Factors Influencing the Development of Lateritic and Laterite Soils in the Hawaiian Islands[1]

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THE PARENT MATERIALS of the soil of the Hawaiian Islands have weathered under climatic conditions which are favorable for the development of lateritic and laterite soils. Cline (in press), in his classification of Hawaiian soils, has recognized the following four groups of lateritic and laterite soils: (a) low humic latosols—a group of soils which have developed in regions having a rainfall ranging from 15 to 80 inches. These soils have silica to sesquioxide ratios varying from 1.3 to 1.8; (b) humic latosols—this group of soils has developed in areas having a rainfall from 60 to 150 inches. These soils have developed silica to sesquioxide ratios varying from 0.5 to 0.8; (c) hydrol humic latosols—these soils are found in the regions receiving a very heavy rainfall, 120 to 300 inches. The silica to sesquioxide ratios of this group of soils vary from 0.3 to 0.6; and (d) ferruginous humic latosols—soils belonging to this group have a concentration of heavy minerals in the A_2 horizon. These soils have developed in regions receiving a relatively wide range of rainfall, 25 to 150 inches. The silica to sesquioxide ratios of these soils show great variation, ranging from 0.05 to 1.0.

Each group of soils possesses clays which have distinct and definite chemical properties and these properties were used as a basis for the classification of lateritic soils into the four groups. Since each group of these soils occurs in regions having different climatic conditions, it is likely that climate plays a major role in development. Since the geological ages of the parent materials vary greatly, the time of exposure of the parent material to soil-forming processes will also have had a major effect on soil development. Due to the great variation of the age of the soil parent material, and the great variation in climate due to the effects of elevation and trade winds on temperatures and rainfall regions, a very complex pattern of soil development has resulted. It is the object of this paper to consider the effects of climate and age on the development of lateritic and laterite soils in the Hawaiian Islands.

REVIEW OF LITERATURE

Most of the research work involving Hawaiian soils has had for its objective the solution of agronomic problems. Kelley and his coworkers (1912, 1914, 1915) have published several papers on the general chemical composition of certain Hawaiian soils. Moir (1935), in reviewing the work on chemical composition, has concluded that Hawaiian soils have lost a large portion of their silica.

More recently, Hough and Byers (1937) have reported data from a very complete chemical analysis of soils from seven Hawaiian soil profiles. These workers pointed out the very uniform composition of the profiles of the red soils (low humic latosols) and suggested that the clay of these soils was of the kaolinite type. Their data also revealed an unusually high titanium oxide content. Later Hough *et al.* (1941) reported the chemical composition of 21 soil profiles which were selected to range in length of time of weathering from very recent to very old. From the data obtained, these workers suggested that Hawaiian soils were the products of the soil-forming process called podsolization, and were, therefore, podsolic. They based their hypothesis on the following points: first, the

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parent materials of Hawaiian soils, basalt and trachyte, are relatively free of quartz, so that quartz could not accumulate in the A horizon; second, there is an accumulation of titanium oxide in the A horizon of Hawaiian soils. It was their assumption that titanium minerals are resistant to weathering and would, therefore, accumulate where quartz would normally be found in a podsolic profile.

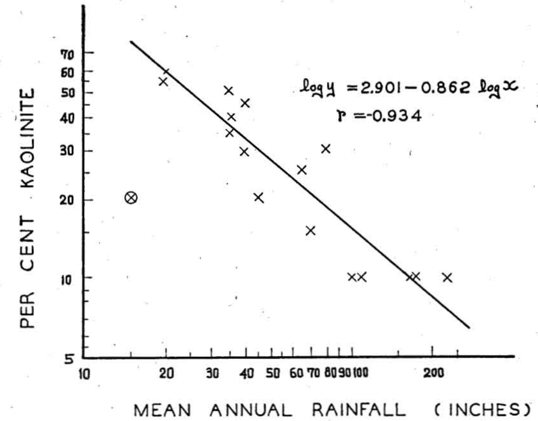

FIG. 1. The relationship between the kaolinite content of the soil colloid and mean annual rainfall.

Dean (1947) and Tanada (1944) have shown that a high kaolinite content in Hawaiian soils developed in regions receiving 25–35 inches of rainfall annually and that the kaolinite content decreased with increasing rainfall. This relationship between rainfall and kaolinite content is illustrated in Figure 1. Subsequent work has shown that the kaolinite content in certain Hawaiian soils (ferruginous humic latosols) decreases with age regardless of the amount of rainfall under which the soil has developed (Sherman *et al.,* 1949). The results of work in our laboratories have supported the hypothesis that in the weathering of tropical soils two weathering processes are ocurring, namely, clay mineral formation (kaolinization) from the decomposition of primary minerals of the soil parent material, and clay mineral decomposition with free oxide accumulation from the decomposition of the kaolinite type of clay minerals. The recent publications from this Station (Sherman *et al.,* 1949, and Fujimoto *et al.,* 1949) have described soils belonging to the ferruginous humic latosol in which the kaolinite clay minerals have undergone almost complete decomposition resulting in the development of soil horizons having a high concentration of iron and titanium oxides. Hematite, goethite, and anatase have been identified as the dominant minerals occurring in these horizons.[3] The decomposition of the kaolinite and the accumulation of these free oxides of secondary origin have occurred under a rainfall of 35 inches per annum and thus can be attributed only to age.

Mohr (1944), in describing the factors which influence soil weathering in tropical regions, has placed considerable emphasis on the part played by rainfall distribution, profile drainage, and age or time of exposure to soil forming processes. He has divided the types of rainfall distribution into five groups, depending on the number of months receiving an average monthly rainfall of less than 60 mm. (which are classified as dry months) and the number of months receiving an average rainfall higher than 100 mm. (which are classified as wet months). His groups range from regions in which most of the months are classified as dry, to regions which are predominantly wet. Closely associated with the distribution of rainfall is the type of water movement in the soil. This is extremely important in tropical regions since the internal drainage soils may be restricted due to formation of impervious clay layers. Under appreciable rainfall this can produce conditions which result in the upward movement, from the zone of saturation, of a considerable portion of the water entering the soil and the lateral movement of water through the horizons of soils which have developed on slopes.

Mohr (1944), in his discussion of the age of soils, recognizes five stages of soil weathering. The five stages of soil weathering which he feels every soil must pass through are fresh, juvenile, virile, senile, and "laterite." According to his hypothesis, the end-product of tropical soil

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weathering will be the iron oxide "laterite crust" as the surface soil and a layer of bauxite as the subsoil.

The soil associations which occur in the Hawaiian Islands appear to fit into several phases of Mohr's hypothesis of tropical soil weathering. The distribution of rainfall in the Hawaiian Islands fits all five of Mohr's groups. Laterization is occurring in soils which have developed in areas which are predominantly dry, those which have alternating wet and dry seasons of variable duration, and under predominantly wet and continuously wet conditions. Also there is good evidence that examples of all five stages of soil weathering described by Mohr do exist in the Hawaiian Islands. The recent discovery of a soil horizon resembling the "laterite crust" supports this contention (Fujimoto *et al.*, 1949).

RELATIONSHIP OF SOIL GROUPS TO RAINFALL DISTRIBUTION IN THE HAWAIIAN ISLANDS

The Hawaiian soils which are developed by the soil-forming process, laterization, occur under a wide range of rainfall. Casual observations would suggest that each of the latosol groups occurs under rather definite regions of rainfall distribution. Further inspection of the actual rainfall for each month at different locations on the island of Oahu revealed a similar rainfall distribution for soils belonging to each latosol group. The data given in Table 1 were obtained by classifying the rainfall distribution of the regions where each soil group is developed according to the wet and dry months proposed by Mohr (1944). The data show that the soils belonging to the low humic latosol and the ferruginous humic latosol have a definite dry season. The lack of a clear-cut difference between the rainfall distribution would suggest that the ferruginous humic latosol may develop from the low humic latosol with age. The humic and hydrol humic latosol have developed under continuous wet conditions. The data include the number of very wet months, or the months receiving more than 8 inches of rainfall. This information is given to show the very wet condition under which the hydrol humic latosols are developed. The chemical analysis of soils has revealed a marked difference in the composition of soils developed in the regions having a definite dry season and of the soils developed under continuous wet conditions. The

TABLE 1

THE RELATIONSHIP BETWEEN THE RAINFALL DISTRIBUTION AND SOIL GROUPS DEVELOPED ON THE ISLAND OF OAHU*

GREAT SOIL GROUP	SOIL FAMILY	NO. OF DRY MONTHS†	NO. OF INTERMEDIATE RAINFALL MONTHS†	NO. OF WET MONTHS†	NO. OF VERY WET MONTHS†
Low humic latosol	Molokai	8	4	0	0
Low humic latosol	Lahaina	6	6	0	0
Low humic latosol	Wahiawa	5	4	0	0
Low humic latosol	Kahana	2	7	3	0
Low humic latosol	Kohala	1	4	8	0
Ferruginous humic latosol	Mahana	9	2	1	0
Ferruginous humic latosol	Naiwa	5	3	4	0
Humic latosol	Kaneohe	1	5	6	0
Humic latosol	Honolua	0	4	8	0
Hydrol humic latosol	Koolau	0	0	8	4
Hydrol humic latosol	Koolau	0	0	3	9

* Mohr's definition of dry and wet months was based on mean monthly rainfall. The data given in this table are based on monthly median rainfall as presented by Halstead and Leopold (1948).

† Dry months, less than 2⅜ inches of rainfall; intermediate rainfall months, 2⅜–4 inches; wet months, 4–8 inches; very wet months, more than 8 inches.

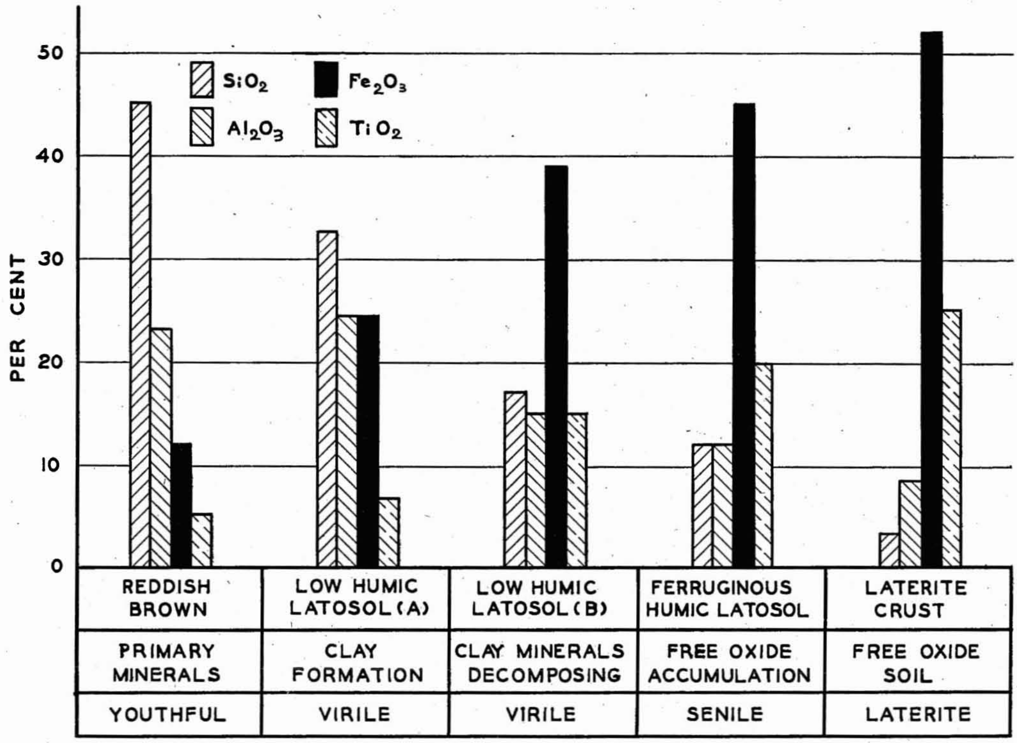

FIG. 2. The influence of the lengthening of the wet season of an alternating wet and dry season climate on the chemical composition of the A horizon of the soil. The wet season increases in this series of soils from left to right. (A) and (B) profiles are two different soils belonging to the low humic latosol.

fact that the soils differ greatly in their chemical composition and physical properties would indicate that the distribution of rainfall must play an important role in the type of weathering which has occurred in the soil.

CHEMICAL COMPOSITION OF SOILS DEVELOPED UNDER A DEFINITE DRY SEASON

The chemical analysis of several soil profiles belonging to the low humic latosol and ferruginous humic latosol to determine their "major" oxide content was made by methods described by Piper (1944). The soils were selected to represent the following successive stages of weathering: (a) the youthful soil containing most of its primary minerals; (b) the peak of clay formation—kaolinization; (c) the stages showing the cessation of clay formation and the increasing oxide formation or clay mineral decomposition; and (d) the final end-product of weathering—the free oxide soil. With the exception of the end-product stage, these stages of soil weathering are found under increasing rainfall. The end-product stage—the oxide soil—exhibits evidence of lateral movement of water through the soil solum. Likewise, the stages of soil weathering exhibit the progressive effect of the shortening of the drought season of these soils.

The results obtained from the analysis of soil samples from the A horizons of the selected soil profiles presenting successive weathering stages are shown graphically in Figure 2. The data show a steady decrease in the silica content of the A horizons with the advancement in the weathering of the soil. Alumina content of the soil increases with the clay formation and decreases rapidly as the clay minerals decompose. The iron and titanium oxides accumulate as the

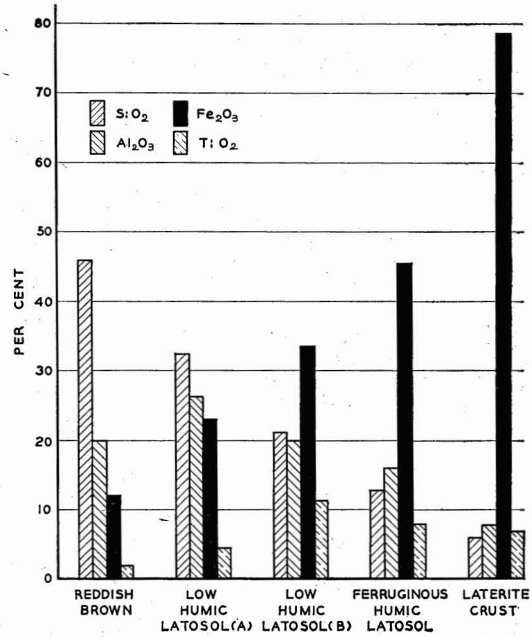

FIG. 3. The influence of the lengthening of the wet season on the chemical composition of the B horizons of the soils shown in Figure 2. (A) and (B) profiles represent two low humic latosols.

soil weathering progresses and in the "laterite crust" they constitute almost 80 per cent of the soil. These oxides are present as two secondary minerals—hematite and anatase.

The data presented graphically in Figure 3 were obtained from the chemical analysis of soil samples representing the B horizons of the soils shown in Figure 2. The silica, alumina, and iron oxide show exactly the same trends as were found for the soils representing the A horizon. Titanium oxide content of the B horizons fails to increase with weathering. Since these soils are very acid, it is probable that the titanium was converted to metatitanic acid and moved upward to the A horizon where it was dehydrated during the dry seasons ultimately to form anatase. The iron oxide of the B horizon of the "laterite crust" exists as hematite and goethite.

The data presented in Figures 2 and 3 represent, in general, a sequence of conditions emphasizing a range in the proportion of dry months to wet months. The range spans from 12 dry months to approximately 3 dry, 3 wet, and 6 intermediate months per year in the ferruginous humic latosol. It is obvious that the effectiveness of an alternating wet and dry season on the rate of soil weathering is governed by the following factors: (a) amount of rainfall during the wet season and (b) the intensity and duration of the dry season. However, the question arises as to the effect of time. Will the soils belonging to the low humic latosol continue to weather until they take on the characteristics of the ferruginous humic latosol? It is reasonable to assume that they will continue to weather toward the end-product, the "laterite crust." The following evidence would support this contention: (a) the increase in area of soils belonging to the ferruginous humic latosol with the geological age of the parent materials and a simultaneous decrease in area of the soils belonging to the low humic latosols. The island of Kauai, geologically the oldest of the major Hawaiian islands, has the greatest area of ferruginous humic latosols, and the low humic latosols show greater advancement in weathering than the same type of soil on younger islands; (b) the decrease in kaolinite content and the increase in iron oxide content in low humic latosols on the older geological parent materials; (c) the occurrence of the "laterite crust" on relatively dry slopes receiving a rainfall comparable to that of the drier low humic latosols on the island of Kauai; and (d) the increase in compaction of the subsoils of the low humic latosols with age, which may favor formation of an impervious subsoil which will in turn develop conditions favorable for the lateral movement of water through those soils occurring on slopes. In the drier regions of the low humic latosols the rainfall will probably never be sufficient in quantity to produce this transformation but in those which have a definite wet season, time will certainly produce ferruginous humic latosol.

CHEMICAL COMPOSITION OF THE SOILS DEVELOPED IN AN ABSENCE OF A DEFINITE DRY PERIOD

The soils belonging to the humic latosol and the hydrol humic latosol have been developed under conditions in which the soil solum rarely dries out. These soils in the Hawaiian Islands are covered with dense cover of ohia, tree ferns, and staghorn fern. The latter two produce an extremely acid forest floor (Sherman, 1947). These soils have been separated in the field on the basis of their clay properties. The clay of the humic latosol can be pressed into a ribbon between one's fingers while that of the hydrol humic latosol will smear. A series of soil profiles representing a sequence of these clays developed under increasing rainfall was selected for analysis. These soils range from a soil profile belonging to an intrazonal group (brown forest) developed under 70 inches of rain per annum to a hydrol humic latosol profile developed under 273 inches of rain per annum; all have developed on parent materials made up of volcanic ash. The data obtained from these analyses are given graphically in Figure 4.

The data presented in Figure 4 show an increase in the alumina content with an increase in rainfall. The silica and iron oxide content appears to decrease with an increase in rainfall. This would suggest that under continuously wet conditions the alumina will become stabilized and iron oxide will become unstable and leach away. Tanada (1944) has identified bauxite and limonite as the minerals representing alumina and iron oxide in these soils. It is likely that as this soil continues to weather, the bauxite will continue to accumulate as a result of the destruction of the kaolinite clay minerals and the removal of silica and iron oxide by leaching. Thus, the end-product of weathering in the very wet tropics will probably be a "bauxite laterite."

DISCUSSION

The author has presented two sequences of soil weathering which are considered to be fun-

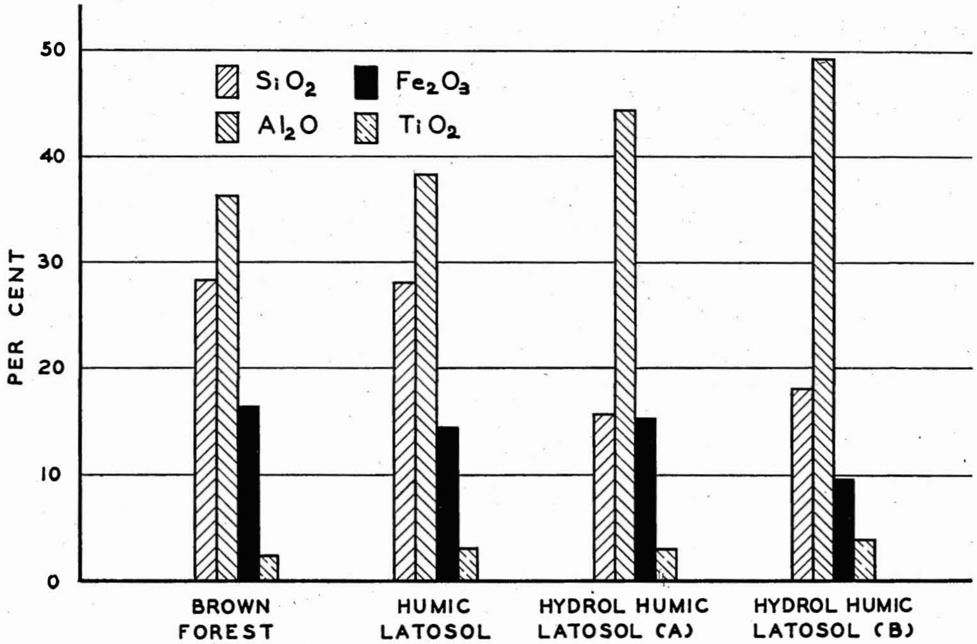

FIG. 4. The influence of an increase in annual rainfall on the chemical composition of soils developed in a continuously wet region.

damental in any interpretation of the soil associations which occur in tropical regions. In this presentation every effort has been made to avoid the complexities in the soil associations due to transition zones, degradation due to shifting climatic conditions or to lowering of the general elevation of volcanic areas, and differences in the composition of the weathered geological materials.

The initial weathering of parent materials is the breakdown of the primary minerals with the formation of secondary clay minerals of the kaolinite type. The rate of decomposition of the kaolinite minerals appears to be closely related to the amount of rainfall under which the soil is formed. Under extremely heavy rainfall the formation of the secondary clay mineral and its subsequent decomposition may be so rapid and transitory as to leave the outline of the original minerals and stratification of the parent materials. The hydrol humic latosols often show the stratification of the original parent material.

The distribution of rainfall plays an important role in the nature of the ultimate end-product of laterization in tropical soils. The stabilization of the iron oxide in soil has resulted from an alternating wet and dry season climate. Under a continuously wet soil profile environment, alumina becomes the stabilized free oxide. The amount of iron remaining in these soils depends on the amount of rainfall and aeration. This would explain to some degree the occurrence of aluminum oxide laterites and iron oxide laterites. The effect of the alternating wet and dry season can be destroyed by the development of a poor internal drainage in the soil solum. If this condition promotes lateral movement of water, as it will on slopes, it will facilitate the development of the iron oxide "laterite crust." If the impervious condition produces a stagnation of the water in the profile, a certain amount of resilication will take place with the removal of the easily reducible iron in the slow leaching of the impervious layer. The result of this condition will be the development of the profile of a very wet soil.

CONCLUSION

The data presented in this paper have emphasized several important fundamental reactions which occur in tropical soil. In the development of tropical soils two weathering actions are taking place: (a) the formation of clay minerals of kaolinite type from the primary minerals, and (b) the decomposition of the clay minerals with the accumulation of free oxides of iron, aluminum, and titanium.

The distribution of the rainfall and proportion of months receiving less than 2⅜ inches of rain (the dry months) and the months receiving more than 4 inches (the wet months), play an important role in the nature of the free oxides which will become stabilized and will accumulate in the soil solum. In evaluating the quantity of rainfall it was found necessary to introduce the number of very wet months (more than 8 inches of rain) in order to differentiate between the humic latosol and hydrol humic latosol which are developed under very wet conditions.

The low humic latosol and the ferruginous humic latosol have developed in a climate having a definite dry season alternating with a wet season of varying length and intensity. The soils developed under this type of season would exhibit the following chemical properties with increased weathering due either to the intensity of the alternating wet or dry conditions or to time of exposure of this type of weathering condition: (a) in the early stages both the kaolinite and alumina content increase and both decrease with further weathering; (b) silica content of the soil decreases with the age of weathering of the soil; (c) the content of iron and titanium oxides in the soil increases with the weathering age of the soil; and (d) the final end-product of weathering under these conditions is a "laterite crust" having a high content of iron and titanium minerals.

The humic latosol and hydrol humic latosol are developed under climates which have no definite dry season. Soils developed under these conditions have the following chemical properties: (a) the rapid decomposition of the clay minerals to the free oxides; (b) an increase in the alumina content with increase in rainfall; (c) decrease in the content of silica and iron oxide with increase in rainfall; and (d) the ultimate end-product of soil weathering will be an "aluminum oxide laterite," probably a "bauxite laterite."

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