THE NATURE AND PROPERTIES OF THE SOILS
OF THE RED AND BLACK COMPLEX OF THE HAWAIIAN ISLANDS

Goro Uehara and G. Donald Sherman

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INTRODUCTION

The occurrence of red soils developing alongside black soils under apparently similar climatic conditions has interested soil scientists for some time. These diverse soil types develop from the same parent material and in close proximity to one another. The interest in these soils lies not only in their color dissimilarity but also in their differences in mineralogy, chemistry, and physical properties. To identify related red and black soils throughout the world the term "red and black complex" has been used.

The soils of the red and black complex have been described in Australia by Hosking (*13*), Teakle (*36*), and Bryan *et al.* (*4*); in India by Nagelschmidt *et al.* (*23*), Raychaudhuri (*27*), and Raychaudhuri *et al.* (*28, 29*); in South Africa by Merwe and Heysteck (*20*); and in Indonesia by Mohr (*22*). It is evident from the localities listed above that the soils of the red and black complex are common to tropical regions, and it is not surprising to find similar soils in the Hawaiian Islands.

The soils in the tropics are normally formed under relatively high temperature and rainfall. High temperature accelerates chemical weathering and favors oxidation; high rainfall facilitates solution and removal of soluble weathering products. Both oxidizing conditions and intense leaching with resultant increase in acidity are favorable to the process of latosolization (laterization) so that free oxides and kaolin minerals become a common constituent in the clay fraction. In the Hawaiian Islands, every stage of weathering, beginning with fresh lava and ending with the titaniferous and ferruginous latosols, may be observed.

Mohr (*21*) working with tropical soils recognized five stages of weathering and set out to separate soils on this basis. The stages of development as proposed by Mohr are as follows: (1) fresh, (2) juvenile, (3) virile, (4) senile, and (5) laterite stage. A soil scientist working in the tropics cannot help but be impressed by the diverse soil types in varying degrees of development occurring within a small area. The separation of soils

on the basis of weathering stages is a natural tendency in the tropics. Jackson and his colleagues (15), working at the University of Wisconsin, published fundamental generalizations tracing the course of weathering of clay-size minerals in soils and sediments. They established a weathering sequence of primary and secondary minerals according to chemical stability. The chemical stability series was in turn based on minerals found and on the crystal chemistry. Primary and secondary minerals were divided into 13 groups according to their susceptibility to weathering. Under conditions of equivalent weathering intensity, members of early groups would decompose before those of later groups. The weathering sequence of Jackson and his co-workers has proved helpful in interpreting results of mineralogical work on soils in the tropics.

The purpose of this investigation is to describe and attempt an explanation for the existence of the soils of the red and black complex in the Hawaiian Islands. The problem at hand involves the interpretation of mineralogical and chemical data obtained from the study of the soils of the red and black complex. The final conclusion about the nature of these soils will be based on data obtained by other workers in tropical regions and on new concepts and recent advances made in soil science.

The differential thermal apparatus will be briefly reviewed since an intelligent interpretation of the thermal data requires an understanding of the principles involved in this equipment. A discussion of the important minerals identified by the thermal apparatus is also considered helpful to this problem.

REVIEW OF LITERATURE

Before any discussion of the theory relating to the formation and development of the soils of the red and black complex is attempted, it may be well to review several related laboratory and field studies which have been conducted by other workers. Several investigators including Norton (24), Ewell and Insley (6), and Noll (16) have succeeded in synthesizing clay minerals in the laboratory. Norton (24) subjected a number of feldspars and clay minerals to CO_2-charged percolating water under high pressure and temperature in a reaction chamber and succeeded in forming beidellite and kaolinite. He suggests that the end product is determined by the cation or the crystal structure of the parent mineral. In the materials tested there was evidence indicating that the materials with lower total alkali content were more stable.

Ewell and Insley (6) synthesized kaolinite by heating coprecipitated Al_2O_3-SiO_2 gels and mixtures of Al_2O_3 and SiO_2 with water in a hydrothermal bomb at 310°C. Similarly beidellite was prepared from mixtures of Al_2O_3 and SiO_2 at higher temperatures. The results showed that soda was a necessary factor in the formation of beidellite. The effect of soda

on the preparation of kaolinite was more difficult to prove, owing to the difficulty of preparing a coprecipitated gel completely free of soda.

Kelley *et al.* (*16*) and others have discussed the synthesis of kaolinite and montmorillonite by hydrothermal bomb experiments as conducted by Noll. According to Noll, the amount and type of alkalies and alkaline earths present and the pH are of greater importance than the relative amounts of silica and alumina. Whereas Ewell and Insley demonstrated the importance of soda, Noll's work showed the effect of a wider range of cations in the formation of montmorillonite. Noll's results point out the role not only of Na but K, Ca, Mg, Cs, and Be as well. If, however, the same mixture of silica and alumina was subjected to the same heat and pressure in the absence of these cations, kaolinite is formed.

Ross and Hendricks (*30*) criticize Noll's work on grounds that Noll overemphasizes the importance of pH. They propose that the bases play a more important role in the end result than pH.

Such factors as temperature, pressure, bases, pH, and parent material have been cited as important in determining the nature of the type of clay minerals formed in these experiments. In the final analysis, whether kaolinite or montmorillonite forms in the soil depends on the absence or presence of bases. Although these laboratory experiments cannot duplicate the conditions under which these minerals form in the soil, most workers agree that the results are indicative of the process that occurs naturally.

In a series of studies conducted in the field, several workers have discussed the soils of the red and black complex in tropical regions. Hoskings (*13*) studied and identified the clay mineral fractions of a number of Australian soils. He discovered that clays from granitic parent material weathered to kaolinite irrespective of the nature of the soil forming process. However, clay developed from basaltic material weathered to kaolinite or montmorillonite depending on the conditions under which they were formed. If conditions of free drainage were maintained, kaolinite formed; if, on the other hand, drainage was restricted, montmorillonite formed.

Merwe and Heysteck (*20*) made a study of the mineralogical constitution of the colloids of the South African lateritic soils. They found that under good drainage conditions and high rainfall the soil colloids consisted only of kaolinite, gibbsite, and iron oxide. When rainfall was below 30 inches, undecomposed quartz and mica appeared in the colloidal fraction and the clay mineral was sometimes illite. Under poor drainage intrazonal black clays with montmorillonite as the clay mineral were formed.

Nagelschmidt *et al.* (*22*) investigated the minerals in the clay fraction of a black cotton soil and a red earth from India. The red soil contained predominantly kaolin, whereas the black clay contained montmorillonite.

They concluded that the principal factor effecting the mineralogical difference was topography.

Agarwal and Mukerji (1) in making a survey of Indian gangetic alluvium identified three major soil types, depending on degree of calcium leaching. The effect of topography on the formation of the three types was brought out. Soils developing on the uplands were low in calcium and silica; an opposite effect was noted in the soils of the lowlands.

Raychaudhuri and his co-workers (27, 28, 29) have conducted a thorough research on the red and black soils of India. In one paper (29) they showed that the percentage of free silica increased with depth in both the red and black soils. They further demonstrated that free silica and free alumina were higher in the black soil, while the percentage of free iron oxide was higher in the red soil. In another paper (28) Raychaudhuri and Chakravorty found a significant negative correlation of the SiO_2/Al_2O_3 of the clay fraction with altitude and rainfall.

In a study of the red and black soils of Australia, Bryan and Teakle (4) suggested that a difference in time factor caused their occurrence in the same district on similar parent material and slope. They proposed that the red soils formed under an earlier, wetter environment; later, a black soil formed where unweathered basalt was exposed. The failure of the red soil to exhibit convergence with the new soil was attributed to a process in soil formation which they termed pedogenic inertia. They further proposed that once a soil forming process was initiated, this process continued in spite of environmental changes. A trivial variation in drainage or slope resulting in the initiation of two soil forming processes might, as a result of pedogenic inertia, bring about increasing divergence of the two soils.

Sherman and Uehara (33), while making a study of olivine-basalt rocks in the subsoil of Kunia, Oahu, discovered kaolin forming on the upper portion of large boulders and montmorillonite beneath the same boulder, where the weathering material was protected from percolating waters. Figure 1 shows this mineralogical difference clearly. Similarly a mineralogical study of a weathered rock showed kaolin to be more common on the upper layer, while montmorillonite appeared in increasing amounts in the lower sections (fig. 2).

In accordance with laboratory synthesis the bases seem to play an important part in the formation of montmorillonite. With the removal of bases and the subsequent increase in acidity montmorillonite desilicates into kaolin. This observed fact is inconsistent with the solubility of silica in the laboratory. An explanation for this apparent paradox has been forwarded by Fieldes and Swindale (7). They propose that acid solution may penetrate between silica sheets in a 2:1 structure. The external silica sheets are exposed to the acid solution, but the sandwiched alumina sheet, which is more susceptible to acid, is protected. The acid solution between the layers does not attack the silica itself but instead
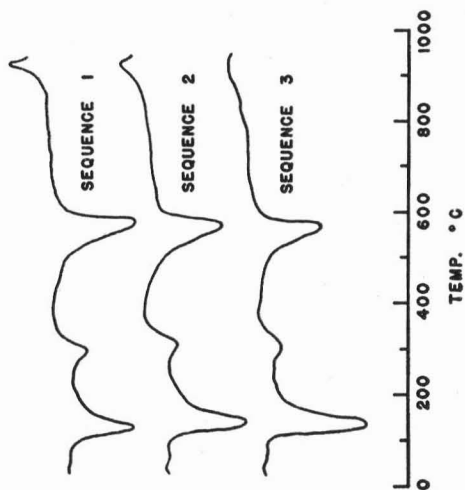
Fig. 2. Differential thermal curves of samples from a decomposed olivine rock showing increase in montmorillonite with increase in depth. An opposite effect is noted for kaolin.
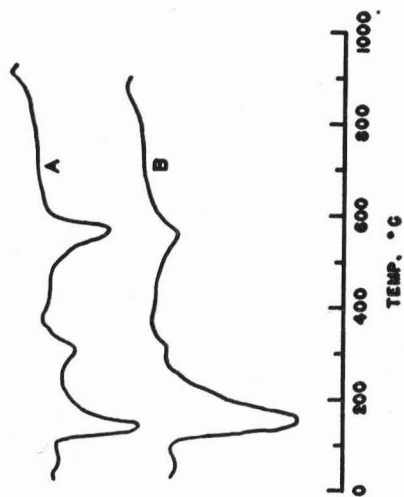

Fig. 1. Differential thermal curves of soil sample taken from Kunia road, Oahu: A, above rock; B, below rock.

attacks the aluminum which has replaced silicon in the structure. Removal of the aluminum destroys the silica sheet. They also believe that removal of one silica sheet from montmorillonite results in the formation of kaolinite.

Jackson *et al.* (*15*) suggests that soil acidity is not sufficient for insolubilizing silica since marked insolubility of silica begins at negative pH values.

Kaolin need not necessarily be a weathering product of montmorillonite. Sherman (*31*) suggests that under certain rainfall conditions parent rock may weather directly to kaolin. Alexander *et al.* (*2*) discovered gibbsite as the first weathering product of primary minerals. Where silica was liberated in close proximity to the gibbsite, resilication to kaolinite occurred.

In this study of the soils of the red and black complex the occurrence of kaolin and montmorillonite soils in close proximity to each other will be explained.

PROCEDURE

A very useful technique in the study of clay minerals is differential thermal analysis, a method which is qualitative as well as quantitative in nature. This method of analysis detects and indicates the thermal effects that accompany the loss of water, oxidation, decomposition, or changes in crystal structure that may occur when a substance is heated. A differential thermocouple (two-headed thermocouple) is used as the heat sensitive device. The thermocouple junction can be made in the laboratory by simply joining two wires of different metals (chromel-alumel) at their ends and heating them until a bead is formed. Two such junctions are made. One junction is inserted in an inert material (Al_2O_3) which does not undergo either exothermic or endothermic reactions through the temperature interval that is studied; the other is placed in the sample holder containing the soil sample that is to be tested. Both junctions are then heated in a furnace to a temperature of $950°C.$ at a constant rate of 15 degrees per minute. An endothermic or exothermic reaction at the junction of the soil sample will create a potential between these two junctions, thus causing an electrical current to flow from the hotter to the colder junction. The potential is proportional to the concentration of the mineral giving the reaction. A reflecting galvanometer is used as a measuring device for detecting any temperature difference between the sample and the aluminum oxide. A mineral may exhibit a characteristic reaction or reactions at a specific temperature range, thus allowing an easy means of identification. A plot of galvanometer readings against temperature gives a curve which shows a quantitative as well as a qualitative picture of the soil minerals in the sample.

Since the various clay minerals in a soil sample yield sufficiently different peaks, the temperature at which a peak occurs is often indicative of which mineral is present. The rate of reaction, the amplitude and the shape of a peak are all dependent on the type of change occurring in the sample. The 2:1 layered silicates, 1:1 layered silicates, and the hydrous oxides give major peaks at different temperatures so that identification is simple and accurate. The identification of a mineral by differential thermal analysis is not final. A positive identification would require several different analytical methods, such as elemental analysis, x-ray diffraction, and electron microscopy. Familiarity with the soil and a fair knowledge of the soil forming process is often helpful in anticipating the soil minerals.

The application of the differential thermal analysis to the quantitative treatment of clay minerals has been mentioned. Speil (34) and Kerr et al. (18) have shown in precise mathematical terms that the concentration of a clay mineral in an unknown sample can be related to the area between a peak and the base line of a thermal curve. More exact determination of comparatively simple systems can be made by running known mixtures and preparing a calibration curve of area versus percentage of each component. However, if a mixture of two or more components has peaks in the same temperature interval, the area of that peak will be an additive function of the components. Fortunately, most clay minerals show at least one peak which is specific for itself. In this study the absolute concentration of the mineral in question is of little import, rather it is the ability to show comparative concentrations between samples that is of major interest. It suffices to say that as the concentration of the reacting substance giving the peak increases, the area under the peak increases.

The apparatus was standardized with pure kaolinite from the McNamee mine, South Carolina. The resistance was adjusted so that this clay gave an endothermic deflection of 30 units at the peak of reaction (see fig. 3).

The sample to be tested by the differential thermal apparatus was passed through a 65-mesh screen and maintained at 50 percent relative humidity until equilibrium was reached. Kerr et al. (17) suggest that any attempt to attain equilibrium with a specified humidity is unnecessary, but considering the different degrees of wetness of the soil samples studied and the importance of the adsorbed water peaks in this work, such a procedure was believed justified.

After the sample was loaded, the specimen holder was covered with a metal plate and enclosed in the furnace. The galvanometer was switched to the "on" position and zeroed. A watch with a large minute hand was used, since readings were made every 60 seconds. Because error in the number of readings per given time interval can easily occur, the minute hand was synchronized with the long hour hand so that "n" number of revolutions by the minute hand equaled the number to which the long

hour hand was pointing. This procedure merely facilitated the detection of error. The furnace was then started; the rate of heating was controlled by a calibrated voltage transformer and the temperature was read from a pyrometer wired to the sample thermocouple. Galvanometer readings were made every minute, with care being taken to maintain the heating rate at 15 degrees per minute. The record was made from room temperature to approximately 950°C.

The basic structure of the montmorillonite group minerals is related to the mineral pyrophyllite (25) which consists of a single gibbsite sheet between two sheets of silica tetrahedrons. In montmorillonite (18) magnesium is substituted for aluminum in octahedral coordination. This results in negative charges on the three-layer sheet which in turn are balanced by intersheet cations such as calcium and sodium. The structural units are stacked one above another and are loosely held with water molecules present between them. This interlayer water can be removed without disruption of the crystal structure and is important in the identification of the montmorillonite group minerals by thermal means. Numerous isomorphous replacements make positive identification of minerals difficult by chemical methods. Jackson (14) prefers to use the term montmorin to include the isomorphous series of 2:1 layer silicates such as montmorillonite, beidellite, saponite, nontronite, and other isomorphous relatives.

The montmorillonite group minerals are characterized by having high cation iron exchange capacities (150 m.e./100 grams of clay). Soils having montmorillonite group minerals are highly plastic, will swell upon wetting, and shrink and form large cracks when dried. These minerals are generally found in soils having neutral to alkaline reaction.

The differential thermal curves of the montmorillonite group minerals have been reviewed by many workers (9, 17, 18, 34). The salient feature of the thermal curve of the montmorillonite group is the adsorbed water peak between 100° and 200°C. Initial destruction of lattice begins at about 500°C. for nontronite and about 600°C. for montmorillonite. This decomposition is mainly due to the loss of the hydroxyl groups in the form of water (18) and is represented on the thermal curve by a weak endothermic peak. A third and final endothermic peak at about 900 degrees which corresponds to the breakdown of the lattice is also characteristic of this group. None of the Hawaiian clays analyzed show the endothermic peaks at 600° or 900°C.

The thermal curve for the montmorillonite group of minerals is unfortunate in that the main endothermic peak between 100° and 200°C. is not specific for this group. Other substances such as organic matter, excess moisture, allophane, halloysite, and 2:1 intermediates all give similar peaks in this temperature range. However, with a fair knowledge of the sample, much of the above-listed interfering substances can be ruled out. For example, organic matter in amounts adequate for

giving a strong peak between 100° and 200°C. will necessarily give a strong exothermic peak immediately after 200°C. as a result of oxidation. An endothermic peak between 100° and 200°C. without the following exothermic reaction rules out organic matter. Organic matter in soil samples may be destroyed with hydrogen peroxide.

Excess moisture is simply treated by placing the sample at 50 percent relative humidity until equilibrium is reached.

The adsorbed water peak for montmorillonite and allophane is very similar except that allophane gives off water over a wider temperature range resulting in a broader peak. More important than the minor difference in the shape of the adsorbed water peak is the sharp exothermic peak at 950°C. characteristic of allophane and the kaolin group minerals. The best evidence against allophane in the samples studied is the unlikeliness of its forming under low to moderate rainfall conditions.

There is no satisfactory means of differentiating between the adsorbed water peak for montmorillonite and halloysite. However, for most of the soils studied a strong kaolin peak between 500° and 600°C. was generally associated with a weak adsorbed water peak. This may indicate that kaolinite is the dominant 1:1 alumino-silicate or that halloysite is present in the less hydrated forms.

The illites and related 2:1 intermediates give weaker but similar adsorbed water peaks. In this study no attempt is made to differentiate these minerals from the montmorillonite group minerals.

For the sake of brevity, the term montmorillonite will henceforth be used to include all 2:1 layered silicates and will not necessarily refer to the specific mineral itself.

Four polymorphic varieties have been described for the kaolin group minerals (12). They are kaolinite, nacrite, dickite, and halloysite. Base exchange capacities are low because the apparent lack of variable valence substitution (Al^{+++} for Si^{++++}) in the structure (11) does not permit electrostatic charges external to the sheet except on the broken edges. Strong hydrogen bonding between the gibbsite sheet of one unit and the silica layer of the next gives the kaolin group minerals a rigid structure. As a result, the kaolin minerals, unlike the montmorillonite minerals, do not swell upon wetting and are characterized by having good physical properties in the field. The kaolin minerals have certain basic structural similarities and are often referred to as having a 1:1 lattice.

The crystal structure of kaolinite consists of a single silica-tetrahedral sheet topped by a gibbsite sheet, both being joined by condensation and splitting off of water between adjoining hydroxyl groups. A single oxygen from each silicon tetrahedra remains and is shared by the two layers (3), resulting in a primary valency bond between the sheets.

Kaolinite, dickite, and nacrite differ only in the manner of stacking of the sheets (18). Halloysite differs from the kaolinite structure in that the sheets are not bonded together through oxygen linkages (3). Only

kaolinite and halloysite have been reported as occurring in soils (*12*, *18*, *4*).

Kerr *et al.* (*18*) state that the kaolin family exhibits a major endothermic peak between 600° and 700°C. when analyzed with the differential thermal apparatus. A sharp exothermic peak at about 1,000 degrees is also characteristic of the kaolin minerals. In practice, however, such factors as degree of crystallinity, concentration, rate of heating, etc. (*9*, *32*), bring the endothermic and exothermic peaks at 500° to 600°C. and 900° to 950°C. respectively for the soils studied. No attempt is made to distinguish between kaolinite and halloysite, although Luis *et al.* (*19*) and Dean (*5*) have made a detailed study for such a differentiation. It is only necessary to state in this study that kaolinite and halloysite are chemically and structurally related and that they both lie in the same category in the mineral weathering sequence.

Free and hydrous oxides of iron and aluminum are common constituents of tropical soils. In this discussion the term hydrous oxide will be restricted to those minerals giving an endothermic reaction between 300° and 400°C. with the differential thermal apparatus (see fig. 4). Of the iron oxide minerals goethite is probably the most important. Hydrous oxides of aluminum in the form of gibbsite have been reported in soils.

The free oxides give no identifying thermal reaction and can only be assumed in the samples studied. Such resistant minerals as rutile, ilmenite, anatase, hematite, and magnetite may occur in high concentration in some lateritic soils.

EXPERIMENTAL RESULTS AND DISCUSSION

A systematic survey of several red and black soils from the islands of Oahu and Molokai was made. Four major variations in the soils of the red and black complex, differing in modes of formation, were recognized. Type I consists of black soils forming under low rainfall at low elevation adjacent to red soils forming under higher rainfall on upper elevations. Type II black soils may form under heavier rainfall than type I, but are stabilized by bases received from seepage waters from adjacent red soils in the uplands. Type III comprises a number of black soils developing under restricted drainage conditions near red soils having better internal drainage. Type IV consists of several profiles of alluvial and ash material where a red topsoil rests upon a black subsoil. In every case, except one, kaolin was found to be the dominant clay mineral in the red soil and montmorillonite in the black soil, with a kaolin-montmorillonite mixture in the transitionary zones. A critical analysis of each soil examined for this problem will be attempted in the following paragraphs.
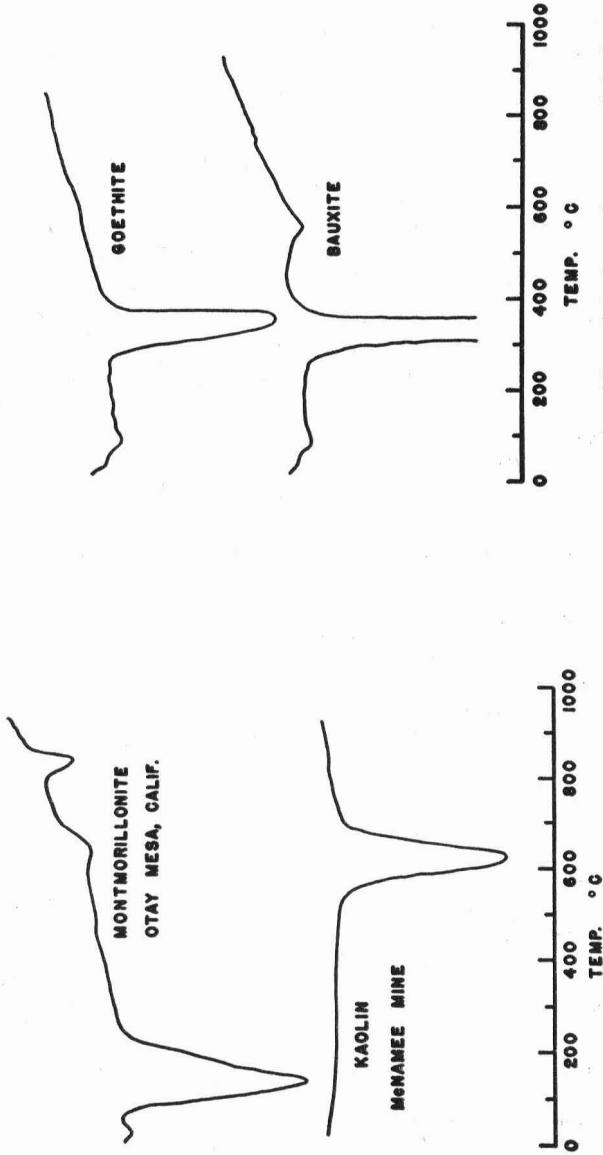
Fig. 4. Differential thermal curves of hydrous oxides of iron (goethite) and aluminum (bauxite).

Fig. 3. Differential thermal curves of standard kaolin and montmorillonite.

Type I Soils of the Red and Black Complex

Samples for the type I soils of the red and black complex were taken from the Waianae region on the island of Oahu. There are several valleys including Makaha, Waianae, Lualualei and Nanakuli, which begin at the shoreline and extend to various distances into the Waianae range. Rainfall is uniformly low near the shoreline, but increases as one goes into the valley and approaches the mountains.

A person interested in soils is at once impressed by the dark soil occurring in the valley floor which contrasts sharply with the red soil on the slopes at the head of the valley. The soils on the valley floor are characterized by their black color and their cracked surfaces. When irrigated, the soils become highly dispersed and sticky and plastic to the feel. The dark surface layer apparently is not associated with an exceptionally high content of organic matter. The dark color grades into a lighter gray in the lower horizon, where gypsum crystals are common. Coral outcrops are common in some areas. Sherman *et al.* (*32*) established a process of dolomitization of the calcium carbonates in which magnesium replaced part of the calcium. The source of magnesium is from the olivine minerals common in the basaltic parent material. These dark clays formed from basaltic parent material in arid regions of the Hawaiian chain have been named "Dark Magnesium Clays" and possess properties similar to the black earths of Australia and the "Regurs" of India.

The red soils on the other hand, aside from their contrasting red color, have better physical properties than the black soils in spite of their higher clay content (see table 1). The cation exchange capacities and percent base saturation are comparatively low; pH is expectedly lower, but organic matter is higher in the red soil than in the black soil.

TABLE 1. Chemical Data from Typical Red and Black Soils

DETERMINATION	RED*	BLACK†
Cation exchange capacity	12.2 m.e./100 g.	44.2 m.e./100 g.
Exchangeable calcium	2.79 m.e./100 g.	34.85 m.e./100 g.
Exchangeable magnesium	2.28 m.e./100 g.	11.30 m.e./100 g.
Organic matter	3.41%	2.03%
Soil separate:		
Sand	11.6 %	22.8 %
Silt	32.5 %	45.6 %
Clay	55.8 %	31.7 %

* Low Humic Latosol from Poamoho, Oahu.
† Dark Magnesium Clay from Lualualei, Oahu.

In order to ascertain the mineralogical constitution of the soils of the red and black complex of the Waianae region a number of differential thermol analyses were performed. Samples were taken at regular inter-

vals, starting from a typically red soil, passing through the transitionary zone and on until a normal black soil was reached. Samples in figure 5, taken from Makaha Valley, show the change from a dominantly kaolin mineral in the red soil to a montmorillonite mineral in the black soil. Similar data obtained from Waianae Valley are shown in figure 6. According to Jackson's sequence of mineral weathering (15), kaolin comes later in the sequence than montmorillonite and, therefore, has gone further along in weathering. Before a difference in degree of weathering can occur on the same parent material, one or more factors affecting the rate of weathering must vary between the two areas. If Jackson's weathering rate equation were to be applied here,

weathering rate$=f$ $(T, H_2O, H^+, e^-, s, k_m, t)$

where T is temperature, H_2O the rate of water movement, H^+ the acidity of the solution, e^- degree of oxidation, s the specific surface of the particles, k_m the specific nature of the material being weathered, and t is time, then the differentiating variable is the factor H_2O or the rate of leaching provided by internal drainage. All other factors affecting the weathering rate are nearly equal between the red and black soils and may be considered secondary in importance with respect to the formation of the two soils.

For the sake of simplicity a hypothetical case is used. If two soils developing in two different localities from similar parent material were to be subjected to equal intensity and capacity factors, at a given time "t" the degree of weathering for these two soils should be equal. However, should any one of the factors affecting the rate of weathering differ from one soil to the next, then the two soils will differ in degree of weathering. This difference in degree of weathering is a function of the unequal variable. Although one factor may play the dominant role in separating the two soils, it is more likely that the difference is a function of several factors since the variables are probably not independent of each other.

Returning to the real problem, difference in rainfall was cited as one cause for the formation of red and black soils from the same parent material. Rainfall data in table 2 show the yearly rainfall for the black soil and red soil to be 13 and 30 inches, respectively. The effect of rainfall is probably accentuated by the ease of leaching from soils forming on the higher slopes as compared to the soil forming in the low lying areas. Rainfall need not be the only factor affecting the rate of leaching; as will be described later, such factors as water table and parent material may also alter the rate of percolation. Rainfall is not the only cause for the formation of the black clays in the Waianae region. The formation of black clays from alluvium receiving seepage waters rich in bases and silica from adjacent uplands has been cited. Identical black clays can, however, form from porphyritic basalts containing large phenocrysts of olivine if rainfall is sufficiently low.

Fig. 6. Differential thermal curves of samples taken from Waianae Valley showing a change from kaolin in the red soil (location A) to montmorillonite in the black soil (location C).
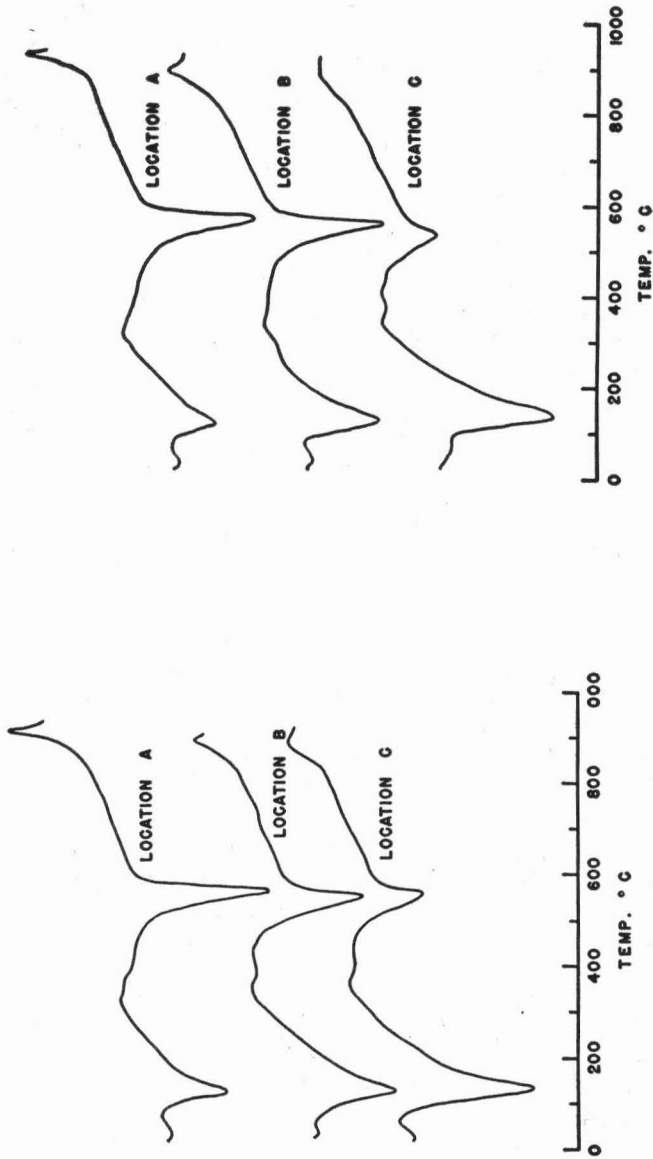

Fig. 5. Differential thermal curves of soil samples taken from Makaha Valley showing a mineralogical change from a dominantly kaolin clay in the red soil (location A) to montmorillonite in the black soil (location C).

TABLE 2. Rainfall Data for the Soils of the Red and Black Complex

(From M. H. Halstead and L. B. Leopold, *Monthly median rainfall maps*, PRI & HSPA Report No. 2, 1948.)

SAMPLE AREA	RAINFALL IN INCHES PER YEAR	
	Red	Black
Waianae-Makaha	30	13
Kunia-Honouliuli	23	17
St. Louis Heights	100	40
Halawa Valley	27	----
Molokai Airport*	20.86	----

* Average rainfall data for 21 years obtained from Meteorology Department, Pineapple Research Institute.

Samples taken at the transitionary zones (see fig. 7) show a kaolin surface and a montmorillonitic subsoil. This phenomenon is readily explained by the fact that intensity factors are greater at the surface than at the lower horizons. Laterally moving seepage waters possibly replenish the bases and silica in the subsoil, thus stabilizing montmorillonite.

Type II Soils of the Red and Black Complex

The type II soils, which are very similar to the type I soils of the red and black complex, were examined and studied in the St. Louis Heights area of Honolulu. The Heights is a ridge between two valleys and extends from the top of the Koolau range to the low plain in the Kapahulu region. Soils in the upper regions are red, and roadcuts show profiles weathered to 15 feet or more in depth. These soils have formed under rainfall of 100 inches or more. Thermal curves (fig. 8) of samples taken at various depths from a roadcut show a dominantly kaolin profile with detectable amounts of hydrous oxides near the surface. The occurrence of oxides in the upper layers is in accordance with Jackson's concept of weathering as a horizon depth function, which simply states that "the weathering stage of the colloid of a soil horizon or of a sediment tends to advance with increasing proximity to the surface."

As one drives down the ridge, a change in vegetation and soil type becomes evident; tall trees associated with high rainfall disappear and are replaced by xerophytic *Lantana camara* L., *Opuntia* sp., and *Prosopis* sp. Roadcuts show soils of a shallower nature impregnated with large boulders. In the lower horizons black clays begin to appear (see fig. 9). The intensity of the red color and the depth of the red layer decrease as one continues down the Heights until a totally black profile appears at the junction of the ridge and the valley floor. Mineralogical data (fig. 10) show montmorillonite to be dominant throughout the black profile. Although the study of the red and black soils of this area seems merely to duplicate the findings already discussed, a significant difference in rainfall is noted in the black soils of the two regions. Whereas, the black soils of the Waianae region enjoy a low rainfall of
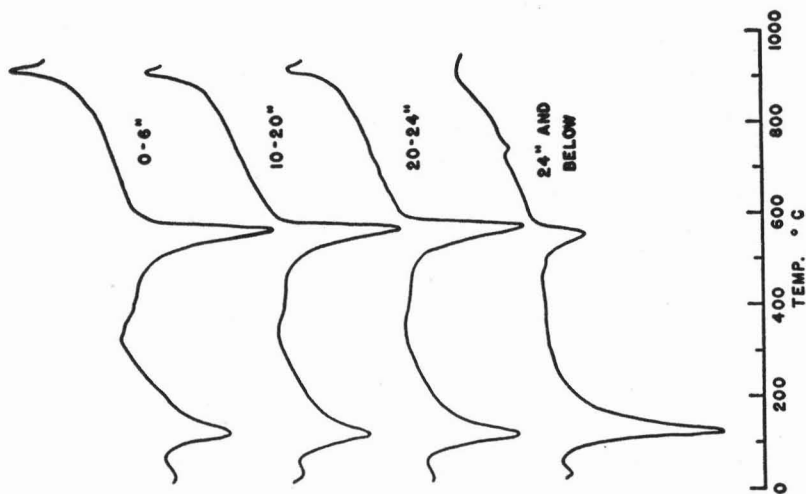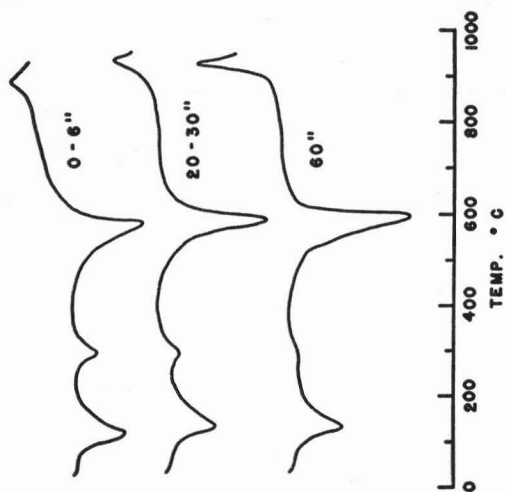
Fig. 8. Differential thermal curves of a red profile from upper St. Louis Heights. The profile is mainly kaolin except for some hydrous oxides near the surface.

Fig. 7. Differential thermal curves of a soil profile from the transitionary zone in Makaha Valley. The red surface material is essentially kaolin, whereas the subsoil is montmorillonitic.

less than 20 inches per year, similar black soils are stabilized under rainfall exceeding 40 inches in the St. Louis Heights area. Apparently the black clays are replenished with bases received through seepage waters from adjacent uplands.

Type III Soils of the Red and Black Complex

The type III red and black complex has properties similar to the type I and II complexes, but differs in its manner of formation. The samples for the type III soils of the red and black complex were taken from the Kunia-Honouliuli area of Oahu, where a red soil grades into a dark gray soil. The transition occurs as one moves from the Kunia area toward Ewa. In this region the slope is not so pronounced and the change from red to black covers a greater distance. Samples were taken at regular intervals between the area of the red and black soils. Figure 11 shows the change from kaolin to montmorillonite as sample sites moved from the red to the black region.

Rainfall data (10) for both the red and black soils taken over a ten-year period vary within a narrow range of 17–23 inches per year. Formation of a deeply weathered red soil under 20–25 inches is inconsistent with the rate of weathering of basaltic parent material. Two opinions have been expressed for the formation of red soils in this region: (a) formation of red soil under a formerly wetter climate, (b) formation of red soil on ash parent material.

Proposition a is based on the theory that the red soil developed under formerly wetter climate. The continuation of the kaolinization process may be explained in terms of Bryan and Teakle's pedogenic inertia. Whether such a process as pedogenic inertia is presently in progress has as yet not been established.

The development of a red soil from ash material is the basis for the second proposition. The porous nature and high specific surface of ash favors rapid weathering in contrast to soil formation on basalt. The high degree of weathering of the red soil makes positive identification of the parent material difficult. The pattern of volcanic deposition, beginning with magma and terminating with ash, supports this view. Further evidence for soil formation on ash can be deduced by analogy with the common occurrence of ash material on the younger islands.

The great difference in properties between the red and black soils cannot be explained in terms of rainfall since this factor is nearly equal in both soils. The black soil in this case is apparently the result of restricted drainage arising from a high water table. Within the black soil a separation can be established on the basis of drainage. As the water table rises, leaching is inhibited and reducing conditions are favored, which in turn aid in the stabilization of montmorillonite. The black soil in this region has probably formed under conditions similar to the "tirs" of Morocco as described Villar (38).

Fig. 10. Differential thermal curves of a black profile from lower St. Louis Heights. Montmorillonite is the dominant mineral throughout the profile.
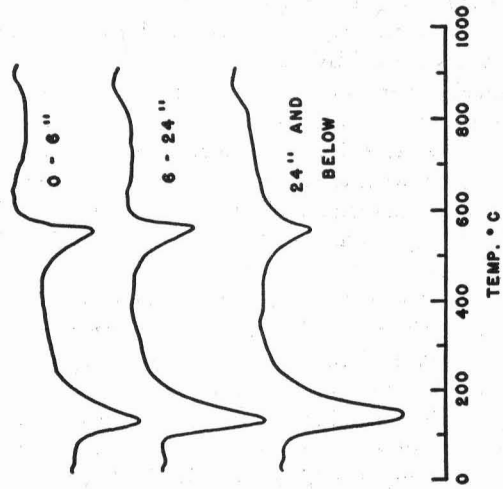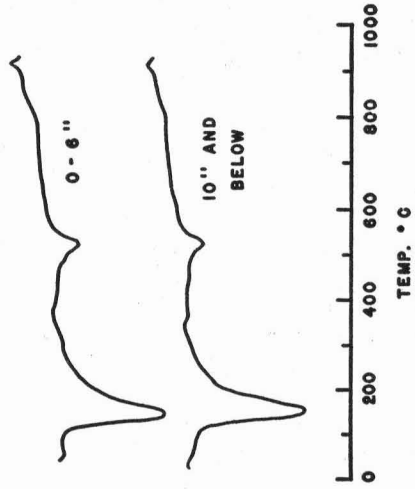
Fig. 9. Differential thermal curves of a red and black profile from St. Louis Heights showing change in mineralogy from kaolin to montmorillonite with depth.

Type IV Soils of the Red and Black Complex

So far the soils of the red and black complex described included only those in which red and black soils occurred in adjacent lots. The type IV soils of the red and black consist of a number of soil profiles in which a red surface horizon rests upon a black sub-horizon. Samples for this type were taken from alluvial soils in Halawa Valley on the island of Oahu. The complete profile is 10 feet or more in depth and consists of various unweathered alluvium and black clay in the subsoil and red kaolin material on the surface. The black material probably is transported material, but the red kaolin is most likely a weathering residue of the black subsoil since it occurs consistently on the surface and never in the subsoil. Figure 12 shows the thermal curves of a typical red and black profile taken from this area.

A case in which a red and black layer rested upon another red and black layer was found (fig. 13). In this instance a red and black formed over another red and black as a result of weathering on two alluvial deposits.

The occurence of red soil over black is not surprising if Jackson's principle of weathering depth function is understood (15). According to Jackson the top soil should be more weathered than the subsoil since it is further away from the parent material, and one might expect the proportion of kaolin to be greater near the surface. Given enough time the whole profile may become kaolinitic, but the presence of kaolin over montmorillonite is another evidence that kaolin follows montmorillonite in the weathering sequence.

A study of another red and black profile from the island of Molokai was made. Thermal analysis of both the red and black horizons revealed kaolin as the dominant mineral in both horizons, with the exception of a higher hydrous oxide content near the surface (see fig. 14). The absence of montmorillonite in the sub-horizon is not surprising since the parent material is in all probability volcanic ash. The black color may be remnant of a previously montmorillonitic horizon now completely kaolinized. Determination of cation exchange capacities on related red and black profiles from Molokai shows significantly higher capacities in the lower horizons. This may be evidence that in some profiles the sub-horizon is still montmorillonitic.

Nature of the Red and Black Color

The cause of the red and black color has not been mentioned heretofore. One might be led to believe that the colors are inherently part of the clay minerals; this is not the case. Pure kaolin and montmorillonite tend toward whiteness; apparently the color of the soils is imparted by some mineral other than kaolin or montmorillonite.

FIG. 12. Differential thermal curves of a red and black profile from Halawa Valley, Oahu. Kaolin appears in the upper red horizon and montmorillonite in the lower black horizon.
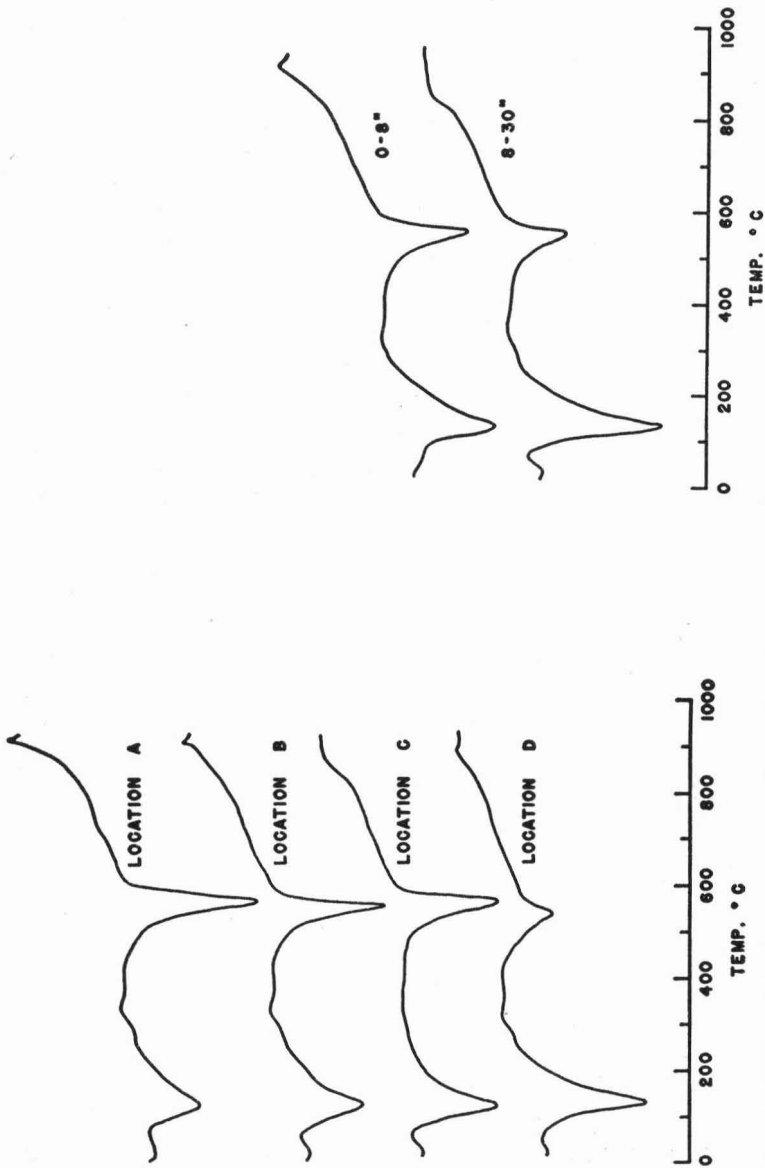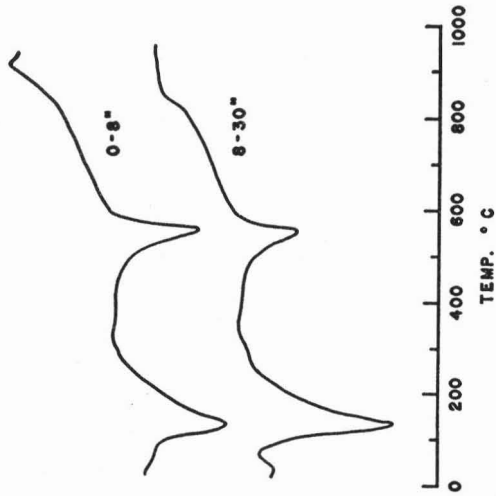

FIG. 11. Differential thermal curves of samples taken from the Kunia-Honouliuli area of Oahu showing change from a kaolin in the red, well-drained soil (location A) to montmorillonite in the dark soil (location 4) having a high water table.

Most workers agree that hematite is the main cause of red colors in soils. However, the term "red" is rather loosely applied in some cases since the so-called red soils range in color from yellow, orange, and brown to red. The appearance of an endothermic reaction near 300 degrees on the thermal curve (figs. 8, 14) suggests the presence of hydrous oxides. The hydrous oxides are probably those of iron rather than aluminum, since under low rainfall and an alternating wet and dry climate iron oxide is the more stable oxide of the two. Goethite, a hydrous oxide of iron, and hematite are probably two of the important coloring agents in the red soils. The occurrence of lepidocrocite, another red hydrous oxide of iron, has been reported as unlikely in soils (26). Recently Tamura (35) has listed it as a possible constituent in soils.

The nature of the black color in soils presents a more difficult problem. Raychaudhuri (27) in a review of the subject lists two possibilities, iron oxide and humus, as the cause of the black color. Mohr (22) cites the work of Theron and Van Niekerk (37) as the only conclusive investigation contributing to the understanding of the black color. These two workers propose that a peculiar type of humification and not the quantity of organic matter is responsible for the black color. Villar (38) suggests that sodium-dispersed organic matter sometimes causes the black color in the "tirs" of Morocco. Gill and Sherman (8) have cited magnesium-dispersed organic matter as the cause for the black color in the Dark Magnesium Clays of the Hawaiian Islands.

Recent investigation (33) of black clays forming under basalt rocks in Kunia, Oahu, sheds new light on the subject. These black montmorillonitic clays forming 10 feet or more beneath the surface, in small protected areas beneath basalt rocks, have an organic carbon content of 0.13 percent. It is rather dubious that such a low carbon content in any form can be the cause of the soil color. Furthermore, similar black montmorillonitic clays have formed from the decomposition of olivine crystals within basalt rocks whose matrix is still undecomposed. Entrance of organic matter into these rocks is hardly expected.

The little work that has been done in this connection leads one to believe that possibly organic matter is not the cause of the color in the black tropical soils.

SUMMARY

A study was made of the mineralogical constitution of the soils of the red and black complex of the Hawaiian Islands. The application of differential thermal analysis established kaolin as the dominant mineral in the red soils and montmorillonite as the dominant mineral in the black soils. To aid in the understanding and interpretation of the experimental data a discussion of the differential thermal apparatus and the clay minerals was given.
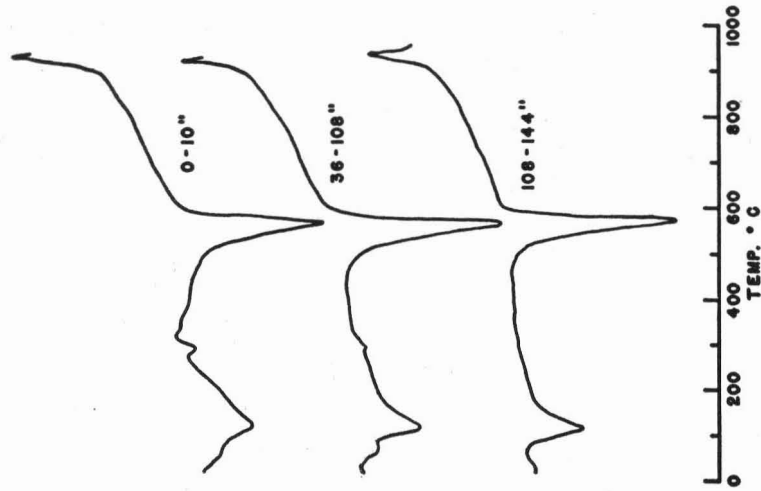
Fig. 14. Differential thermal curves of a red and black profile from Molokai showing kaolin as the dominant mineral throughout the profile, with the exception of small amounts of hydrous oxides at the surface.
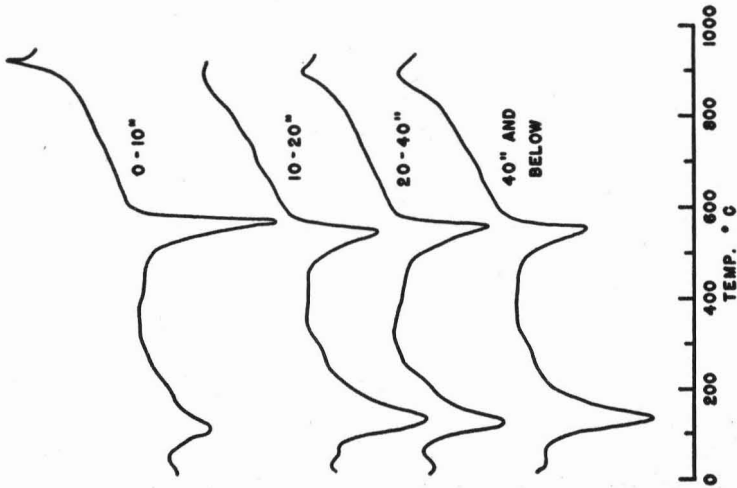

Fig. 13. Differential thermal curves of a red and black profile from Halawa Valley in which a red (0–10"), and black (10–20") layer formed over another red (20–40"), and black (40" and below) as a result of weathering on two alluvial deposits.

Four major variations in the soils of the red and black complex, differing in modes of formation, were recognized. The first type consists of black soils forming under low rainfall at low elevations adjacent to red soils forming under higher rainfall on upper elevations. Type II black soils may form under heavier rainfall than type I, but are stabilized by seepage waters from adjacent red soils. Type III comprises a number of black soils developing under restricted drainage, as a result of a high water table, near red soils having better internal drainage. Type IV consists of several profiles of alluvial and ash material, where a red top soil rests upon a black subsoil. In every case, except in a red and black profile from Molokai, kaolin was found to be the dominant clay mineral in the red soil and montmorillonite in the black soil, with a kaolin-montmorillonite mixture in the transitionary zones. Under intense leaching and oxidation, kaolin formation was favored. In situations where retention of bases and silica was favored, montmorillonite formation occurred.

The cause for the soil colors was reviewed. Hematite and goethite were listed as the main cause for the color in the red soils. Investigation of black soils low in organic carbon from Kunia road supports the view that the black color need not necessarily be associated with organic matter.

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