (3) precipitation from solution. Although it is possible that the mineral may form directly from feldspar, halloysite is the common crystalline intermediate on both the megascopic and microscopic scales.

An amorphous transition state, probably ranging in composition from allophane to Al-gel, exists as part of the change from halloysite to gibbsite as evidenced by electron microscope and diffraction work on pseudomorphs after halloysite tubes found in certain samples studied in more detail than others.

Volcanic glass is the apparent source of most Al-Fe-Si gel material which upon dehydration becomes allophane, cliachite, or gibbsite depending on the kind and relative proportion of the cations present.

INTRODUCTION

The climate of the major islands of the Hawaiian archipelago is conducive to the weathering of parent basaltic rocks into various silicate, oxide and hydroxide minerals and mineraloids. Some of the quantitatively important transformations are illustrated in Fig. 1. As indicated here, the general pattern of weathering in the Islands involves chemical leaching and ultimate

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removal of bases and silica, addition of hydrogen, and retention of Al, Fe and Ti. Formation of layer lattice silicates is an important step in the production of various oxide and hydroxide end products. However, the presence or abundance of a weathering product at any given locality depends upon climatic and other factors now or previously dominant there. A mineral that exists as a transition phase under conditions of high rainfall may be an "end product" of weathering in a more arid part of the same island.

Five factors are most important in affecting the rate and amount of weathering and the nature of intermediate and end products in Hawaii:

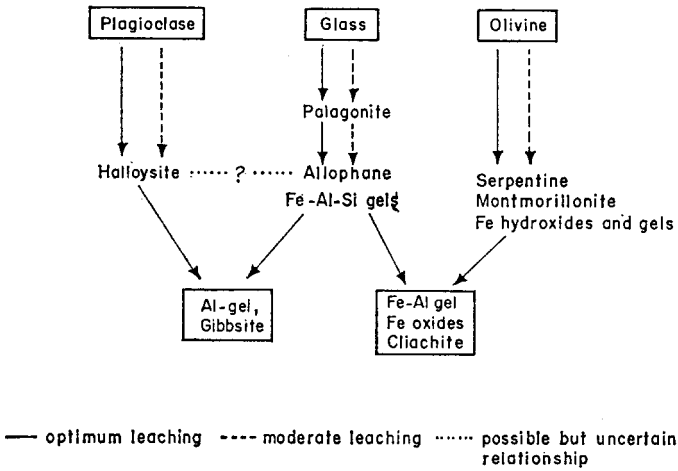


FIGURE 1.—Transformations during weathering.

age, composition and texture of the rocks; amount and seasonal distribution of rainfall; and the nature of the slope and the resulting drainage pattern. In accounting for a particular weathering sequence or product the role of no single factor can be isolated completely from that of the others; but in Hawaii, because of the unusually sharp regional to local variation in each, the "weight" of individual factors in explaining local situations can be assessed reasonably well.

Whereas desilication appears to be the rule in the Hawaiian weathering picture, resilication may be locally important where movement of silica is temporarily halted and silica is reconcentrated as it moves outward from the center of a "fresh" boulder core, upward by capillary movement in a soil profile, or downward along a stream course. In such situations Al-Fe hydroxides or gels may be reconverted to Al-Fe-Si gel material or clay minerals prior to ultimate removal of the silica.

The nature and products of rock weathering in Hawaii have been discussed previously by a number of workers, among them Hinds (1929); Palmer (1931); Hough and Byers (1937); Wentworth, Wells and Allen (1940); Hough, Gile and Foster (1941); Sherman and his co-workers in a number of papers (*e.g.* Sherman, 1950, 1958; Sherman and Uehara, 1956; Tanada (1951); and Tamura, Jackson and Sherman (1953). Abbott (1958) provides excellent data on the formation of gibbsite on the Island of Kauai.

Acknowledgments

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GENERAL PATTERN OF WEATHERING IN HAWAII

Although the present paper deals primarily with the formation and interrelationships of halloysite and gibbsite, it is pertinent to consider the distribution and importance of these two weathering products in the light of the overall pattern of weathering. Since most weathering in Hawaii is chemical in nature and results from the action of solutions upon the parent rock, the amount and location of various mineral alteration products depend primarily upon the amount and seasonal, as well as geographic distribution of rainfall. The five largest islands—Kauai, Oahu, Molokai, Maui and Hawaii—all have extreme variation in geographic distribution of annual rainfall ranging from 0–20 in. along the leeward (southwest) coast to 200–400 in. in the mountains. Within a few miles, therefore, vegetative cover changes from rain forest to cactus and the depth of rock weathering varies from many tens of feet to inches. Where the mountains rise above about 8,000 ft (as do Haleakala on Maui, and Mauna Loa and Mauna Kea on Hawaii) precipitation takes place part way up the slopes and mountain tops are dry, reversing the usual trend of increased weathering with higher elevation.

Since the prevailing trade winds are from the northeast, the mountains and upland slopes on this side of each major island are bathed in rain throughout most of the year with the result that rocks and weathering

profiles are continuously wet and the leaching process uninterrupted. In contrast the leeward side of each island receives abundant rainfall only when low pressure areas sweep across the islands from the West bringing the so-called Kona weather. This is seasonal in nature, being most common from October through April. Because of the torrential nature of many of the Kona rains, erosion is very great particularly on the otherwise "dry" side of each island where there is lack of protective vegetative cover; and much material, produced by many years of weathering, may be swept to sea in a few hours.

Much of each island is, of course, in an intermediate situation between the "continually wet" and "very dry" extremes. Here the rock and soil above the water table are in an alternately wet and dry condition and weathering is rapid.

For the Islands as a whole, there are fairly obvious relationships between annual rainfall, amount of leaching, removal of silica and bases, and nature of weathering products. Some of these relationships express themselves in the resulting residual soils and are taken account of in the classification of Hawaiian soils into different great soil groups (Cline *et al.*, 1955, pp. 89-95). Insofar as broad mineral groups are concerned: (1) dry areas where leaching has not yet removed all bases are characterized by the presence of montmorillonite-group clay materials; (2) areas sufficiently wet to permit leaching of bases but not all silica will have abundant halloysite and allophane; and (3) areas continually wet or alternately wet and dry for long enough periods of time to allow removal of silica will consist either of hydrated alumina and aluminum-iron gel material, or laterite and gibbsite if dry periods have been involved. Considerable overlapping is, of course, expected and found, owing to the abundance of halloysite and allophane in area 1 and continuous gradation from 1 to 3; but only an unusual set of circumstances would produce gibbsite in area 1 or montmorillonite in area 3.

Areas representative of the type 1 situation are the Kona coast of Hawaii, the Ulupalakua and Lahaina areas on Maui, the Aina Haina to Makapuu coast of Oahu, and the Kekaha region on Kauai. Here the soil is commonly thin and rock exposures are fresh. Weathering is directly and obviously related to texture with the permeable clinker, cinder and ash beds being most affected. Montmorillonite, halloysite and allophane formed at the surface are commonly moved downward either through the rocks in colloidal suspension or on the surface during heavy rains. Thus, some of the so-called dark, magnesium-montmorillonite clay concentrates found at various places on Oahu and near Kekaha, Kauai, occur in alluvial sediments formed where intermittent drainage has brought weathered material with a high content of montmorillonite from adjoining higher slopes and concentrated it in drainage "catch basins." The holes and cracks of fresh to partly weathered vesicular basalt rocks in dry areas commonly are filled

with waxy yellow, brown, to red montmorillonitic clay. Evidence that clay colloids are carried hundreds of feet through fissures and pores of fresh rock is afforded in many of the tunnels driven into the mountains to tap water trapped in the rocks. Seepage water from the surface often coats the tunnel walls with the orange, brown to yellow or cream-colored gel and clay having the consistency of mayonnaise.

Since the gradation between types 1 and 3 is continuous, the geographic areas representing type 2 situations lie between the dry and wet portions of the Islands. Thus, on Maui, in passing from the dry Ulupalakua district to the gibbsite-rich Haiku area an intermediate zone having abundant halloysite but little to no gibbsite or montmorillonite is traversed. The same situation exists throughout the Islands along such sections as Kekaha to Kilohana crater on Kauai, Waihee, to Kahekuloa on Maui, and various traverses from base to summit of the Koolau Mountains on Oahu.

Examples of areas that have received enough rainfall to permit production of significant amounts of gibbsite in surface horizons include much of Kauai east of the mountains dominated by Waialeale, the northeast portion of West Maui and Haiku district of East Maui, the Hamakua coast of Hawaii, and the upper slopes of the Koolau range on Oahu. All these areas receive 100 in. or more of rainfall per year with the exception of those on Maui where there are indications of a wetter climate in former years where the rainfall is now 30–100 in. Within these areas, of course, other factors cause local variation in the type and amount of end products.

WEATHERING ON WEST MAUI

Introduction

Of the many areas that might be used to provide data as to the formation of halloysite and gibbsite from parent materials, that along the northeast coast of West Maui has been chosen as the most suitable. The road between the coastal villages of Waihee and Kahakuloa roughly parallels the coast at distances of 0.1–1.0 miles inland of the 100–500 ft sea cliffs which border the island in this area. Between the two towns, which are at sea level, the road climbs to a maximum elevation of 1000 ft in the interfluvial area. Road cuts are plentiful and provide excellent opportunity for studying and sampling all stages in the alteration of parent rock to soil.

Geologic and Climatic Setting

The western part of the Island of Maui is an elliptical volcanic complex about 18 miles long in a north–south direction and 12 miles wide. The land surfaces slope upward at an average gradient of 600–1200 ft per mile to culminate in the 5788 ft peak, known as Puu Kukui, which lies just south

of the center of the ellipse. Extensive dissection has produced steep V-shaped valleys which radiate like spokes from the center outward. Near the periphery they are separated by broad interfluvial areas sloping gently toward the sea; whereas at the higher elevations the topography is a rugged combination of precipitous canyons and steep-sided mountains, some of which are capped by narrow to broad, undissected upland swamps maintained by perched water tables and high rainfall.

Annual precipitation at the summit of Puu Kukui is over 350 in., whereas at the town of Lahaina just six miles away on the leeward (west) coast the figure is 15 in. Along the northeast or windward coast in the area to be discussed, the rainfall increases from 30 to 50 in. per year from the town of Waihee at the south to the village of Kahakuloa approximately five miles to the north.

The rocks exposed on West Maui consist of the Wailuku, Honolua and Lahaina volcanic series. In the area to be described herein the Lahaina series is absent, and thick, well exposed flows of the Honolua andesite overlie those of the older Wailuku basalt. Although the descriptions to follow deal with the weathering of the Honolua, Table I is included to illustrate the compositional variation found between adjacent flows of two different series. Obvious differences may be noted in Si, Fe, Mg, Ca, Na, and K content. According to Macdonald (Stearns and Macdonald, 1942, p. 316) the rocks differ mineralogically in that a typical Honolua oligoclase

TABLE I.—REPRESENTATIVE CHEMICAL ANALYSES
OF TWO WEST MAUI ROCK TYPES

	Wailuku ¹	Honolua ²
SiO ₂	47.72	59.74
Al ₂ O ₃	15.44	18.86
Fe ₂ O ₃	0.23	1.94
FeO	9.52	3.75
MgO	11.31	0.90
CaO	10.23	3.00
Na ₂ O	2.31	7.33
K ₂ O	0.63	2.89
H ₂ O ⁺	0.46	0.12
H ₂ O ⁻	0.05	0.26
TiO ₂	1.81	1.02
P ₂ O ₅	0.15	0.26
MnO	0.16	0.13
Total	100.02	100.20

¹ Olivine basalt, Wailuku volcanic series. Stream boulder, Iao Valley; M. G. Keyes, Analyst (Washington and Keyes, 1928, p. 203).

² Oligoclase andesite, Honolua volcanic series. Stream boulder, Iao Valley. M. G. Keyes, Analyst (Washington and Keyes, 1928, p. 203).

andesite will have approximately 80 percent oligoclase, 10 percent olivine and pyroxene, 8 percent iron oxides and a little biotite, amphibole and apatite; whereas the Wailuku olivine basalts of the composition tabulated may have about 40 percent feldspar of labradorite composition, 15 percent olivine, 36 percent pyroxene, 8 percent iron oxides and a little glass.

The texture of comparable flow units of the two rock types is quite different with the result that the rate and pattern of weathering differ in the uniformly dense, fine-grained, trachytic Honolua as compared to the more inhomogeneous, normally coarser, more vesicular Wailuku. In the latter, the more permeable portions of the flow weather more rapidly, leaving "interfluvial" areas which are gradually trimmed by enveloping solutions to the rounded boulders characteristic of "spheroidal weathering." The distribution of the boulders depends somewhat on accessibility of the descending solutions to different parts of the exposed flow but more upon textural variation within the flow itself. With respect to relationships of texture to permeability, it is important to note that the most porous rocks are not necessarily the most permeable, and as a result the unweathered cores of spheroidal boulders may be highly vesicular.

In the Honolua, particularly as illustrated along the Waihee-Kahakuloa road, solutions from above tended to be channeled into definite planes diagonal to top and bottom surfaces of the flow which intersect, on the typical road-cut exposure surface, in a pattern of triangles of varying size and shape (Plate 1). As the corners of the triangles become rounded, spheroidal boulders are, of course, produced; but their distribution in this case is different from that in the Wailuku reflecting as it does the "drainage" pattern of solutions more or less unaffected by local textural differences in the rock. The solution channels are sharply marked because, as areas of most effective leaching and redeposition of colloidal material, they become the sites for veins of pure to Mn-stained, often porcelain-type halloysite which subsequently may change to gibbsite where conditions are appropriate.

Field Relationships

Fig. 2 shows, in a somewhat generalized way, the various stages of alteration of the Honolua andesite as illustrated in the area mentioned. The first stage, represented in the section at the left, shows the incipient stages of weathering observed at the "dry" end of the traverse a mile or two north of Waihee. Thin veinlets of halloysite have developed along fractures which penetrate from the surface into the bulk of the formation. In the upper part some of the feldspar has weathered to halloysite leaving the rock more soft and powdery and providing clay material to the downward moving solutions. Farther down, the secondary, vein halloysite is in sharp contrast to fresh rock (F) on either side. The vein material varies from

smooth, porcelain-type clay to that having a sandy to pebbly texture. In contrast to later stages of development, local concentrations of manganese are not yet evident.

Throughout the weathering process, solutions from above not only follow the fractures but percolate through the entire rock mass. One important result is that these permeating solutions move leached elements outward from inside the triangular areas toward the veins. In cases studied this outward movement appears to be more evident and important than the effect of solutions from the vein penetrating into the rock. However, although predominant flow of active leach solutions is from rock toward veins, the

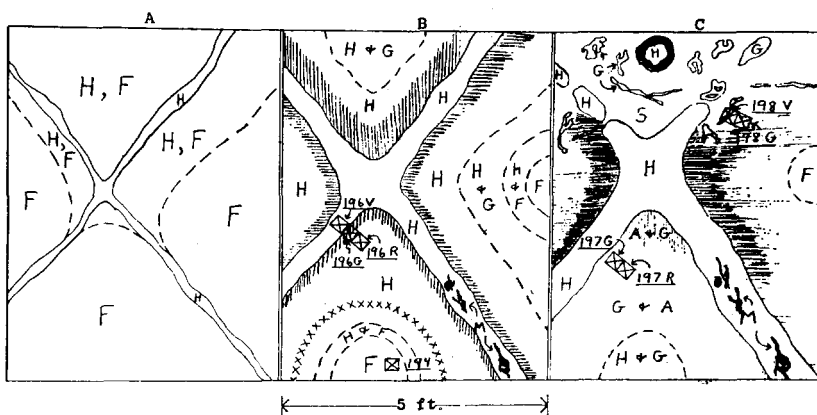


FIGURE 2.—Alteration stages in the weathering of the Honolua andesite. (F, fresh rock; H, halloysite; G, gibbsite; A, amorphous; M, manganese oxides; S, "soil"; $\times\times\times\times$, high Si and Fe; shaded areas, gray to black "waxy" material.)

extent to which alteration has affected the fresh rock will, in part, depend on other factors such as distance from solution channels and ion concentration in solutions carrying leached material from above.

In a somewhat higher and wetter area farther north along the road weathering has produced relationships like those represented in the center section of the figure. Halloysite veins have widened considerably and commonly contain spotty concentrations of black manganese oxides (M). Except for this material the vein clay appears very pure and has the typical snow-white to blue porcelain appearance with vitreous luster and conchoidal fracture. Moist samples prove to be of the $4\text{H}_2\text{O}$ variety. In the bottom quadrant of the area a core of unweathered andesite (F) is surrounded by a broad area of partly altered rock in which halloysite and in some cases a little allophane, is pseudomorphous after feldspar. Within such areas rings concentric to the unweathered core are often set apart from the surrounding material by difference in color or hardness, or both. These rings, cross-sections of concentric shells, arise by outward diffusion and reprecipi-

tation of Si and Fe. [Numerous examples of spheroidal weathering, throughout the Islands, indicate that the width and number of weathered shells concentric to the core of a boulder (or irregular inter-channel rock mass such as those pictured in Plate 1) are determined by the varying concentration of the leached elements (primarily Si and Fe) as they diffuse outward through the rock.] Adjacent to the vein (Fig. 2, B) may often be found a gray, "waxy" zone characterized by halloysite and a high allophane concentration, and by a more "dense" appearance than the material nearer the core. Thin sections show that the zone differs from the adjacent weathered rock in that pores have been filled with clay and gel material coming either from the adjacent vein or possibly precipitated from solutions diffusing toward the veins.

In the upper part of the section (Fig. 2, B) where more silica has been removed and none is available from the already leached area above to keep solutions saturated, weathering has proceeded farther changing the former core of fresh rock to halloysite and the latter, in part, to gibbsite as silica moves out. The gray waxy area is broader and darker in color due primarily to precipitation of iron and manganese from outward-diffusing solutions. The right side of Fig. 2, B, pictures an intermediate situation where the rim of the feldspathic, fresh core is altering to halloysite, solutions are changing the halloysite in the adjacent shell to gibbsite, and the next outer shell is still halloysite because further desilication has been prevented by the high silica content of solutions moving outward from the adjacent inner zone.

As leaching progresses further (Fig. 2, C) the upper part of the profile finally is changed almost completely to iron and aluminum oxide and hydroxide material while the lower part still contains some silica. Exposures of such a situation often show a sharp demarcation between the upper part which is yellow to orange and red due to iron oxidation and the bottom part which is still gray. In the bottom section of the illustration the feldspathic core has altered completely to halloysite and gibbsite while the remainder of the rock consists largely of gibbsite and hydrated amorphous Al-Fe material with possibly some allophane. As is the case at other stages of the process, Si and Fe increase (relative to Al) away from the core toward the vein. X-ray, DTA and light microscopy (Plate 2, A) show that sample 197G has more halloysite and allophane and less gibbsite than sample 197R. Former pores are filled with yellow amorphous material, and the gray to black hand specimen is very waxy in appearance.

In the final stage (upper part of Fig. 2, C) the black, waxy material becomes veined and pocketed with streaks and patches of yellow to orange-brown amorphous, gel-like material which grow in size at the expense of the dark matrix. These new veins vary from barely visible stringers to areas an inch or two in width, and pockets may be greatly enlarged at the

intersections of veins. Upon dehydration much of the yellow to orange gel crystallizes to porous veinlets and nodules of gibbsite (Plate 2, B) whereas some appears simply to harden to Al-Fe mineraloid material having the properties and appearance of the substance sometimes called clachite. Sample 198V consists of a gibbsite concentration adjacent to the black, waxy material of sample 198G which, in turn, still contains a large amount of silica in the form of halloysite and allophane. On drying, the black, formerly waxy, matrix material becomes very crumbly taking on the characteristics of a soil (*S* in diagram). In fact, it is probably in this manner that many of the gibbsite-rich soils of the islands are developed since the gibbsite stringers, irregular nodules and "boxwork" structures found in the soils have direct counterparts in the textures produced by the veining and "pocketing" of the black, waxy material with concentrations of Al and Fe-Al gel. If the process occurs in a high-rainfall area where dehydration does not take place, the material remains in the hydrated state and solutions percolating through the soil may become heavily loaded with colloidal, orange-colored gel material of the type commonly found flocculated in the quiet waters at the edge of streams in such areas.

As indicated in Fig. 2, C (right and bottom) unaltered or partly unaltered boulder "cores" are not infrequent in the most weathered portion of such profiles and even in deeply weathered soil, their existence being due probably to a combination of factors including original textural difference, distance from solution channels and formation of "protecting" shells. An interesting characteristic of the weathered Honolulu material is the presence of halloysite "nodules" (Fig. 2, C, top) in the crumbly, dried out, black matrix material. These vary in size from less than 1 in. to 5 or 6 in. and appear simply as unusually hard concentrations of black, waxy material until broken open to expose highly fractured, blue to white, porcelain halloysite. An X-ray pattern of one of these revealed that it retained the water of $4\text{H}_2\text{O}$ halloysite even though the material outside the nodule had dried out. Former portions of the halloysite veins also retain their halloysite long after surrounding material has broken down, presumably due to the fact that they represent unusually dense concentrations of high silica content. The initial and final stages in the gibbsitization of a halloysite vein are illustrated in Plate 2, C and D.

Microscopic Relationships

Light and electron micrographs illustrating various aspects of the transition from feldspar to halloysite, and halloysite to gibbsite are shown in Plates 3 and 4. Alteration of the feldspar crystals commonly begins in the central, more calcic portion of the lath and is evidenced in the light microscope by loss of birefringence. Isotropic veinlets soon breach the surrounding

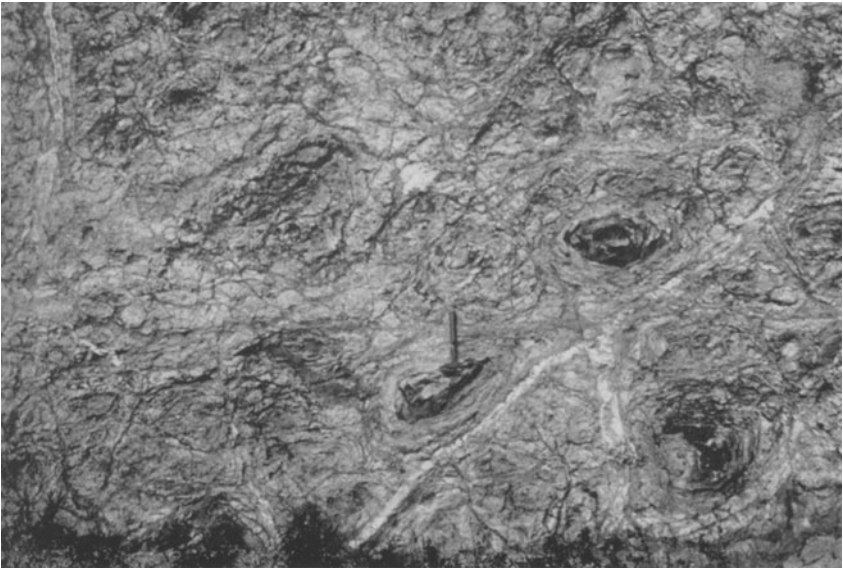


PLATE 1.—Weathered Honolua andesite, West Maui. Top of road cut is 3 ft above top of photograph.

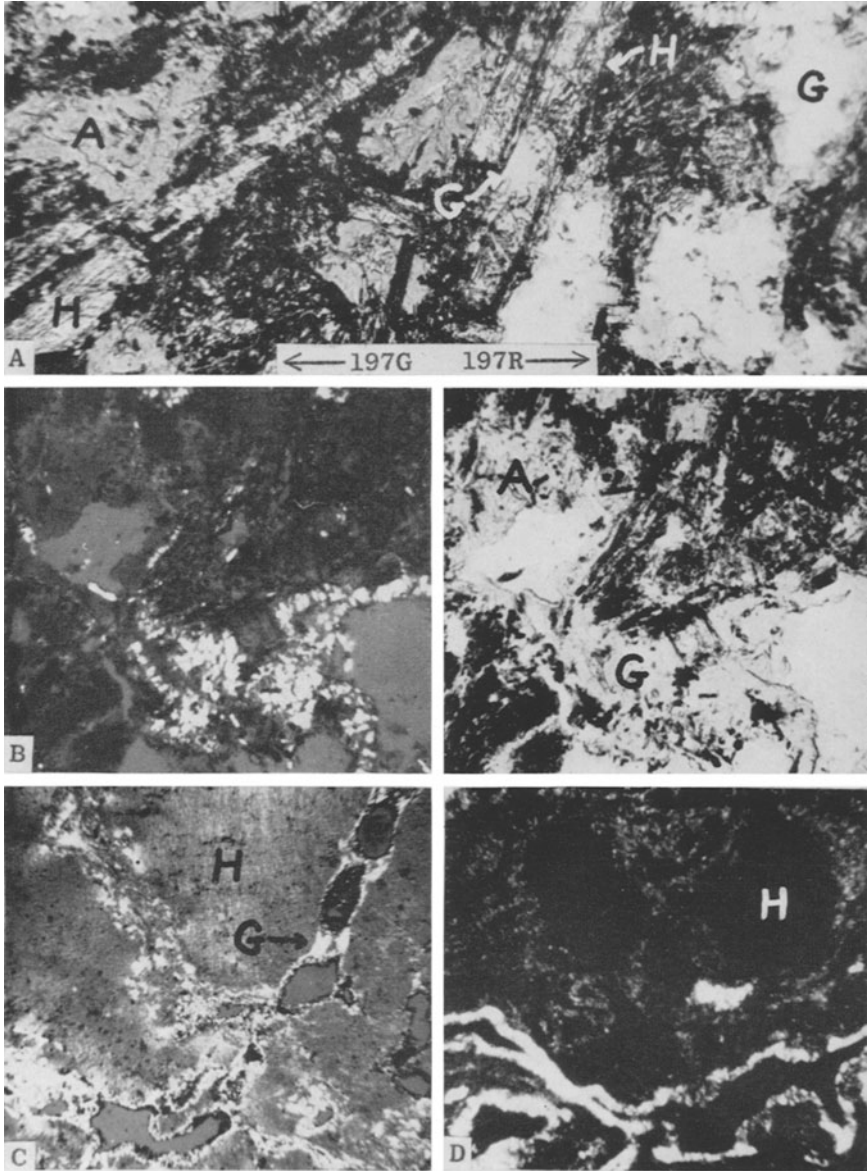


PLATE 2.—Light micrographs illustrating changes during weathering. (G, gibbsite; H, halloysite; A, amorphous.) (A) Transition from gibbsitized (197R) to non-gibbsitized rock (197G) still containing halloysitized feldspar laths and amorphous Al-Fe-Si gel material. Nicols at 75°. $\times 178$. (B) Change of amorphous material to gibbsite. Area at A is still amorphous; that at G is now crystalline gibbsite. Left: Nicols at 75°; right: plain light. $\times 80$. (C) Gibbsite forming from vein halloysite. Nicols at 75°. $\times 35$. (D) Largely gibbsitized halloysite vein. Black areas (other than at H) are holes. Nicols crossed. $\times 32$.

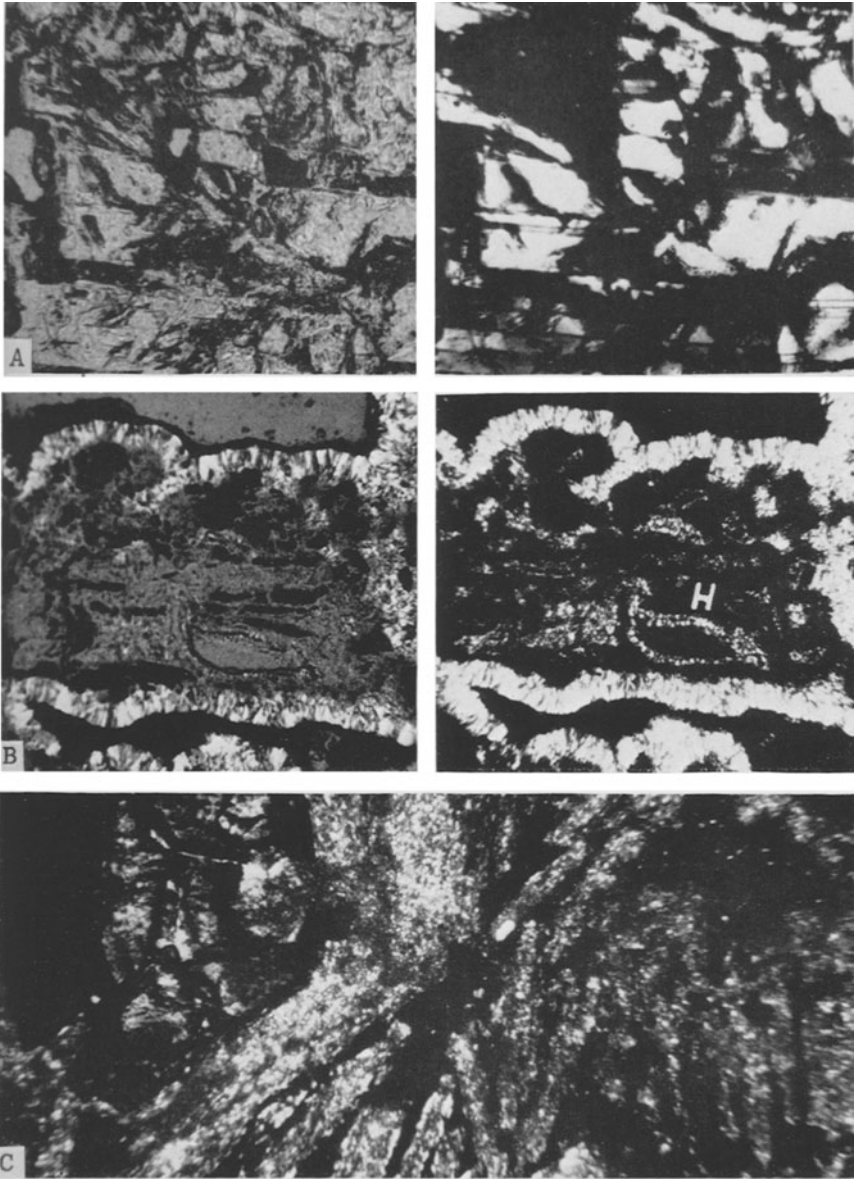


PLATE 3.—Feldspar—halloysite—gibbsite transitions. (A) Partial change of birefringent feldspar to isotropic halloysite. Left: plain light; right: Nicols crossed. $\times 30$. (B) Gibbsite (white) forming in halloysitized feldspar lath (H) and by precipitation at edges of holes and fissures. Black areas at left are Fe oxides. Left: Nicols at 75° ; right: Nicols crossed. $\times 130$. (C) Completely gibbsitized feldspar laths. Black areas are Fe oxide. Nicols crossed. $\times 180$.

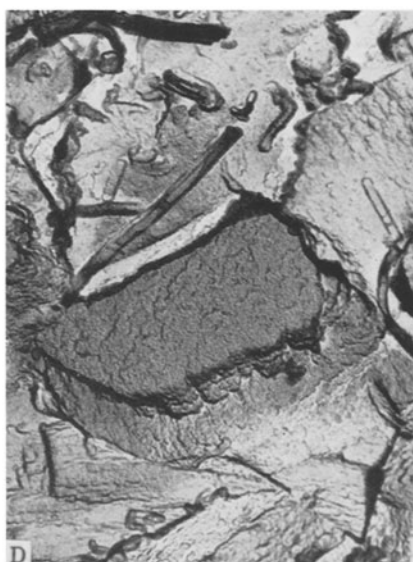
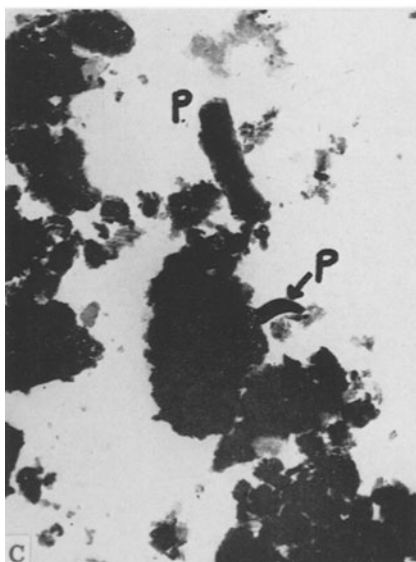


PLATE 4.—Electron micrographs ($\times 18,800$). (A) Halloysite formed during first stage of weathering of feldspathic Honolua andesite. (Pt-C replica.) (B) Halloysite and allophane from clay-filled solution channel. (Pt-C replica.) (C) Electron-diffraction-amorphous pseudomorphs of halloysite tubes from allophane-rich sample 197G. (D) Gibbsite with possible pseudomorphs of halloysite tubes. Similar forms from this sample give single crystal electron diffraction patterns of gibbsite.

envelope of apparently unaltered birefringent feldspar (Plate 3, A) and in subsequent stages the entire lath becomes isotropic. Electron micrographs indicate that the halloysite formed at this stage (Plate 4, A) consists of poorly developed, short tubes without obvious preferred orientation. Better crystallinity is in evidence in the halloysite in adjacent fissures (Plate 4, B). Here tubes are longer and some curved laths are apparent. Study has not yet established whether any of the poorly crystallized clay replacing feldspar can properly be called allophane. Spherules typical of this material are common in many of the micrographs but may not be derived from the feldspar since allophane is a common product of alteration of the glassy component of the rocks. X-ray patterns of the first stage of feldspar alteration show the typical halloysite characteristics.

As the leaching solutions continue to remove silica, tiny birefringent specks of gibbsite appear in thin section in the isotropic, halloysitized feldspar laths. As the new crystals increase in number, holes appear in the lath, presumably as the result of the loss of silica. Subsequently, these holes and adjoining fissures may become coated and possibly filled with gibbsite precipitated from solution (Plate 3, B). This latter type of gibbsite is readily distinguished from that resulting from desilication of halloysite by its occurrence in larger crystals commonly aligned in parallel or near-parallel orientation.

Plate 3, C shows one type of end product of the alteration process wherein the feldspar laths have been changed completely to gibbsite.

Initial electron microscope and diffraction studies provide some evidence as to the nature of the halloysite-gibbsite transition in these samples. Pictures such as C and D, Plate 4, of gibbsitized halloysite show that some tubular structures are preserved but most are lost in the process. Since the birefringent gibbsite specks seen in a halloysite background in the light microscope are much larger than individual halloysite tubes, both light and electron microscopic studies indicate that the change of the bulk of the halloysite to gibbsite involves more atomic rearrangement than the simple removal of the silica sheet from the halloysite tubes.

Similar conclusions may be drawn from electron diffraction patterns of pseudomorphs of single tubes found in electron microscope fields of sample 197G and 198V (Plate 4, C and D). The former represents the gray waxy zone residual after the parent rock but now characterized by the presence of Al-Fe-Si gel material (Plate 2, A) and not yet completely gibbsitized; whereas the latter represents the end product consisting only of gibbsite. As the micrographs indicate, the alteration process obliterates most of the structures characteristic of the clay; however, occasional bent but recognizable pseudomorphs of halloysite tubes remain. In the transition sample 197G, single crystal electron diffraction work on these relics yields no patterns, thereby indicating that the crystallinity of the original halloysite

has been lost and the somewhat battered-looking former tubes are now electron-diffraction-amorphous. In contrast, from pseudomorphs in sample 198V, single crystal patterns of gibbsite are obtained. Thus, in these particular samples, it appears that an intermediate phase, amorphous to the electron beam, is part of the transition from halloysite to gibbsite. It has not yet been established whether any "memory" of the arrangement of the aluminum atoms in the original halloysite is involved in the development and orientation of the single crystal of gibbsite from the same tube. As in most other cases involving the alteration of one substance to another, the significance and amount of "intermediate-stage" material probably varies considerably depending upon local conditions. In this particular set of samples a recognizable, amorphous intermediate stage is evident.

Summary

For the example described in the previous pages the evidence indicates that the weathering process is primarily one of desilication complicated by temporary reconcentration of the silica as it moves out of the rocks. The oligoclase feldspar of the highly feldspathic Honolua flows loses its alkalis and some of its silica, and gains OH and H₂O to become halloysite (4H₂O). No evidence of an intermediate mica stage has been observed, and it is for this reason—in the opinion of the author—that no kaolinite is formed. Under continued leaching the halloysite loses its silica and, if conditions of humidity are correct, changes to gibbsite. As part of this change an intermediate amorphous state does occur, as established by electron diffraction studies of individual, somewhat distorted, elongate particles pseudomorphous after halloysite tubes. The relationships suggest that, as the silica is removed, the material changes from halloysite through the allophane composition range to Al-gel. Subsequent dehydration to gibbsite will depend upon local conditions of humidity. Detailed questions as to the chemical character, importance, longevity and necessity of the intermediate phase cannot now be answered.

CONCLUSIONS

The Hawaiian Islands provide an excellent laboratory in which to study the tropical weathering of basic igneous rocks and the formation of clay minerals, iron and aluminum oxides and hydroxides, and mineral gels. Short-range variation in rainfall, slope, rock composition, texture, and age—plus easy accessibility to exposures in large portions of the area—make it possible to evaluate the relative importance of the variables that are involved in weathering processes now in operation.

Weathering in Hawaii is largely a process of desilication. As silica, together with bases, is taken into solution and removed to the sea, the primary

silicates change to clay minerals (largely halloysite, allophane and nontronite) and ultimately to oxides and hydroxides of Fe, Al, and Ti. Gels produced largely by the hydration of volcanic glass are common in wet areas and, in places, dry out to form similar oxide and hydroxide end products. Locally the process of desilication is interrupted and even reversed where dry conditions, impounding of Si-rich solutions, or variations in rock composition and texture impede the attack of rain water and leaching solutions.

Figure 1 summarizes the mineral changes observed in the weathering of feldspar, glass and olivine of the parent rocks. Optimum leach conditions (solid arrows) for sufficient time produce the Al and Fe end products shown at the bottom of the chart. As part of the process, development of intermediate products is the usual step, though perhaps not a necessary one. The abundance and "longevity" of intermediate products varies with local character of the rocks and climate. Mg minerals are common only in dry areas, gibbsite only in regions of moderate to high rainfall. Halloysite is common in both since it represents the first stage of feldspar alteration and is the last crystalline intermediate to retain its silica. Kaolinite is not evident as a weathering product, probably because its common paty progenitors, muscovite and the fine mica formed from K-feldspar alteration, are not common in the Islands.

Gibbsite forms in at least three ways in Hawaii: (1) by removal of silica from halloysite; (2) by dehydration of Al and Fe-Al gels; and (3) by precipitation from Al-rich solutions. All three are common and often evident in a single thin section of a weathered rock. However, in contrast to types 1 and 3, type 2 is to be expected only where desiccation has been possible either through surface exposure or the advent of dry climatic conditions.

Gel material plays an important role in the weathering picture, the greatest quantities being most easily accounted for as a product of alteration of the volcanic glass. Detailed study of samples described herein shows that amorphous material—probably ranging in composition from that of halloysite through allophane to Al-gel—is also produced as an intermediate state in the change of halloysite to gibbsite.

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