

HYDROTHERMAL ORIGIN OF THE CLAYS FROM THE UPPER SLOPES OF MAUNA KEA, HAWAII

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Abstract—The soils of the summit region of Mauna Kea are similar to the soils of the high mountain deserts and to the soils of cold deserts. Dramatic differences, however, exist between the soils of the summit and other neighboring cones and the soils of the glaciated terrain. The soils of some of the cones of the summit area are clay rich and contain phyllosilicate minerals; the soils of the glaciated terrain are sandy and contain X-ray amorphous clay. Montmorillonite and a Mg-rich trioctahedral mineral identified as saponite are the clay minerals of the summit. Because the summit area of Mauna Kea supported an ice cap at the time of the formation of the cones, the origin of the smectite minerals could have resulted from the alteration of the tephra by steam and water released in the melting of the ice. Hypogene fluids are, however, more likely to be responsible for the genesis of the phyllosilicate minerals.

INTRODUCTION

The soils of the summit region of Mauna Kea (Fig. 1) are analogous to the soils of the high mountain deserts of the world and similar to the soils of the cold deserts of the polar regions. The climate of the high elevations of Mauna Kea, a dormant volcano rising some 4200 m above sea level, is cool to cold and extremely dry, with nocturnal freezing temperatures throughout the year (Raine, 1934; Woodcock *et al.*, 1966; Tagliaferro, 1971). Bioclimatically, the mountain top has been defined as a semi-arid, barren alpine desert tundra (Mueller-Dombois and Krajina, 1968) characterized by a very low density of vascular plants. Pleistocene ice caps have repeatedly covered the summit area and recent work of Porter (1970) indicates that three and possibly four episodes of glaciation can be recognized.

The soils above 3500 m and formed on glacial deposits are poorly developed: they lack an organic surface layer, have a desert pavement, show coarse texture and display below the desert pavement a brown yellowish-red horizon. Similarly, in general terms, their chemistry and mineralogy indicate incipient weathering as manifested by small clay content and the dominance of X-ray-amorphous colloids over crystalline material. These characteristics are expected considering the severe bioclimatic environment, the age, and the volcanic nature of the terrain. Notably, exceptions are found with respect to texture and mineralogy. The exceptions occur on the summit of Mauna Kea, Douglas Cone, Puu Waiiau, and other sites on the north side of the summit (Fig. 1). In these areas the soils show dramatically different texture and mineralogy, indicating a more advanced stage of weathering

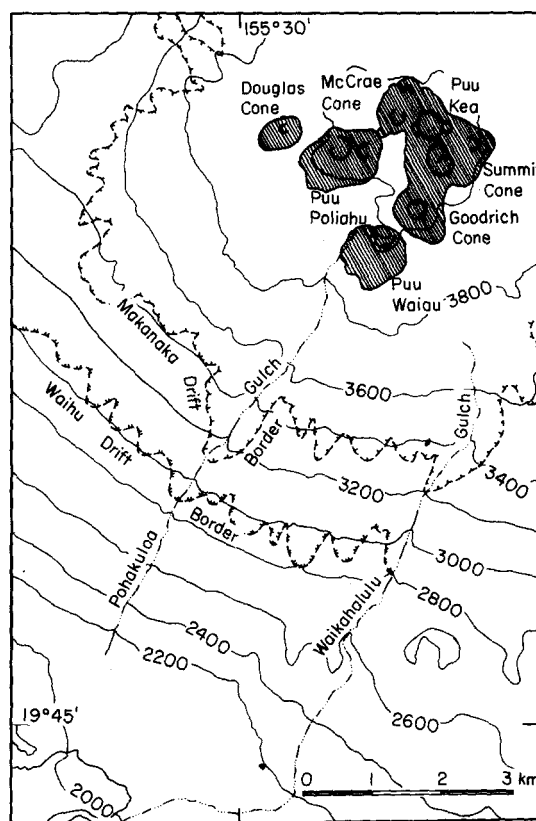


Fig. 1. Map of the south slopes of Mauna Kea showing the pyroclastic cones on the summit plateau (shaded), and the limits of the Makaanaka and Waihu ice caps. Contours are in meters (modified after Porter).

than the rest of the soils derived from the Makaanaka glacial drift, the youngest recognized glacial deposit (Porter, 1971).

The occurrence in the same area of these different pedological conditions conjures curiosity and asks for explanations. Three explanations can be offered: (1) the summit area has experienced formerly different climates than the present, and the soils containing phyllosilicates are relict, (2) the weathering has taken place under the present subaerial conditions or when glacial water was plentiful, and (3) hydrothermal alteration has occurred induced by volcanic eruptions. The first explanation could not be very well substantiated. The cluster of cones in the summit area are penecontemporaneous with the next to last glaciation (Porter, 1972), and in the summit area (Woodcock *et al.*, 1966) as well as at lower elevations (Ugolini and Bockheim, 1972), there is no evidence that the climate has been markedly different, except perhaps wetter, than in postglacial time. Although evidences have been presented for intense chemical weathering and clay formation in alpine areas (Reynolds, 1971), the cool-xeric conditions of the upper slopes of Mauna Kea are far from the maritime glacial environment of the high Cascade Mountains reported by Reynolds (1971). The case for weathering by glacial water is also untenable. The entire summit area has been glaciated and permeated by water discharged from the wasting of an ice cap. Chemical leaching and alteration should have occurred extensively and not only been restricted to scattered areas in the summit cones. The occurrence of phyllosilicates is most reasonably ascribed, then, to hydrothermal alteration.

Clay formation as the result of hydrothermal action has been reported in connection with metallic ores, hot springs, geysers and fumarolic emanations (Grim, 1968; Millot, 1970). Montmorillonite and smectites in general, have been identified and ascribed to relatively slight hydrothermal alkaline conditions and presence of ferromagnesian minerals, plagioclase and alkalis, and alkaline earth ions, except potassium (Grim, 1968). The argillation at the summit of Mauna Kea could have been produced (1) by the emanating hydrothermal solution and/or (2) by the percolating waters released by the rapid melting of glacial ice on the still-hot cinders or melting of intergranular ice in permafrost. According to Porter (1972), concomitant with the presence of the summit ice cap, possibly during the Early Wisconsin, subglacial eruptions induced extensive melting as exemplified by widespread ice-contact lava flow margins. Presence of permafrost containing intergranular ice has been reported in the crater of the summit and other cones (Woodcock *et al.*, 1970). Field evidence seems to indicate that processes 1 and 2 may

have operated. At Puu Waiiau, Puu Kea, Douglas and Summit Cones, the phyllosilicate-rich zone is found inside the crater. On the other hand, a fissure vein cutting across beds of unaltered cinders and containing clay is visible in the upper part of the Summit Cone. This vein may represent the fissure through which volcanic emanations intruded and altered the tephra. More extensive observations and borings are required for establishing the origin of the hydrothermal alteration.

Morphologically, the soils derived from the hydrothermal deposits differ from the soil formed on glacial debris. The former have a clay texture responsible for the formation of a surficial crumb structure common to grumosols and vertisols (Hallsworth *et al.*, 1955). These soils have also a more reddish color and hold more moisture than the soils derived from the glacial deposits. A soil profile from the Summit Cone (Profile 17) shows that only the upper 15 cm have been affected by pedogenesis and periglacial conditions; below this thickness, one encounters a variegated, clay-rich soil, massive with pseudomorphs, apparently weathered *in situ*.

METHODS

The $<2 \mu\text{m}$ clay fraction was separated from soils derived from glacial debris (Profile 3) as well as from the soils derived from hydrothermally altered tephra from the summit cone (Profile 17). The clay fraction of samples 3-2 and 17-5 was deferrated according to Mehra and Jackson (1960), saturated with Mg, and glycolated. A clay aliquot from sample 17-5 was K saturated and heated at 550°C for 2 hr. The Greene-Kelley (1955) test and the determination of the 06 spacing (Rich, 1957) were performed for establishing the presence of trioctahedral phyllosilicates. X-ray studies used a Picker unit with $\text{CuK}\alpha$ radiation and a Ni filter; the unit was operated at 30 kV and 20 mA. Aliquots of untreated clays were equilibrated at 56 per cent r.h. and thermally analyzed with an Aminco thermoanalyzer.

Cation exchange capacity for the clay of sample 17-5 was determined at pH 7, after Jackson (1956), and for the clay of sample 3-2 at pH 4 and 8 following the procedure of de Villiers and Jackson (1967).

Elemental analysis was performed according to Kanehiro and Sherman (1965).

Silicon was determined colorimetrically by the molybdosilicate yellow method (Jackson, 1956); iron with orthophenanthroline (Jackson, 1956); aluminum colorimetrically (McLean, 1965); and magnesium by atomic adsorption.

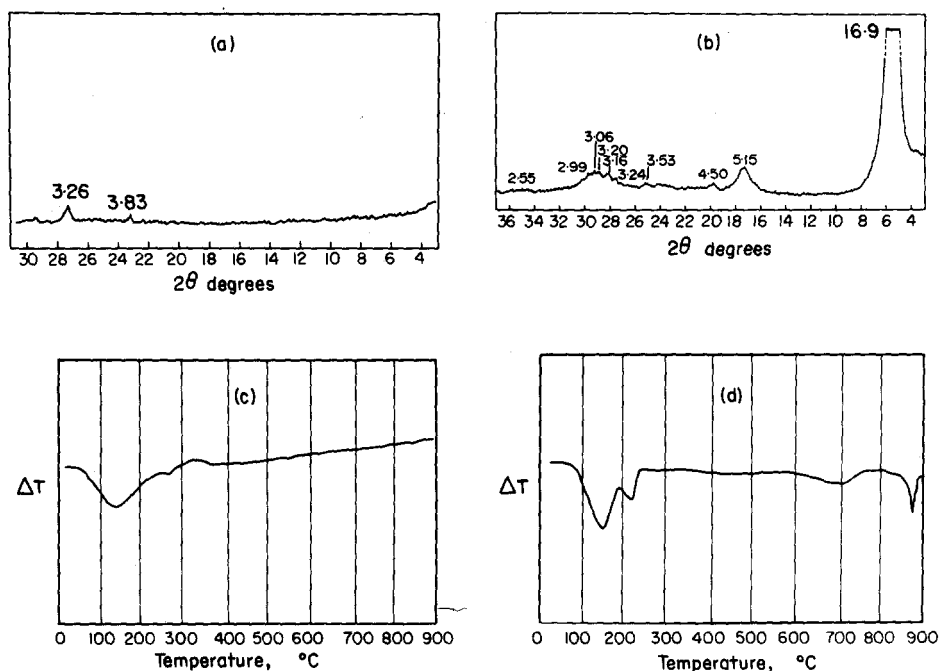


Fig. 2. X-ray diffraction patterns and differential thermograms: (a) X-ray diffractogram of Mg-saturated $<2.0 \mu\text{m}$ clay fraction (oriented mount). Glaciated plateau, sample 3-2, Mauna Kea, Hawaii. (b) X-ray diffractogram of Mg-saturated $<2.0 \mu\text{m}$ clay fraction (oriented mount). Summit, sample 17-5, Mauna Kea, Hawaii. (c) Differential thermogram of clay ($<2.0 \mu\text{m}$). Glaciated plateau, sample 3-2, Mauna Kea, Hawaii. (d) Differential thermogram of clay ($<2.0 \mu\text{m}$). Summit sample 17-5, Mauna Kea, Hawaii.

RESULTS AND DISCUSSION

The clay fraction from the glacially derived soil (Profile 3) consists of amorphous material except for clay-size feldspars (Fig. 2a). Differential thermal analysis (Fig. 2c) also reveals the absence of phyllosilicate minerals in addition to indicating the presence of hydrated amorphous material. In contrast to these results, the clay derived from the hydrothermally altered tephra (Profile 17) appears to be dominated by crystalline components, namely, montmorillonite-saponite (Fig. 2b). Verification of the presence of montmorillonite was obtained through differential thermal analysis (Fig. 2d) and chemical methods. The X-ray diffraction pattern of the magnesium-saturated mineral shows expansion to 18 \AA upon glycolation and collapse to 10 \AA following K saturation and heating at 550°C . The thermal curve shows a double endothermic peak due to interlayer water in the $100\text{--}200^\circ\text{C}$ region and two additional endothermic peaks due to dehydroxylation at 700°C and at about 870°C (Fig. 2d). The CEC of the clay from the summit also indicates the presence of an expanding mineral (Table 1). Elemental analysis (Table 2) reveals a magnesium content relatively high for montmorillonite (Grim, 1968; Ross and Hendricks, 1945). Even if one assumes that the smectite

is Mg-saturated and subtracts the exchange Mg from the total, the percentage of MgO remains at 11.35 per cent. Whereas this value is high for montmorillonite, it is about half the value reported for saponite (Grim, 1968; Ross and Hendricks, 1945). A distinction between montmorillonite and the other members of the smectite group can be obtained by performing tests suggested by Greene-Kelly (1955) and by Rich (1957). The appearance of an expanded peak at 17 \AA of Li-saturated-heat and glycolated clay (Fig. 3) indicates the presence of trioctahedral phyllosilicate. A peak at 1.55 \AA (06 reflection) further corroborates the presence of a trioctahedral mineral. Considering the Mg content of the clay from Mauna Kea, it is suggested that saponite is the other mineral associated with montmorillonite.

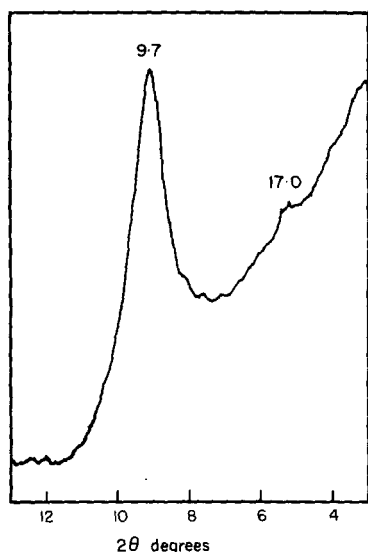
An additional test for Mg was performed to establish whether the Mg-enrichment of the clay was due to hydrothermal fluids of hypogene origin or due to the presence of high Mg in the tephra of the summit. If the tephra did contain high Mg, then the formation of saponite would be independent from the hypogene fluids and the resulted alteration induced by water and heat: water being of supergene origin derived from the melting of ice. The Mg content of fresh tephra collected

Table 1. Cation exchange capacity of $<2\ \mu\text{m}$ fraction for samples 17-5 and 3-2, Mauna Kea, Hawaii

Sites	Sample	Cation exchange capacity (m-equiv 100 g ⁻¹)			Δ C.E.C. (m-equiv 100 g ⁻¹)
		pH 4	pH 7	pH 8	
Summit	17-5	—	87.0	—	—
Glaciated plateau	3-2	39.0	—	67.0	28.0

Table 2. Elemental analysis of $<2\ \mu\text{m}$ fraction for samples 17-5 and 3-2, Mauna Kea, Hawaii

	Summit (17-5)	Glaciated (3-2) plateau
SiO ₂ (pct.)	51.1	37.7
Al ₂ O ₃ (pct.)	13.4	21.8
Fe ₂ O ₃ (pct.)	6.2	11.6
MgO (pct.)	13.7	4.2
SiO ₂ /Al ₂ O ₃	6.4	2.3

Fig. 3. X-ray diffractogram of Li-saturated, heated over 2 hr at 300°C and glycolated $<2.0\ \mu\text{m}$ clay fraction (oriented mount). Summit sample 17-5, Mauna Kea, Hawaii.

at the summit is considerably less (3.14% MgO) than the Mg content of the clay (13.70% MgO). The difference between these values seems to indicate that the genesis of the clay was more the result of hydrothermal alteration due to the influx of hypogene fluids than due to water and steam from the melting of the ice.

The elemental analysis of the amorphous clay of Profile 3 (Table 2) shows that SiO₂, Al₂O₃, FeO₃ and water make 95 per cent of the constituents. A value of 2.3 for the SiO₂/Al₂O₃ ratio is not as narrow as reported for other amorphous material (Tan, 1969; Sung-Ho and Swindale, 1969) but still within the range

for clays derived from volcanic ash and pumice (Aomine and Wada, 1962; Jackson, 1965). The presence of feldspars among the amorphous fraction may have widened the ratio. On the basis of the values of SiO₂/Al₂O₃ molar ratios, Jackson (1969) differentiated between very siliceous amorphous material with ratios from 2.9 to over 4, siliceous amorphous material with molar ratios of 2.8 to 1.4 and aluminous amorphous material with ratios of 1.1 ± 0.3 . These criteria as well as other data available in the literature (Briner and Jackson, 1970; Mokma *et al.*, 1973), are not strictly applicable in this study since the SiO₂/Al₂O₃ molar ratio of sample 3-2 (Table 2) was calculated from the elemental analysis rather than from the Na or KOH extract.

Another chemical feature of amorphous material is the high CEC and the dependence of this capacity on the pH. Aomine and Jackson (1959) introduced the concept of cation exchange capacity delta value for disclosing and estimating amorphous material in soil. The values reported in Table 1 show that the noncrystalline clay of Profile 3 displays a pH-dependent CEC with an intermediate delta value consistent with the SiO₂/Al₂O₃ molar ratio (Hendricks, Whittig and Jackson, 1967; Jackson, 1969).

In conclusion, X-ray, differential thermal and chemical analyses are all in agreement in indicating the amorphous nature of the clay fractions of the glaciated plateau and the high degree of crystallinity of the clay from the summit. Late volcanism associated, but not necessarily instrumental, with the melting of an ice cap and permafrost provided the hydrothermal conditions for the argillation. This event explains not only the incongruent association of soils dominated by amorphous clay with soils containing phyllosilicate minerals, but also a stage of alteration for the summit and other areas far more advanced than would be expected from subaerial weathering considering the existing climate.

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Résumé—Les sols de la zone du sommet du Mauna Kea sont semblables aux sols des déserts de haute montagne et aux sols des déserts froids. Des différences considérables, cependant, existent entre les sols du sommet et d'autres cônes voisins, et les sols du terrain qui a été recouvert par la glace. Les sols d'un certain nombre de cônes de la région du sommet sont riches en argile et contiennent des minéraux phyllosilicatés; les sols du terrain qui a été recouvert par la glace sont sableux et contiennent de l'argile amorphe aux rayons X. La montmorillonite et un minéral trioctaédrique riche en Mg identifié à la saponite sont les minéraux argileux du sommet. Etant donné que la zone du sommet du Mauna Kea était recouverte d'une calotte de glace à la période de formation des cônes, l'origine des minéraux du type smectite pourrait être trouvée dans l'altération de la tephra par la vapeur et l'eau libérées lors de la fusion de la glace. Cependant, les fluides de profondeur sont plus probablement responsables de la genèse des minéraux phyllosilicatés.

Kurzreferat—Die Böden der Gipfelregionen des Mauna Kea ähneln den Böden der hohen Bergwüsten und den Böden der kalten Wüsten. Drastische Unterschiede bestehen jedoch zwischen den Böden des Gipfels und anderer benachbarter Kegel und den Böden des vereisten Gebietes. Die Böden einiger der Kegel des Gipfelgebietes sind tonreich und enthalten Phyllosilicatminerale. Die Böden des Vereisungsgebietes

sind sandig und enthalten röntgenamorphe Tone. Montmorillonit und ein magnesiumreiches trioktaedrisches Mineral, das als Saponit identifiziert wurde, bilden die Tonminerale des Gipfels. Da das Gipfelgebiet des Mauna Kea zur Zeit der Bildung der Kegel eine Eiskappe trug, könnte die Entstehung der Smectitminerale das Ergebnis der Umwandlung der Tephrite durch Dampf und Wasser sein, die beim Schmelzen des Eises frei wurden. Mit größerer Wahrscheinlichkeit sind jedoch hypogene Lösungen für die Entstehung der Phyllosilicatminerale verantwortlich.

Резюме — Почвы площадей горных вершин Мауна Кеа подобны почвам высокогорных пустынь и холодных пустынных территорий. Однако, резкие различия существуют между почвами горных вершин и соседними конусами и местностями, охваченными оледенением. Почвы некоторых конусов на площади горных вершин богата глиной и содержит листовый силикат; земля местностей, охваченных оледенением песчаная и содержит аморфную глину с характерным спектром Р.л. Монтмориллонит и триоктаэдральный минерал богатый содержанием Mg идентифицированный как сапонит являются глинистыми минералами горных вершин, так как во время образования конусов площадь вершин гор Мауна Кеа была покрыта ледниковым покровом, зарождение смектитовых минералов произошло вследствие изменения температуры паром и водой, образовавшихся при таянии льда. Однако, более вероятно, что гипогенные жидкости отвечают за происхождение листового силиката.