Soil Sequences in the Hawaiian Islands[1]

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THE WIDE RANGE of conditions under which soils have developed in the Hawaiian Islands has produced a pattern of soil geography which reflects the differential influence of the intensity and capacity factors of soil weathering.

Soil formation is the product of two actions, weathering (W) and leaching (L), on the surface and near the surface of the earth's crust. Weathering is the process of mineral decomposition, and leaching is the solution of more or less soluble constituents and their removal in the percolating waters. Both of the processes occur at different degrees of intensity but under the normal temperatures and pressures of the earth's surface. Soil is formed from its geological parent materials by decomposition of various products of volcanic action *in situ* or after their transportation either in their natural state or after the action of various agencies of disintegration and erosion, or after partial or complete decomposition to secondary minerals *in situ* or after deposition of more or less soluble constituents. In all instances soil is the product of these actions on the surface under the prevailing environment to form surface horizons which are distinct and parallel to the topographic surface rather than to the geological formations of the earth's surface.

The weathering action in soil formation (WxL) is strongly influenced by intensity factors of environment and time, and by capacity or inherent (resistance) factors of the parent material. The intensity factors are age or time of exposure (A), climate, including temperatures and rainfall (C), drainage (D), and vegetation (V), all of which govern the rate of action. The capacity factors are size of the units or texture (T), the inherent stability of mineral to decomposition (M), and the nature of the surface of mineral unit or coating (S). Thus the rate of soil formation may be expressed by the formula:

$$K \text{ (rate of soil formation)} = (WxL)\,\frac{ACDV}{TMS}$$

Since this reaction theoretically has been in existence since the formation of the earth's surface, K is a dynamic transitory equilibrium which is proceeding toward a system having some form of static equilibrium. In reality it cannot become a static system, since, over geological time, almost imperceptible changes continue to occur causing real changes. Therefore the system is considered a dynamic static system. Thus the products of soil formation will occur as a sequence, reflecting the influence of age, climate, etc. The members of a sequence in the early dynamic stage will exhibit great variation, but with time (A) it approaches a dynamic static system as the influence of the intensity and capacity factors approach zero. During this process, then, soils in any environmental area range from great variability in early stages to a high degree of uniformity in old age.

Sequences of soils in Hawaii occur which reflect the differing degrees of dominance of one or more of the soil-forming factors during the process of soil formation from a single type of parent material—e.g., in the different areas of one lava flow. Studies are being made of the inter-relationships of the soils in these sequences as means of gaining a better understanding of soil genesis. The soils of these sequences reflect the effect of increasing intensity of the soil-forming factors, as, for example, increasing amounts of annual rainfall, age or increasing time of exposure to weathering processes, and increase in the amount of specific surface in the weathering material due to differing rock textures.

The Hawaiian Islands are a natural laboratory for the study of soil formation. The islands have a remarkably uniform subtropical climate with very little difference between the mean temperatures of winter and summer. On the other

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hand, there is a wide range of annual rainfall—from 5 to over 500 inches per year, the heaviest occurring at the higher elevations of 2,000 to 4,500 feet. The distribution of rainfall varies from strongly seasonal in some areas to rather uniform distribution in others. The variable rainfall results in widely different types of vegetation—shrub, open forest, and rain forest. These vegetation types range from a high base circulating system in low rainfall areas to a very acidic system of the fern forests of the tropical rain forest areas.

The islands have developed as peaks of a mountain built up by volcanic action on the ocean floor. Progressive lava flows of basalt, andesite, and trachyte and their pyroclastic deposition of volcanic ash and cinders have built up a series of islands ranging in geological age from several million years to current depositions of lava. The oldest island is Kauai at the northwestern end of the island chain, and the most recent is Hawaii at the southeastern end of the chain. The range of geological ages represented by the different islands affords excellent facilities for a study of age on soil development on relatively similar parent rocks having a low quartz content. The mountainous character of the islands provides a great variety of drainage conditions. Thus, soil sequences are developed which reflect the effect of age, rainfall, drainage or percolating water patterns, and parent material.

SOIL SEQUENCE RELATED TO RAINFALL

Tanada (1951) pointed out the relationship between rainfall and kaolin content of soils of the Hawaiian Islands. According to his results, it was concluded that where the rainfall was more than 30 inches per year, the kaolin content of the soil decreased with increasing annual rainfall. Cline et al. (1955) and Sherman (1949) have reported a sequence of soil development which was related to both the amount of annual rainfall and its monthly distribution. The former, in an indirect manner, described and classified soils by the association of increasing content of free oxides to increasing rainfall. Sherman (1949), having the benefit of a broader knowledge of chemical composition, was able to make more specific conclusions as to the type of oxides which would be concentrated in the soil solum with the varying distribution patterns of rainfall. He found that the soils developed under a climate having alternating wet and dry seasons would show an increasing content of iron and titanium oxides and a corresponding loss of kaolin with increasing rainfall. Aluminum oxide would increase in the soils formed under a rainfall distribution which resulted in continuous moist conditions in the soil solum, and again with a loss of kaolin. In subsequent work, Sherman (1952) showed that these relationships would hold only under conditions of free internal drainage. If the internal drainage became restricted, resilication or kaolinization would occur in the soil. The data given in Table 1 show the mineral composition of a sequence of soils formed on a single basalt lava flow. As annual rainfall increases, the kaolin content decreases as long as the internal drainage of the soil is good. The Koolau soils, which have poor internal drainage, have a high content of kaolin. As rainfall increases, gibbsite increases in this soil sequence as long as internal drainage of the soils is good; again, this is shown by the Koolau soils.

A sequence of soils will develop under very low rainfall conditions which do not provide sufficient leaching for the removal of the bases. Under these conditions, the content of the montmorillonite type of clay minerals will increase with rainfall up to a point where the base removal has been sufficient to produce an acid condition resulting in an instabilty of the 2:1 layered alumino-silicate crystal lattice structures. At this point, kaolinization will be initiated. From this point, the kaolin content will continue to increase until base removal in the leaching nears completion, creating a very acid condition in which kaolin becomes unstable and decomposes, and further desiccation occurs. This will lead to the formation of free oxides. A sequence of soils having an increasing content of montmorillonite minerals has not been observed in the Hawaiian Islands. Soils developed on volcanic ash under an annual rainfall between 2 and 20 inches will probably show this condition. Our preliminary examination would support this possible relationship. A sequence of soils showing increasing kaolin content has been found in the soils of the Low Humic Latosols

TABLE 1

A SEQUENCE OF SOILS OCCURRING WITH INCREASING RAINFALL ON A SINGLE BASALT FLOW ON THE ISLAND OF KAUAI FROM ANAHOLA TO WAIPUHI FALLS IN A DISTANCE OF 6 MILES

Dry months	8–9	4–5	2–5	2–4	0–2
Wet months	3–4	4–5	4–6	5–8	8–12
Total rainfall	40–45	50–70	70–100	100–150	150+
Soil family	Kahana	Puhi	Haiku	Halii titaniferous phase	Koolau
Great soil group	Low Humic Latosol	Ferruginous Humic Latosol	Ferruginous Humic Latosol	Aluminous Ferruginous Latosol	Hydrol Humic Latosol
Clay minerals in order of abundance and in per cent of soil	Halloysite 70 Goethite 20 Ilmenite 5	Halloysite 35 Geothite, Hematite 40 Anatase, Ilmenite 10 Gibbsite 10	Goethite, Hematite 45 Gibbsite 25 Halloysite 20 Anatase, Ilmenite 10	Halloysite 30 Gibbsite 30 Anatase 30 Goethite, Magnetite 10	Kaolin 50 Gibbsite 15 Anatase 15 Goethite 10
Parent material of soil	Kaolinized basalt	Kaolinized basalt	Ferruginous bauxitic saprolite	Ferruginous bauxitic saprolite	Possibly volcanic ash
Parent rock	Basalt	Basalt	Basalt	Basalt	Basalt

formed where the annual rainfall is 15 to 40 inches, with the help of some low rainfall intergrades. The intergrade soil will have decreasing amounts of 2:1 layered alumino-silicate clays with increasing kaolin clay content as rainfall increases. The peak of kaolinization will occur in soils developed under about 35 inches of rainfall. An excellent sequence of this type can be found on the island of Oahu near the West Loch area of Pearl Harbor. Beginning at this point, and following the Kunia road, one encounters, in order, soils of the Honouliuli family → Molokai family → Lahaina family developed on alluvial materials. These soils are formed under 15 inches of rainfall, in the case of the soils of the Honouliuli family, to 35 inches for soils of the Lahaina family, and show the mineral relationships described as above, from montmorillonite type of clay minerals to a completely kaolinized profile.

SOIL SEQUENCE DUE TO AGE

Mohr (1944) has pointed out that soil formation progresses through stages of development ranging from youthful to senile. Soil formation is a dynamic process which proceeds at various intensities depending on the weathering environment. The influence of time on soil formation has been studied in the Hawaiian Islands. Attempts are being made to study sites which have identical climatic conditions with comparable parent materials. Since age is the variable being studied, it is impossible to find on a single island soils showing a sequence of the effect of this soil-forming factor. Therefore, to make this study, it is necessary to select sites on different islands.

The first observed effect of age on soil formation is the disappearance of soils of two prominent great groups occurring on the geologically young islands of Hawaii and East Maui—soils of the Reddish Prairie and Latosolic Brown Forest groups. These soils are absent on the older islands with the exception of a small area on Molokai having soils of the Oli Series which belong to the Reddish Prairie group. However, the soils of these two great groups, on chemical and mineralogical examination, show evidence of strong development of Latosol features. Both soils have weak A_1 horizons which grade gradually to a lighter-colored B horizon, which in turn overlies an unweathered volcanic ash. The difference between the groups is largely in the degree of removal of bases by leaching and the increased content of free oxide. Generally, soils of the Low Humic Latosol and Ferruginous Humic Latosol occur on the older islands in areas of similar environmental conditions, but do not occur on the younger islands. The work of Tamura et al. (1955) supported the hypothesis that the soils of the Latosolic Brown Forest were the precursors of the Ferruginous Humic Latosol. This conclusion was based on similarities in mineral composition of soils of the Naiwa family of the Ferruginous Humic Latosol group of West Maui, and the soils of the Olinda family of the Latosolic Brown Forest group of East Maui. The similarities between the soils of the Reddish Prairie group and soils of the Low Humic Latosol group are even greater.

An attempt has been made to study the changes made by weathering in soils of the same type from different areas, but formed under the same climatic environment and from very similar parent materials. Field observations indicated that a Lahaina soil developed on the Waimea volcanic series of Kauai (the oldest flows of the Hawaiian Islands) showed morphological properties suggesting a greater decomposition of clay minerals than was normal for these soils, which are made up predominantly of kaolin clays. Chemical analyses of samples of soil of this profile were compared with the analysis of a soil belonging to the Lahaina family formed under almost identical conditions but from Molokai, a younger island. The results of these analyses are given in Table 2, for the younger Lahaina soil, and in Table 3 for the older Lahaina soil. A comparison of the data reveals that the older soil has lost more silica, calcium, and magnesium than has the younger. The higher content of titanium and iron oxides in the surface horizon of the older Lahaina soil would suggest that the process of weathering is slowly converting this soil to one having the characteristics of the Ferruginous Humic Latosol group. Further evidence of the greater desilication in the geologically older profile is shown in the molecular ratios of SiO_2 to R_2O_3, which range from 0.84 to 1.14 in the older profile to 1.36 to 1.87 in the younger profile. Likewise, the ratio of SiO_2 to Al_2O_3 was consistently lower in the older profile. The ratio of SiO_2 to Fe_2O_3 was lower in the older profile and also much lower in the surface horizon. This soil must be considered at least an intergrade to the Ferruginous Latosols.

TABLE 2

CHEMICAL COMPOSITION OF A SOIL OF THE LAHAINA FAMILY FROM THE ISLAND OF MOLOKAI; MODERATE AGE OF WEATHERING

CHEMICAL CONSTITUENT, PER CENT	HORIZONS IN INCHES				
	0–3	3–15	15–35	35–46	46–60
SiO_2	31.23	32.23	32.36	32.73	40.80
Al_2O_3	23.84	23.76	24.85	26.30	25.61
Fe_2O_3	23.29	23.96	23.40	23.46	17.84
TiO_2	4.90	5.78	5.81	4.61	3.74
MnO	0.30	0.30	0.22	0.19	0.28
CaO	0.76	0.58	0.72	0.43	0.71
MgO	0.51	0.45	0.43	0.39	0.62
K_2O	0.20	0.13	0.13	0.05	0.07
Na_2O	0.03	0.06	0.03	0.08	0.06
pH	6.2	6.2	5.2	4.9	—
$K=\frac{SiO_2}{R_2O_3}$	1.36	1.40	1.38	1.35	1.87
$K=\frac{SiO_2}{Al_2O_3}$	2.21	2.30	2.21	2.12	2.71
$K=\frac{SiO_2}{Fe_2O_3}$	3.57	3.58	3.70	3.71	6.07

TABLE 3

CHEMICAL COMPOSITION OF A SOIL OF THE LAHAINA FAMILY OF THE LOW HUMIC LATOSOL FROM KOKEE ROAD, KAUAI; EXPOSED TO WEATHERING FOR A LONG GEOLOGIC PERIOD

CHEMICAL CONSTITUENT, PER CENT	HORIZONS IN INCHES						
	0–9	9–14	14–18	18–40	40–48	48–65	65–75
SiO_2	21.08	25.56	27.84	28.04	29.06	29.40	29.44
Al_2O_3	20.64	25.68	28.88	31.04	29.20	29.60	29.28
Fe_2O_3	34.63	27.26	22.42	21.73	23.83	22.22	23.86
TiO_2	10.41	5.48	3.22	3.27	4.92	4.06	4.94
MnO	0.24	0.22	0.20	0.20	0.21	0.20	0.24
CaO	0.09	0.06	0.03	0.03	0.02	0.02	0.02
MgO	0.96	0.66	0.49	0.53	0.54	0.57	0.58
K_2O	0.02	0.11	0.22	0.19	0.07	0.10	0.07
Na_2O	0.14	0.43	0.47	0.56	0.54	0.58	0.55
pH	4.9	4.9	4.8	4.8	4.8	4.6	4.5
$K=\frac{SiO_2}{R_2O_3}$	0.84	1.01	1.10	1.06	1.11	1.14	1.13
$K=\frac{SiO_2}{Al_2O_3}$	1.74	1.70	1.64	1.54	1.69	1.69	1.71
$K=\frac{SiO_2}{Fe_2O_3}$	1.63	2.49	3.31	3.43	3.25	3.53	3.29

The chemical and mineralogical changes occurring in the profile of the older Lahaina soil support the hypothesis of sequence of soil formation presented by Sherman in 1949. In this hypothesis, it was proposed that the kaolin soils of the Low Humic Latosols would lose their bases and would slowly desilicate with geological age and gradually acquire the characteristics of soils of the Ferruginous Latosols.

SEQUENCE OF ROCK WEATHERING

A study of progressive rock weathering as it is related to the origin of the parent material

TABLE 4

CHEMICAL COMPOSITION OF ULTRABASIC BASALT ROCKS AND THE SOIL WEATHERED FROM THEM UNDER DIFFERENT RAINFALLS (THE SOIL SAMPLE IN EACH CASE IS 2 INCHES FROM ROCK)

SAMPLE DESCRIPTION	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	TiO_2 %	LOSS ON IGNITION %
A. From Low Humic Latosol, Kapaa, Kauai—45 inch rainfall					
Rock core	42.4	14.9	14.8	2.1	1.6
Weathered soil	25.9	24.5	30.0	4.7	10.6
B. From transition zone between Ferruginous and Low Humic Latosol groups, 2 miles west of Kapaa, Kauai—60 inch rainfall					
Rock core	42.9	14.6	14.6	2.0	1.3
Weathered soil	24.8	29.0	30.0	4.2	12.1
C. From Ferruginous Latosol, Wailua Homestead, Kauai—90 inch rainfall					
Rock core	45.8	16.2	14.9	2.5	2.5
Weathered soil	18.5	32.2	29.6	5.2	14.4
D. From Ferruginous-Aluminous Latosol, Wailua Game Refuge, Kauai—120 inch rainfall					
Rock core	36.7	10.8	14.2	2.8	—
Weathered soil	2.4	39.3	36.5	6.5	16.7

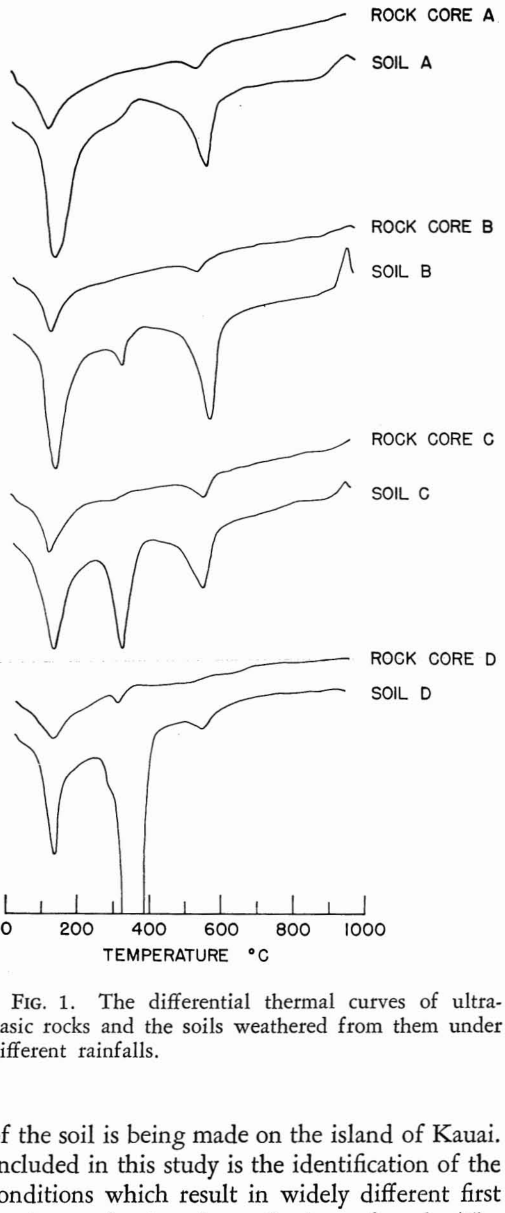

FIG. 1. The differential thermal curves of ultrabasic rocks and the soils weathered from them under different rainfalls.

of the soil is being made on the island of Kauai. Included in this study is the identification of the conditions which result in widely different first products of mineral weathering of rock. The rocks considered in this study are from along a uniform lava flow of a melilite nepheline basalt located in the Wailua Homestead area, and exposed to a range of rainfall of from 45 to 200 inches per year. The rocks immediately below the soils are weathered, most of them to kaolinitic and bauxitic saprolite. Samples of weathered saprolite can be found which have an unweathered core of the rock. In every case, the boundary between unweathered rock and the weathered clay is very sharp and abrupt. The chemical analyses and mineral identification by differential thermal analysis are given in Table 4 and Figure 1. Where the rainfall is between 40 and 60 inches, the first product of weathering is kaolin, having a silica content of 32 per cent and an alumina content of 28 per cent. Under 120 inches of rainfall, the first product of weathering is a ferruginous bauxite containing 2 per cent silica, 39 per cent alumina, and 36 per cent iron oxide. The weathered rocks between these two extreme points vary greatly, but most of them have weathered to either a kaolinitic or bauxitic saprolite. However, they show a gradation of mineral weathering in which gibbsite increases and kaolin minerals decrease, as shown in Figure 1.

The data obtained from the chemical analysis of the rock and its soil product (Table 4) show a relatively uniform composition in the rock cores. Rock D probably has lost some of its silica due to the wetness of its location. The soil analyses show the increasing influence of leaching due to increased annual rainfall. As rainfall increases, the silica content of the soils decreases (from 26 per cent to 2 per cent), the alumina content increases (from 24 to 39 per cent), and iron oxide increases slightly (from 30 to 36 per cent). The chemical and mineralogical analyses by differential thermal methods (Fig. 1) indicate that as rainfall increases, the stability of kaolin type minerals decreases and the free oxides become the stable minerals of the soil. The soil from rock A shows thermal reaction for kaolin minerals while the soil from rock D shows a trace for kaolin and a strong reaction for gibbsite.

SUMMARY

The soils of the Hawaiian Islands offer excellent opportunities for the study of the effects on soil formation of the differential intensity of the factors involved in soil development.

There are sequences of soils which reflect the effect of rainfall: soils rich in montmorillonite type of minerals develop in areas of low rainfall, kaolin develops where rainfall is moderate, and free oxides where the amount of rainfall

favors complete leaching and rapid desilication of the weathering matrix.

The islands offer an excellent site also for the study of the effect of age on soil development. Examples of the transition of one type of soil group to a soil group of greater stability are described.

The interaction between the influence of parent material and of weather and rainfall is being studied. The first phase of this preliminary study is to determine why the products of rock weathering can range from kaolin to ferruginous bauxite on a single lava flow, with rainfall being the chief variable. The second phase is a study of the effect of the nature of the first product of rock weathering on subsequent soil formation. Soils of three great soil groups are developed on this parent material, namely, Aluminous Ferruginous Latosol, Ferruginous Humic Latosol, and Low Humic Latosol.

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