The Role of Dehydration in the Development of Laterite[1]

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SOIL FORMATION in tropical regions is determined by the nature and extent of the chemical weathering of the soil-forming materials. The intense chemical weathering and the varying length of time of exposure of minerals to weathering have resulted in the development of a broad sequence of soil formation in the tropical areas of the world. Sherman (1949) has shown that the soils of the Hawaiian Islands exhibit a sequence of soil development which can be related to a sequence of mineral weathering as proposed by Jackson *et al.* (1948). This sequence of soil formation represents a series of successive stages of secondary mineral development with the following order of soils rich in: (1) primary minerals; (2) montmorillonite; (3) kaolinite; (4) hydrated sesquioxides; and (5) dehydrated sesquioxides. The end product of this weathering cycle would be either a ferruginous laterite or a bauxite laterite, depending on the environmental conditions. These two products represent two extremes of a wide range of weathered end-products, as the intermediate member —a ferruginous bauxitic laterite—is quite common (Harrison, 1934).

Ferruginous laterite was described by Buchanan (1807). As described by Buchanan, laterite is a soil horizon which has a very high content of iron oxides. These iron oxides exist as the minerals, limonite, goethite, hematite, and magnetite. The profile of the ferruginous laterite must have a horizon rich in iron oxide which will harden, on exposure, to an indurate layer with brick-like properties. The ferruginous horizon may contain concretions of iron oxide in which case it is a pisolithic laterite, or the iron oxide may exist as a lens in a porous matrix which is known as a vesicular laterite, according to Pendleton (1941). Ferruginous laterite may also develop as a massive horizon near or at the surface which on exposure will harden and develop a uniform, structureless crust, or corapace. Soils of this type have been described by Aubreville (1947, 1948), Chevalier (1948), and Sherman (1950).

The mode of origin, or formation, of ferruginous laterite has been a point of controversy. Glinka (1927) believed that laterites formed under both evergreen and savannah types of vegetation. Richthofen's views (1860) differed from Glinka's in that he postulated the formation of laterite under a former forest vegetation which had been succeeded by a shrub and grass vegetation. In other words, as soils degraded they could not support the evergreen forest; thus, the forest disappeared and was replaced by a lower level of vegetation. Harrassovitz (1930), Holmes (1914), and Campbell (1917) concluded from their studies that laterite formed only where climatic conditions were conducive to the upward movement of the dissolved soil sesquioxides, which would only occur under alternating wet and dry conditions. On the other hand, Pendleton (1941, 1942, 1946) believes that laterites are formed by the oxidation and

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precipitation of the iron oxides in the zone above the fluctuating water table. This layer is made up of concretions of iron oxide which will harden on exposure to give the ironstone laterite, a material suitable for building material. Finally, there are soil scientists who hold that laterite has developed by residual accumulation as the result of leaching and removal of silica. Marbut (1932) and Fox (1933) were the leading advocates of this hypothesis of the mode of formation of laterite.

In spite of the numerous hypotheses as to the origin of laterite, there are certain facts which are included in all proposals. One of these facts is that in the early stages the weathering surface is losing silica and bases. Desilication is taking place with the progressive development of soils having a sequence of minerals with a lower silica content. Secondly, as desilication proceeds the sesquioxides accumulate in the soil. These weathering processes are accelerated under high rainfall and high temperatures which are common to many tropical regions. Lastly, all ferruginous laterites harden on exposure. The hardened laterite is made up of lenses or concretions of iron oxides often cemented together by a kaolinitic clay.

A number of titaniferous ferruginous laterite crusts have been described in the Hawaiian Islands by Sherman (1952). Each profile of these soils has a massive indurate surface horizon having both a high bulk density and a high particle density. This hardened surface horizon is underlaid by a friable subsoil. This subsoil horizon possesses the bulk density of an average soil. Likewise, the particle density is lower than that of the surface horizon. Below the friable subsoil horizon is an impervious layer which may be the unweathered country rock, a plastic clay, or an unconformity-like relationship which may have developed by pedogenic processes rather than being a geological unconformity.

These laterite crusts were either barren or were covered by scattered bunches of grass or vines. However, some of the areas which exhibited the crust-like surface horizon had a fair amount of vegetation. These areas, also, exhibited a high bulk density and high particle density relationship such as is found in the barren crust areas. From many observations made during wet and dry weather, it was noted that the bulk density of the soil varied according to the soil moisture conditions. In a visit to a barren crust area on Kauai after a heavy rain, a marked difference was observed between the bulk density and hardness of the surface soil of the barren area and the adjacent identical soil under a vegetative cover. It has been observed that the crust will develop on irrigation ditch banks where wetting and drying have occurred at very frequent intervals. The appearance of the hardened crust can be associated with dry periods, suggesting that its formation is due to dehydration. Thus, it is possible that vegetation will protect the hydrated minerals from dehydration and prevent the crust formation.

A study has been conducted to determine the role of dehydration of the hydrated sesquioxides in the development of the laterite crust. The study also included the determination of the effect of dehydration on the physical and chemical properties of the soil. For this study two sets of soil samples from adjacent profiles were selected. The soil profiles were located on the slopes of the western rim of Waimea Canyon on the island of Kauai. A titaniferous ferruginous laterite crust covers a rather level bench on this slope. Profiles were selected at different areas of this laterite crust. The two main profiles used in this study were taken at the edge of the barren crust area so that the profile without a vegetative cover was taken only 3 feet from the site of the profile with a vegetative cover. The morphology of the two profiles was identical except for the obvious difference in the physical condition of the surface horizon. The characteristics of the two profiles are shown in Figure 1.

METHODS OF ANALYSIS

Soil samples were collected from the pro-

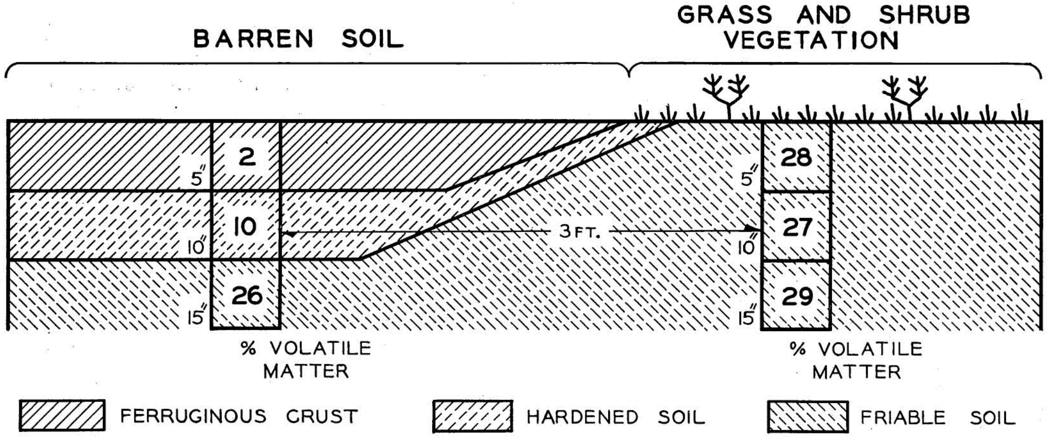

FIG. 1. The location and relationship of the hardened crust and vegetative cover of two adjacent profiles from Waimea Canyon, Kauai.

files as shown in Figure 1 and in a like manner from other similar areas, including the crust developed on an irrigation ditch bank. The bulk density, particle density, differential thermal analysis, cation exchange capacity, and content of the major oxides were determined for each soil sample. The bulk density of the soil was determined by two methods. The first was by removing the soil from a given space and determining its dry weight. The volume of soil was determined by fitting a plastic bag to the space occupied by the soil and ascertaining the amount of water required to fill the hole. The second method was similar except that the soil was taken by a sharp-edged cylinder of a known volume. The particle density of the soil was determined by the pycnometer (Wright, 1934). The cation exchange capacity and the oxide analysis were made by methods described by Piper (1944). Differential thermal analysis was made according to the procedure proposed by Norton (1939).

EXPERIMENTAL RESULTS

Bulk Density and Particle Density: The most striking characteristics of the laterite crust are the high apparent and true specific gravity. Fujimoto *et al.* (1948) have described a laterite crust in which the surface horizon contains more than 50 per cent heavy minerals. In the profile there is a tremendous difference between the indurate surface horizon and the friable layer in their bulk density and soil particle density. This same difference was present in the surface layer of the barren profile but was not apparent in the profile with a vegetative cover. In Table 1 the bulk densities and particle densities of the soils taken from a profile without vegetative cover and a profile with vegetative cover are given. The bulk density of the soil samples from the well-developed laterite crusts was 1.9 or greater, and their particle density was higher than 3.8. The bulk density of the soils from the profile with a vegetative cover was 1.0 or lower and the particle density ranged from 2.7 to 3.3. The highest bulk density and particle density, 2.5 and 4.1, respectively, were found in a fragment of the crust from an irrigation ditch bank wall. The data clearly demonstrate the obvious difference between the soils of the barren areas and those with a vegetative cover. The observations indicate that the vegetative cover does protect the soil from hardening to an indurate horizon. The differences are more clearly demonstrated in Table 2, which presents the averages of the different types of soil profiles in Table 1.

TABLE 1

A COMPARISON OF THE BULK DENSITY AND PARTICLE DENSITY OF DIFFERENT SOIL HORIZONS IN BARREN LATERITE CRUST AREAS WITH ADJACENT AREAS HAVING A VEGETATIVE COVER

BARREN SOILS (CRUST)				VEGETATIVE COVER (NO CRUST)			
LOCATION	DEPTH	BULK DENSITY	PARTICLE DENSITY	LOCATION	DEPTH	BULK DENSITY	PARTICLE DENSITY
	Inches				*Inches*		
Laterite crust Waimea Canyon Site A	0– 7	2.0	3.84	Waimea Canyon Site C near sites A and B	0– 5	0.8	2.86
Laterite crust Waimea Canyon Site A—friable layer	7–14	1.1	2.71	Waimea Canyon Site C near sites A and B	5–10	0.9	2.99
Laterite crust Waimea Canyon Site B	0– 7	2.2	4.43	Waimea Canyon Site C near sites A and B	10–15	0.9	2.82
Laterite crust Waimea Canyon Site B—friable layer	7–14	0.8	2.21	Waimea Canyon Site C near sites A and B	15–20	1.0	2.91
Laterite crust Lower Waimea Canyon Irrigation ditch bank Site E	0– 5	1.9	3.98				
Laterite crust Lower Waimea Canyon Irrigation ditch bank Site E	5–10	2.1	4.16	Waimea Canyon Site D above site C	Matted roots on surface	0.9	2.75
Laterite crust Lower Waimea Canyon Irrigation ditch bank Site E	10–15	2.1	4.25	Waimea Canyon Site D above site C	0– 5	0.9	3.24
Hardened soil Lower Waimea Canyon Irrigation ditch bank	0– 5	1.4	4.00	Waimea Canyon Site D above site C	5–10	0.9	3.21
Hardened soil Lower Waimea Canyon Irrigation ditch bank	5–10	1.3	3.81	Waimea Canyon Site D above site C	10–15	1.0	3.34
Hardened soil Lower Waimea Canyon Irrigation ditch bank	10–15	1.3	3.79				
Loose clod Irrigation ditch bottom	....	2.5	4.14				

Chemical Composition: The soil samples from the two profiles shown in Figure 1 were analyzed for major oxide constituents, and the data obtained are given in Table 3. A marked difference was found in the amounts of certain constituents and also in the weight loss on ignition. The soil of the surface horizon from the area having a vegetative cover showed a loss of weight amounting to 28 per cent on ignition, whereas the soil from the same horizon of the barren profile lost a little over 2 per cent. The same data from the 10–15-inch

TABLE 2

THE AVERAGE BULK DENSITY AND PARTICLE DENSITY OF A SERIES OF FERRUGINOUS LATERITES AT DIFFERENT DEGREES OF HARDENING

AVERAGE	SAMPLES FROM CRUST	SAMPLES FROM HARDENED SOIL	SAMPLES FROM PROFILES HAVING VEGETATION	SAMPLES FROM FRIABLE SUBSOIL
Bulk density	2.13	1.33	0.91	0.95
Particle density	4.13	3.87	3.01	2.46

layer of both profiles showed practically no difference in their loss of weight on ignition, being 26 and 28 per cent.

The content of iron and titanium oxides is the highest in the soil from the 0–5-inch and 5–10-inch layers of the profile of the barren area, while the 10–15-inch layer of both profiles has a very similar amount of these oxides. The aluminum oxide content of soil from the 0–5-inch and 5–10-inch layers of the profile with the vegetative cover is higher than that for the corresponding soil layers of the profile from the barren area. The soils from the profile with a vegetative cover are less acid than the soils from the barren area. In the former the soil reaction ranges from *p*H 4.4 to 4.6 and in the latter from *p*H 3.8 to 4.2.

In Table 4 the data obtained from the analysis of cation exchange capacities of the soil are given. The cation exchange capacity of the soils shows the same relationship as the loss on ignition. The soil from the surface horizon of the profile from the area having a vegetative cover has a much higher exchange capacity than that from the surface horizon of the profile from the barren area, being 41.0 and 3.7 milliequivalents per 100 grams, respectively. Likewise, a difference existed in the 5–10-inch layer of the two profiles in which the cation exchange capacities were 37.0 and 15.6 milliequivalents per 100 grams, respectively. The cation exchange capacities of the 10–15-inch layer were very similar, being 38.4 and 34.9 milliequivalents per 100 grams. The organic matter content of the soil with a vegetative cover was higher than that found in the barren area. The organic matter content is not of sufficient quantity to explain this change in cation exchange capacity, so de-

TABLE 3

THE CHEMICAL COMPOSITION OF LATERITE PROFILES; A COMPARISON OF EFFECT OF DEHYDRATION DUE TO EXPOSURE ON CHEMICAL COMPOSITION

DEPTH	*p*H	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	LOSS ON IGNITION
			Soil with vegetative cover (no crust)			
Inches		*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
0– 5	4.6	7.50	13.00	41.80	6.03	27.92
5–10	4.6	7.84	15.45	40.99	6.29	26.78
10–15	4.4	14.78	22.60	27.40	4.34	28.53
			Barren soil (crust)			
0– 5	3.8	6.46	4.13	56.02	31.02	2.06
5–10	4.0	5.68	9.46	60.63	11.87	10.23
10–15	4.2	13.01	22.58	32.10	5.67	25.72

TABLE 4

THE RELATIONSHIP BETWEEN LOSS ON IGNITION AND CATION EXCHANGE CAPACITY UNDER BARREN LATERITE CRUST AND ADJACENT SOIL WITH A VEGETATIVE COVER

DEPTH	BARREN SOIL (CRUST)				SOIL WITH VEGETATION (NO CRUST)			
	*p*H	ORGANIC MATTER	LOSS ON IGNITION	CATION EXCHANGE CAPACITY	*p*H	ORGANIC MATTER	LOSS ON IGNITION	CATION EXCHANGE CAPACITY
Inches		*Per cent*	*Per cent*	*m.e./100g.*		*Per cent*	*Per cent*	*m.e./100g.*
0– 5	3.8	1.1	2.0	3.7	4.6	8.2	27.9	41.0
5–10........	4.0	...	10.2	15.6	4.6	...	26.8	37.0
10–15........	4.2	...	25.7	34.9	4.4	...	28.5	38.4

hydration is considered to be the cause of its reduction.

Differential Thermal Analysis: The thermal curves obtained from the differential thermal analysis are given in Figure 2 for the soil profile from the barren area and Figure 3 for the soil with a vegetative cover. There is a marked difference in these two sets of curves. The curve for the surface horizon of the soil with a vegetative cover showed a strong exothermic peak at 180°C., whereas the surface soil from the barren area showed no thermal reaction at this temperature. In fact, the curve of the latter soil is very similar to that obtained from a sample of hematite. The thermal curves of the subsoil horizons of both profiles exhibit thermal peaks at 180°C. to 190°C., but none of the soils exhibited a peak at 710°C. which is characteristic of montmorillonite. The thermal curves of this type are probably due to the existence of amorphous hydrated oxides of iron, aluminum, and titanium. Some of the soils have a small peak at 350°C. which is probably due to goethite.

As the differential thermal analysis was made on the untreated soils, the question arises as to whether these curves are influenced by the difference in organic matter content of the soil. The surface soil of the profile with a vegetative cover has a higher content of organic matter than that of surface soil of the barren area. It will be noted that the thermal curves of the 10–15-inch layer of the profile with a vegetative cover are exactly the same as that of the surface horizon. As this horizon has a low organic matter content, the minerals of the soil must be responsible for its thermal characteristics. The loss of water below 300°C. also substantiates the fact that dehydration of minerals is responsible for thermal characteristics of the soil, as the loss of water is the greatest in those soils showing thermal peaks at 180°C.

The ferrous iron content was determined in the surface soils from the two profiles. The soil from the profile with a vegetative cover contained from two to five times as much ferrous iron as the soil from the barren area. As the surface soil from the barren areas is magnetic and has a low ferrous iron content, the presence of maghemite is suggested in these soils. Furthermore, this would suggest the existence of the lepidocrocite-maghemite system in these soils as maghemite is the product of dehydration of lepidocrocite. Further evidence is needed to establish the validity of this suggestion.

DISCUSSION

The results of this study have established that the indurate laterite crust horizon is developed by the dehydration of the hydrated iron and titanium minerals in the soil. The thermal curves from the differential thermal analysis and the loss of water under 300°C. of the two profiles have shown that hardening of the barren area is due to dehydration. In the dehydration of the colloidal hydrated iron oxides, water is lost and the oxides are converted to hematite or related dehydrated iron oxides. The process will cause an increase in particle density and, according to Fujimoto *et al.* (1948), an increase in particle size. The question arises as to the length of time required for a ferruginous horizon to harden to the laterite crust on exposure. Aubert (1949, 1950) has reported the formation of laterite crusts under normal conditions in 35 to 60 years. Chevalier (1949) states that, if the forest is removed by cutting, burning, or loss of cover due to other reasons, the senile stage (the laterite crust) will develop very rapidly. Davis (1940) found that because of the clear culture required in the culture of teak and because teak trees lose their leaves during the dry season, the laterite crust will develop in a very short period of time [one dry season]. The hardening of Hawaiian soils on exposure is very rapid, occuring in less than a year.

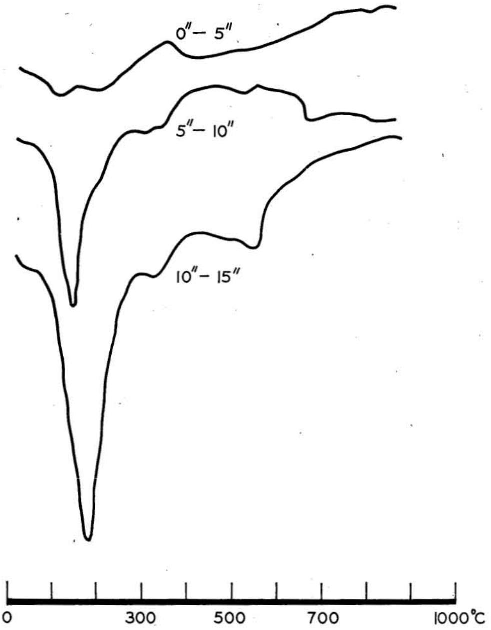

FIG. 2. The differential thermal curves of the profile from the barren area of a humic ferruginous latosol soil.

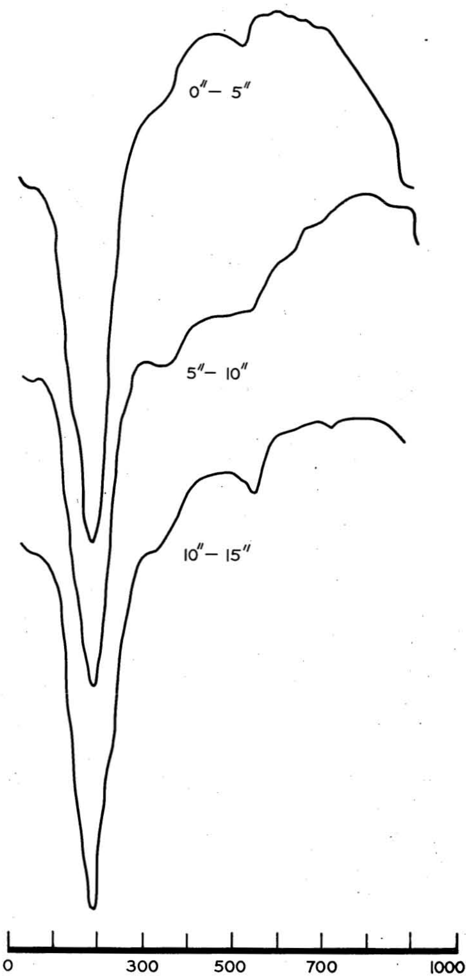

FIG. 3. The differential thermal curves of a profile with a vegetative cover of a humic ferruginous latosol soil.

The dehydration of the soil causes very important changes in the physical and chemical properties of the soil. There is an obvious change in compaction, bulk density, particle density, and particle size. The most important change is the loss of cation exchange capacity. It has been observed that these barren areas are infertile. This infertility very likely is due to the loss of adsorptive surface and to the poor physical condition of the soil. The reforestation of these laterite areas is a slow process as the conditions for growth are very poor.

It has been established by Fieldes *et al.* (1952) that the amorphous colloidal hydrated oxides have a high cation exchange capacity. In a personal communication from these workers, they report that they have found that the hydrated iron oxides lose cation exchange capacity on dehydration. These observations support the findings in this study.

SUMMARY

A study has been conducted to ascertain the role of dehydration in the development of the indurate laterite crust. The following conclusions appeared to be justified:

1. The data obtained from differential thermal analysis, elemental analysis, and physical measurements have established that the dehydration of the colloidal hydrated oxides of the soil is responsible for the development of the indurate laterite horizon when exposed to a drying environment.
2. The dehydration of the titaniferous ferruginous horizon will increase the bulk density and particle density of the soil.
3. Dehydration causes the development of inert dehydrated minerals as shown by the data on loss on ignition and cation exchange capacity. The colloidal hydrated iron oxide is converted to hematite or similar iron oxide minerals.
4. The rates of dehydration of ferruginous layers will probably vary according to the mineral content of soil and the vegetative and climatic environments.

REFERENCES

AUBERT, G. 1949. Observations sur le rôle de l'érosion dans la formation de la cuirasse latéritique. *Bul. Agr. du Congo Belge* 40: 1383–1386.

——— 1950. Observations of the degradation and lateritic-crust formation in North-West Dahomey. [*Fourth*] *Internatl. Cong. Soil Sci., Trans.* 3: 127–128.

AUBREVILLE, A. 1947. Erosion and "bovalization" in French Black Africa. *Agron. Trop.* 2: 339–357.

——— 1948. Casamance. *Agron. Trop.* 3: 25–52.

BUCHANAN, H. F. 1807. *Journey from Madras, Canara, and Malabar.* London. [3 vols., reference to vol. 2.]

CAMPBELL, J. M. 1917. Laterite: Its origin, structure, and minerals. *Mining Mag.* 17: 67–77; 120–128; 171–179; 220–229.

CHEVALIER, A. 1948. Degradation and conservation of soil of tropical Africa: Origin and extension of laterites and of ferruginous shell: Struggle against sterilization of African soil. *Rev. Internatl. Bot. Appl.* 28: 49–66.

——— 1949. Points de vue nouveaux sur les sols d'Afrique tropicale sur leur degradation et leur conservation. *Bul. Agr. du Congo Belge* 40: 1057–1092.

DAVIS, P. W. 1940. Preliminary note on Nilamber soils with special reference to their suitability for teak. *Indian Forester* 66: 658–671.

FIELDES, M., L. D. SWINDALE, and J. P. RICHARDSON. 1952. The relation of colloidal hydrous oxides to the high cation exchange capacity of some tropical soils of the Cook Islands. *Soil Sci.* 74: 197–206.

FOX, C. S. 1933. Laterite and laterite soil. *Indian Forester* 59: 630–635.

FUJIMOTO, GIICHI, G. DONALD SHERMAN, and ADA E. CHANG. 1949. The chemical composition of the separated mineral fractions of a ferruginous humic latosol profile. *Soil Sci. Soc. Amer., Proc.* (1948) 13: 166–169.

GLINKA, K. D. 1927. *The great soil groups of the world.* 150 pp. Edward Bros. Ann Arbor, Michigan.

HARRASSOWITZ, H. 1930. Boden der tropischen Regionen. *Blanck's Handbuch der Bodenlehre* 3: 362–436.

HARRISON, J. B. 1933. *The katamorphism of igneous rocks under humid tropical conditions.* 79 pp. Imperial Bureau of Soil Science, Harpenden, England.

HOLMES, A. 1914. Investigations of laterites in Portuguese East Africa. *Geol. Mag.* 6: 529–537.

JACKSON, M. L., S. A. TYLER, A. L. WILLIS, G. A. BOURBEAU, and R. P. PENNINGTON. 1948. Weathering sequence of clay-size minerals in soils and sediments. *Jour. Phys. Colloid. Chem.* 52: 1237–1260.

MARBUT, C. F. 1932. Morphology of laterites. [*Second*] *Internatl. Cong. Soil Sci., Trans.* 5: 72–80.

NORTON, F. H. 1939. Critical study of the differential thermal method for the identification of the clay minerals. *Amer. Ceramic Soc., Jour.* 22: 54–63.

PENDLETON, R. L. 1941. Laterite and its structural uses in Thailand and Cambodia. *Geog. Rev.* 31: 177–202.

——— and S. SHARASUVANAS. 1942. Analyses and profile notes of some laterites and soils with iron concretions of Thailand. *Soil Sci.* 54: 1–26.

——— ——— 1946. Analysis of some Siamese laterites. *Soil Sci.* 62: 423–433.

PIPER, C. S. 1944. *Soil and plant analysis.* 368 pp. Interscience Publishing Co., New York.

RICHTHOFEN, F. 1860. Bermerkungen über Ceylon. *Deut. Geol. Gesell., Ztschr.* 12: 531–545.

SHERMAN, G. DONALD. 1949. Factors influencing the development of lateritic and laterite soils in the Hawaiian Islands. *Pacific Sci.* 3: 307–314.

——— 1950. The genesis and morphology of Hawaiian ferruginous laterite crusts. *Pacific Sci.* 4: 315–322.

——— 1952. The titanium content of Hawaiian soils and its significance. *Soil Sci. Soc. Amer., Proc.* 16: 15–18.

WRIGHT, C. H. 1934. *Soil analysis.* 236 pp. Thomas Murby & Co., London.