Mineralogy of Selected Soils from Guam

GEOLOGICAL SURVEY PROFESSIONAL PAPER 403-F

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March 3, 1849

Mineralogy of Selected Soils from Guam

By DOROTHY CARROLL *and* JOHN C. HATHAWAY

with a section on

DESCRIPTION OF SOIL PROFILES

By CARL H. STENSLAND

GEOLOGY AND HYDROLOGY OF GUAM, MARIANA ISLANDS

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A mineralogical study of selected soil samples of Guam, including data on chemical composition, grain-size distribution, and comparison with other areas, as well as a description of soil profiles

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GEOLOGY AND HYDROLOGY OF GUAM, MARIANA ISLANDS

MINERALOGY OF SELECTED SOILS FROM GUAM

By Dorothy Carroll and John C. Hathaway

ABSTRACT

Data are given for the grain-size distribution, pH, chemical composition, organic carbon, free iron oxide, ion exchange capacity, and mineralogy of soil samples from 14 profiles on Guam. Six of the profiles are developed on limestone and eight on volcanic rocks. Most of the soils are described as red latosols and are clayey. The principal soil overlying volcanic rocks, the Atate clay, averages 71 percent clay, 23 percent silt, and 6 percent sand. The principal soil overlying limestone, the Guam clay, averages 59 percent clay, 33 percent silt, and 9 percent sand. In chemical composition the Atate clay averages 35.5 percent SiO_2, 27.9 percent Al_2O_3, 14.5 percent Fe_2O_3, and 1.0 percent TiO_2. The Guam clay averages 1.4 percent SiO_2, 39.1 percent Al_2O_3, 20.9 percent Fe_2O_3, and 2.0 percent TiO_2. Comparison of the SiO_2 percentages for weathered rock and surface soil of the Atate clay show that silica has been removed during development of the profile. Alumina and ferric oxide accumulate in these soils.

Normative mineral compositions of representative soil profiles show that a kaolin mineral, goethite, and a little gibbsite make up the bulk of the Atate clay; whereas gibbsite, hematite, and a little kaolin mineral are the main constituents of the Guam clay. X-ray diffraction and differential thermal analysis identify the kaolin mineral as halloysite.

The pH of the Atate clay averages 5.3; that of the Guam clay, 7.4. Other soils have intermediate pH values.

The percentage of free iron oxide, defined as that readily removed and not combined in minerals, shows considerable variation both within the individual profiles and between the profiles. The Atate clay averages 12 percent free iron oxide, and the Guam clay 18 percent free iron oxide. Other soils have as little as 4 percent.

The surface soils contain, on the average, 3.5 percent organic carbon and about 6 percent organic matter. The cation exchange capacity of these soils ranges from 7 to 24 milliequivalents per 100 gram, the capacity being highest near the surface owing to the presence of organic matter.

The minerals in the sand fractions are magnetite, ilmenite, indefinite red and black iron oxides, augite, hypersthene, green and brown hornblendes, and a very small quantity of other minerals, such as zircon and sphene. Magnetite makes up half to more than three-fourths by weight of the heavy minerals. Ilmenite is abundant in some samples. Augite and hypersthene are variable in amount and commonly are concentrated in the surface soils. Grains of these minerals are fresh in the soils on limestone, but they are generally corroded in soils formed from volcanic rocks. The minerals in the silt and clay fractions are halloysite, montmorillonite, mixed-layered montmorillonite-halloysite, goethite, hematite, gibbsite, boehmite, α-cristobalite, anatase, chromite, and weddelite. The most abundant of these minerals are halloysite, goethite, hematite, and gibbsite.

The principal weathering process in the development of the Atate clay is the removal of silica and the consequent accumulation of alumina, iron oxide, and titania. The Guam clay has a more complex genesis as the limestones beneath it vary in their content of insoluble residue and in the kinds of minerals present. In some limestones the residue consists principally of fresh volcanic ash minerals, but in others, soil material from the erosion of land surfaces is present.

The soils developed on volcanic materials on Guam are compared with other lateritic soils and with fossil laterites. Soils thus compared are from the Hawaiian Islands, Norfolk Island, Australia, and Northern Ireland. The clay minerals of all these soils show a progressive change from montmorillonite $\longrightarrow$ halloysite $\longrightarrow$ kaolinite $\longrightarrow$ gibbsite. The Atate clay of Guam is a uniform profile that apparently has not reached the same stage of development as have the older soils of the Hawaiian Islands. The ease of the weathering of the tuffs on Guam that contain zeolites and glass suggests that these soils have developed more rapidly than similar soils on compact basalts and andesites. The soils overlying limestones are compared with terra rossa type soils of other Pacific islands, the West Indies, and the bauxites of Hungary.

INTRODUCTION

Guam lies about 13° north of the Equator in the zone of tropical weathering and soil formation. The island consists of volcanic rocks (largely andesitic in composition) and limestones. The soils are lateritic. Deposits of red earthy material on the limestones appear to be similar to the terra rossa deposits of the Mediterranean region, Jamaica, and some islands in the Pacific.

During the mapping of the soils on Guam by Carl H. Stensland, assisted by James E. Paseur, U.S. Geological Survey, it became evident that much information concerning the origin and development of the soils could be obtained by detailed mineralogical and chemical analyses. Subsequently, Stensland selected 14 soil profiles for further investigation and 70 samples were collected. Six of the soil profiles overlie limestone and eight overlie volcanic rocks. The soils are mostly residual red latosols; but the surface material may be truncated, or other material may have been added to it. There are 5 profiles of Guam clay above Mariana Limestone, 1 profile of Chacha clay on the Agana Argillaceous Member of the Mariana Limestone, 7 profiles of Atate clay on various types of volcanic rocks, and 1 profile of Asan clay on volcanic rock.

Differential thermal analyses were made of some soils during the course of fieldwork on Guam by means of a small portable unit, and subsequently, seven samples were analyzed by George T. Faust, U.S. Geological Survey, using laboratory equipment.

At almost the same time that these soils were submitted for analysis, we were asked to study the insoluble residues of selected samples of limestone from Guam to aid petrographic description (Schlanger, 1963). Information from this study is used here in discussing the origin of the soils overlying limestones.

Data are given in this chapter on the grain-size distribution, pH, chemical composition (including complete analyses for a number of soil profiles), free iron oxide, exchange capacity, and mineralogy of the sand, silt, and clay fractions. X-ray examination of the silt and clay fractions showed the distribution of the various clay minerals within the soil profiles.

The soils of Guam are compared mineralogically and chemically with lateritic soils and terra rossa deposits that have developed on similar types of rocks in other places.

OUTLINE OF GEOLOGY

Geologically and topographically Guam is divided into two parts: a northern plateau of limestone ranging in age from Eocene to Pleistocene, and a southern hilly region consisting of lava flows and associated tuffs and agglomerates (Tracey and others, 1963). The limestones of the northern plateau rest unconformably on volcanic rocks, the Alutom Formation. The Mariana Limestone is the most prominent formation. All the limestones vary in content of insoluble detrital material that has been derived from the weathering of the volcanic rocks or from ash falls during deposition of the limestone.

Chemical analyses of selected limestones having sufficient insoluble residue for optical and X-ray examination are given in table 1. The percentages of insoluble residue may not be the average or the range characteristic of each formation.

The mountainous central core of the island consists of the Alutom Formation, a succession of more than 2,000 feet of folded and faulted marine tuffaceous shale and sandstone, lava flows, limestone, and conglomerate of Eocene and Oligocene age. The Mahlac Member of this formation consists of shale and sandstone and contains planktonic Oligocene Foraminifera. The southern third of the island is a succession of eastward-dipping volcanic rocks and limestones about 2,200 feet thick, which is termed the Umatac Formation and comprises four members: the Facpi Volcanic Member, the Maemong Limestone Member, the Bolanos Pyroclastic Member, and the Dandan Flow Member.

TABLE 1.—*Calcium carbonate, magnesium carbonate, and insoluble residues of limestones from Guam*

[Analysts: J. L. Dinnin, P. W. Scott, and H. F. Phillips, U.S. Geol. Survey. Given in percent]

Sample	$CaCO_3$	$MgCO_3$	Insoluble residue
Mariana Limestone, detrital facies:			
Sw 2-4	65.86	1.36	31.2
Pr 3-3	98.53	1.04	.9
Kr 3-1	------	------	.1
Agana Argillaceous Member:			
Ij 2-1	96.03	1.08	3.5
Barrigada Limestone:			
Nq 15-1	------	------	.1
Alifan Limestone:			
Ru 8-3	88.89	1.04	10.0
Di 2-1	98.17	1.04	1.1
Di 2-2	91.03	1.73	7.5
Ts 9-1	96.74	1.75	1.9
Jl 3-2	98.88	1.04	.3
Janum Formation:			
Ts 5-4	81.75	1.63	14.2
Ts 5-9	97.63	1.50	1.0
Rr 23-1	88.53	1.21	9.8
Rr 5-1	95.14	.98	3.6
Bonya Limestone:			
Ut 6-1	98.17	1.69	0.9
Rr 13-1	97.63	1.38	1.4
Gi 2-1	98.17	1.59	.5
Umatac Formation, Maemong Limestone Member:			
Gi 1-2a	91.03	1.57	7.4
Ef 1-1	98.17	1.80	.3
Ed 1-1b	96.39	2.72	1.6
Ee 2-1	74.07	2.50	23.8
Df 9-1a	78.36	1.27	20.8
Ii 5-2	99.24	.85	.7
Alutom Formation:			
Fk 4-11	97.85	1.79	1.0
Mahlac Shale Member:			
Gj 11-1	52.65	.52	42.4

The oldest volcanic rocks, the Alutom Formation, are characterized by abundant white and light-gray tuffaceous shales which are water-laid pyroclastic sediments. Interbedded with these sediments are lava flows and agglomerates and breccias of volcanic material. Where fresh, the tuffaceous rocks are calcareous, but surface exposures have become silicified. Weathering results in the removal of the calcareous cement, and a soft clayey rock remains.

The Umatac Formation contains more basalt flows and less tuffaceous material than the Alutom Formation. At the base the Facpi Volcanic Member of the Umatac Formation is as much as 1,400 feet thick and consists of mafic lava flows, pillow basalts and dikes, and in some places water-laid tuff and conglomerate. Both the Bolanos Pyroclastic Member and the Maemong Limestone Member are water laid and contain volcanic material. All are deeply weathered.

The volcanic rocks of Guam, more andesitic in character than those of the Pacific basin, resemble rocks of the Pacific margin (Stark, 1963). They range in type from basalt and olivine basalt to andesite, with more than 50 percent mafic andesite; only a very minor percentage are dacites. Thin sections of some of these rocks are shown in figures 1 and 2.

Chemical analyses of samples of these mafic rocks are given in table 2.

The minerals present in the volcanic rocks (Stark, 1963) are plagioclase feldspars and pyroxenes (augite and hypersthene); olivine and quartz are present but are not abundant. Primary accessory minerals are magnetite, hornblende, biotite, alkalic feldspar; secondary and alteration minerals are chlorites, serpentines, epidote, calcite, zeolites, celadonite, opaline silica and clay minerals. The most abundant of these minerals is plagioclase feldspar, followed by monoclinic pyroxene (largely augite); olivine is rarely fresh, its place having been taken by pseudomorphs of serpentine, chlorite, or calcite; hypersthene occurs only in a few samples.

As the parent material of soils, the most important feature of these mafic rocks on Guam is the almost complete absence of minerals that are resistant to weathering processes. These rocks are generally altered to clays, and weathering frequently extends to 100 feet below the surface.

The relation between volcanic rocks and limestones, the types of volcanic rocks, and the insoluble residues of the limestones of Guam are similar to those described for the Lau Islands, Fiji, by Ladd and Hoffmeister (1945).

SOILS OF GUAM

Numerous soil units were mapped by Carl H. Stensland. These include the following associations of upland soils on limestone and volcanic rocks.

Upland limestone soils	*Description*
Guam clay	Reddish friable permeable clay; generally less than 12 in. deep.
Toto clay	Pale-yellow firm plastic clay with reddish stains; slowly permeable; generally deep.
Chacha-Saipan clays	Yellowish-brown firm clay (Chacha) and red firm clay (Saipan), medium-deep to deep.
Saipan-Yona-Chacha clays.	Soils of unit 3 with a shallow brownish clay (Yona) on convex slopes.
Yona-Chacha clays	Shallow (Yona) clay on upper ridge slopes and deeper yellowish-brown (Chacha) clay on toe slopes and in basins.
Upland volcanic soils	*Description*
Atate-Agat clays, rolling	Red granular porous acid clay (Atate) associated with small benchlike mesitas, and a truncated latosol (Agat clay) with solum almost all removed; red staining and reticulate mottling deep into C or saprolitic horizon (the saprolite is in most places 50 ft or more thick over relatively unweathered rock).
Agat-Asan-Atate clay, hilly.	Atate-Agat clays and a truncated latosol (Asan clay) with very little staining or red mottling.
Agat-Asan clays and rock outcrop.	Agat and Asan clays less deeply weathered or more truncated with some rock exposures.

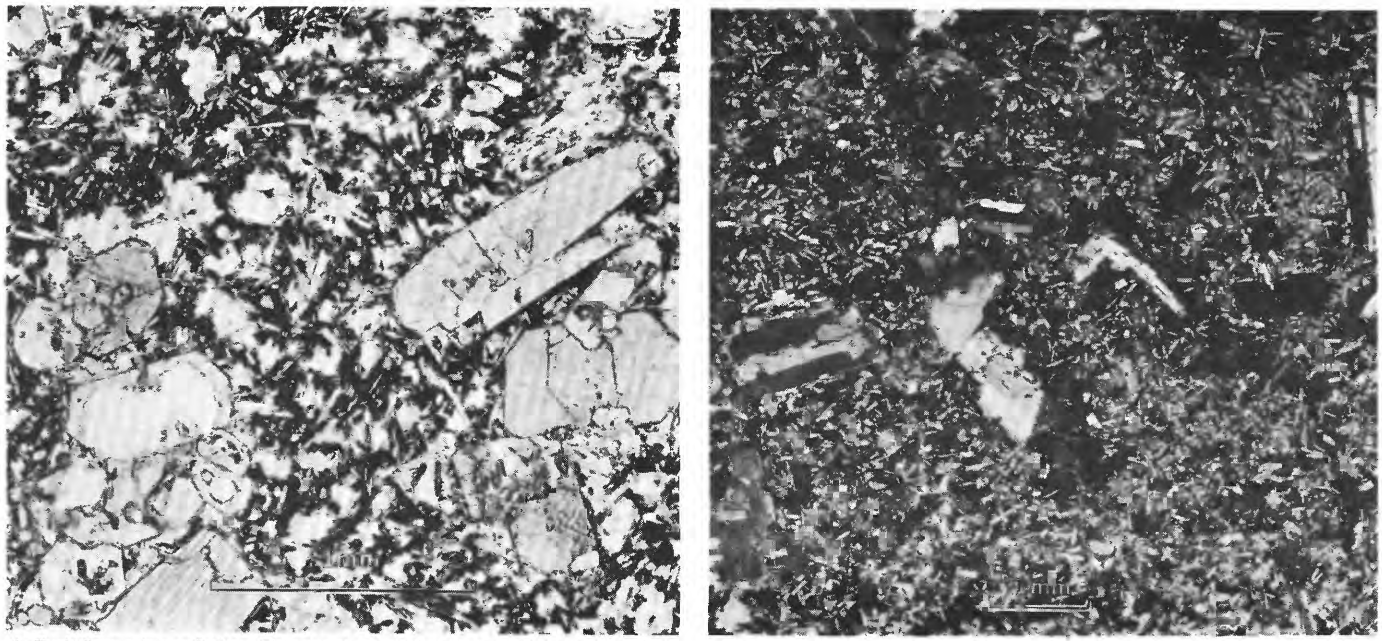
The Guam clay, although relatively thin, has the greatest areal extent of any of the soils on Guam, as it covers the limestone plateau on the northern half of the island. The other types of limestone soil—the Toto, Chacha, Saipan, and Yona clays—are developed on the northeastern and eastern slopes of the higher southern part of the island where they flank the volcanic material.

The soils developed on the weathered volcanic rocks of Guam occur principally in the southern half of the island. The weathering of the marine tuffaceous shales and associated rocks, and of the andesitic or basaltic lava flows, extends to an average depth of 50 feet. The weathered rock is similar in appearance to the saprolite of the southeastern United States; that is, the original textures and structures of the rocks are preserved although the fresh minerals have been replaced by clay. The volcanic parent materials have similar chemical composition; so the principal differences in these soils can be attributed to topography and age. Both regosols (Chacha and Asan clays) and latosols (Guam and Atate clays) are present.

The following samples of soil from profiles developed on limestone and on the volcanic rocks were collected by Carl H. Stensland for the investigation.

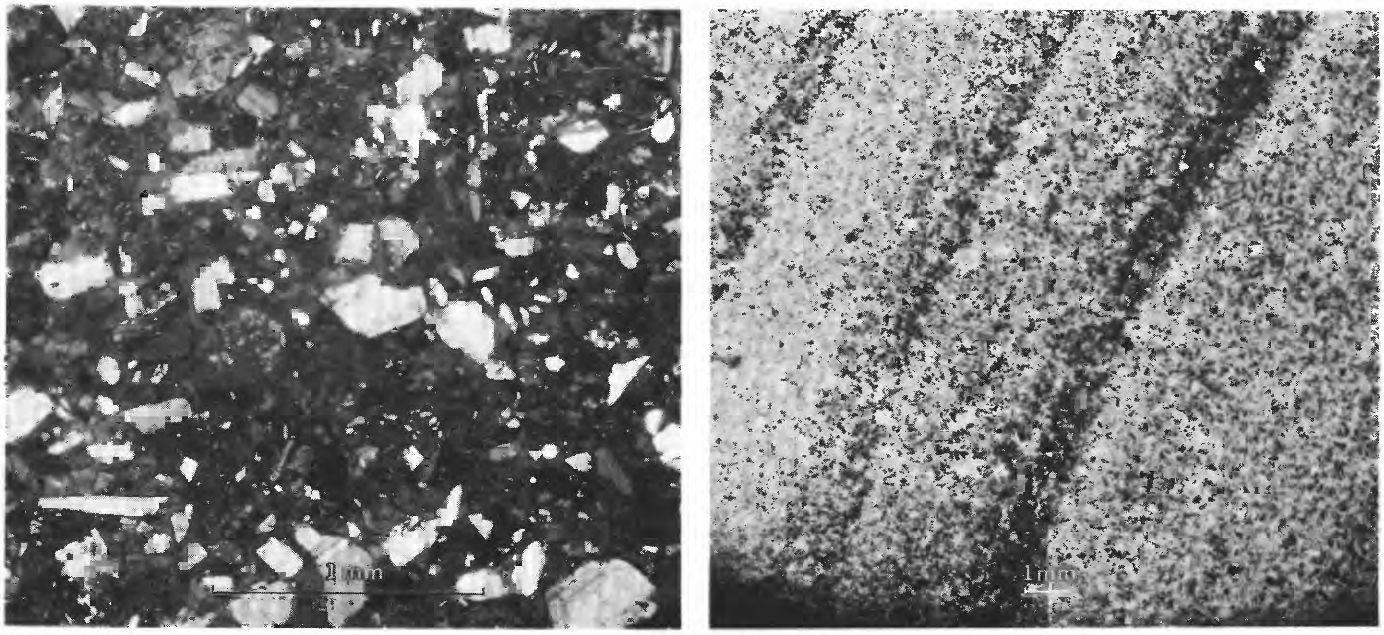
Soil profiles on limestone		*Soil profiles on volcanic rocks*	
S54–16	Guam clay on Barrigada Limestone.	S54–4	Atate clay on Alutom Formation.
S54–17	Guam clay on Mariana Limestone.	S54–5	Atate clay on Alutom Formation.
S54–18	Guam clay on Mariana Limestone.	S54–6	Atate clay on Bolanos Pyroclastic Member of Umatac Formation.
S54–19	Guam clay on Mariana Limestone.	S54–10	Atate clay on Bolanos Pyroclastic Member of Umatac Formation.
S54–24	"Fossil" latosol on Alifan Limestone.	S54–12	Atate clay on Facpi Volcanic member of Umatac Formation.
S54–1	Chacha clay on Agana Argillaceous Member of the Mariana Limestone.	S54–20	Atate clay on Alutom Formation.
		S54–21	Atate clay on Alutom Formation.
		S54–23	Asan clay on Alutom Formation.

Details of these profiles are given in the description of soils by Stensland (p. F43–F49). Locations are shown on figure 3.)



A. Basic flow, calcic andesite. Phenocrysts of augite and zoned feldspars in a matrix of plagioclase, pyroxene, glass, magnetite, zeolites, and alteration products. Ordinary light, × 35. Mount Santa Rosa.

B. Basic flow (Ee 4-2), basalt, near Umatac springs. Plagioclase and augite in a groundmass of plagioclase, pyroxene, and glass, with zeolites. Ordinary light, × 13.



C. Water-laid tuffaceous sandstone (Fo 6-1), Alutom Formation, Spruance Drive. Plagioclase, altered augite, devitrified glass, clay and chloritic minerals. Crossed nicols, × 35.

D. Water-laid tuff altered to red clay in place, Sasa Valley. Some fresh plagioclase, altered pyroxenes, magnetite, and clay minerals. Ordinary light, × 7.

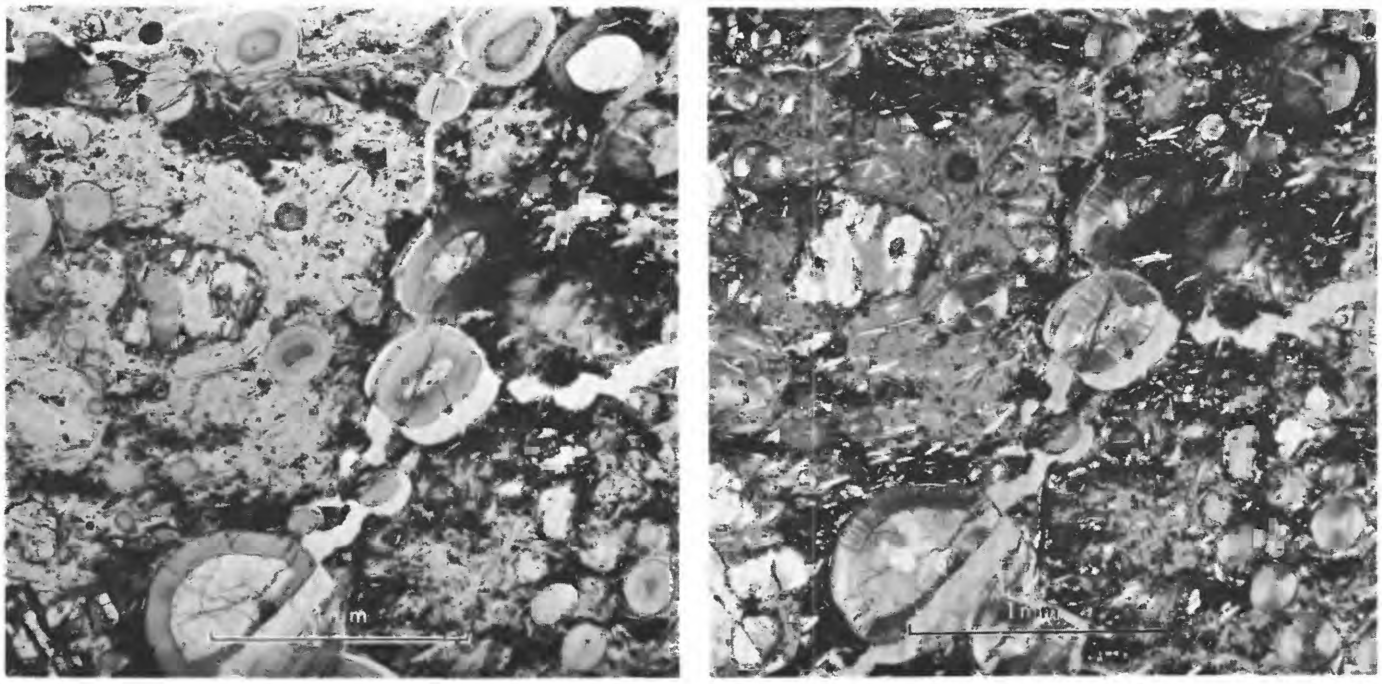
FIGURE 1.—Parent rocks of soils on Guam.

METHODS OF EXAMINATION

Mechanical, chemical, and mineralogical examinations were made on the soil samples of the profiles developed on limestone and on volcanic rocks in order to provide the information required to describe these soils and their development from the underlying rocks. In addition, use was made of petrographic descriptions of thin sections of the limestones (Schlanger, 1963) and of the volcanic rocks (Stark, 1963).

MECHANICAL ANALYSIS

The grain-size distribution for all the samples was obtained by the standard procedure for mechanical analysis of soil (Kilmer and Alexander, 1949, p. 15). This method consists of dispersing the soil with sodium



A. Weathered pillow basalt (Ch 3-1), old road to Facpi Point. Plagioclase, augite, celadonite apparently replacing zeolites, saponite within the radiating celadonite, altered glassy groundmass. Ordinary light, × 34.

B. Same as *A*, but with crossed nicols.

FIGURE 2.—Parent rocks of soils on Guam.

metaphosphate, removing the sand grades with sieves, and determining the amount of silt and clay by pipette analysis. The analyses were made by Paul D. Blackmon, U.S. Geological Survey.

CHEMICAL ANALYSIS

The major constituents of 46 samples of soil representing 13 profiles were determined by rapid analysis methods under the supervision of W. W. Brannock, U.S. Geological Survey. Many of the surface samples contained organic matter which interfered with the methods used and caused low total figures as shown in table 4.

Organic carbon was determined in the surface samples from the profiles by Walkley and Black's rapid titration method (Piper, 1947, p. 223) which consists of oxidation of the carbon in the organic matter by potassium dichromate. The results obtained give 80 to 90 percent of the organic carbon present. Multiplying the figures by 1.72 gives an approximation to the total organic matter present.

The free iron oxide (Fe_2O_3) on the mineral grains of the whole soil was determined by a modification of Deb's method (1950, p. 212), which consists of the removal of ferric oxide by reduction to ferrous oxide with sodium hydrosulfite (dithionate) $Na_2S_2O_4 \cdot 2H_2O$. The iron in solution was determined colorimetrically using potassium hydrocyanite.

The total cation exchange capacity of the whole soils was determined by Bower and Truog's colorimetric manganese method (1940), in which the exchangeable cations are replaced by manganese which is, in turn, replaced by ammonium as ammonium acetate. The amount of manganese equal to the exchangeable cations is then determined colorimetrically with a spectrophotometer.

MINERALOGICAL ANALYSIS

Sand grades.—From the grain-size distribution of these soils (table 3) it is seen that very little material coarser than silt (0.05 to 0.002 mm) is present. It was therefore necessary to concentrate the sand from large samples of soil to obtain sufficient minerals for examination. The clay was removed by washing and decantation, leaving the coarsest material which was then boiled in 1:1 hydrochloric acid, washed, dried, and sieved into fractions of the same size as those of the mechanical analysis. The 0.25- to 0.10-mm and 0.10- to 0.05-mm sand grades were separated in bromoform, the magnetite removed and weighed, and the remaining heavy minerals mounted in Canada balsam for microscopic identification.

Silt and clay grades.—The material passing the 270-mesh sieve in the mechanical analysis procedure was separated into silt and clay fractions and examined by X-ray diffraction, using the methods described by Hathaway (1956) and Hathaway and Carroll (1963).

FIGURE 3.—Localities of soil profiles on Guam.

TABLE 2.—*Chemical composition, in percent, of the volcanic rocks of Guam*

[Samples Ee 4-2c, Fd 2-1b, Go 7-1c, Go 7-1d, Dh 6-1b, Dh 6-1c by rapid methods; analyzed by H. F. Phillips, P. L. D. Elmore, K. E. White. Samples Df 2-1, Ee 4-2, Fd 2-1, Fo 10-1, Go 7-1, Ie 2-1, Go 10-2, If 6-1, Ch 4-3, Ch 4-4, Gm 1-2, Gm 25-1, Go 6-1, Ie 3-1 analyzed by E. J. Thomasi. Samples Ss 9-1, Fm 2-1, Gm 9-1, Gm 21-1, Gm 33-1, Gm 5-1a, Gm 5-1b, Gm 5-1c analyzed by L. D. Trumbull]

Sample	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O-	H_2O+	TiO_2	CO_2	P_2O_5	MnO	Total
A. Basalt and other lava flows															
Ee 4-2c	51. 7	14. 6	4. 5	7. 9	4. 7	9. 1	2. 6	0. 70	[1] 3. 0	------	0. 92	$<$0.05	0. 25	0. 20	[2] 100
Fd 2-1b	54. 1	14. 8	4. 7	6. 1	3. 7	8. 0	2. 8	. 82	[1] 3. 8	------	1. 0	$<$.05	. 26	. 15	[2] 100
Go 7-1c	53. 5	14. 9	3. 7	3. 2	7. 0	7. 8	2. 9	. 62	[1] 5. 4	------	. 50	.50	. 10	. 12	[2] 100
Go 7-1d	47. 7	15. 6	4. 6	3. 8	9. 0	10. 3	2. 0	. 36	[1] 5. 8	------	. 54	.05	. 08	. 13	[2] 100
Df 2-1	50. 85	13. 55	2. 24	5. 43	10. 01	9. 55	1. 58	. 16	4. 13	1. 91	. 34	.07	. 03	. 14	99. 99
Ee 4-2	52. 09	15. 81	3. 71	7. 81	4. 29	9. 44	2. 48	. 76	1. 18	1. 12	. 97	.01	. 24	. 20	100. 11
Fd 2-1	53. 19	17. 51	1. 61	7. 16	3. 97	9. 20	2. 71	. 94	. 85	1. 25	1. 04	.01	. 26	. 19	99. 89
Fo 10-1	48. 48	15. 99	3. 69	4. 64	8. 93	10. 90	1. 80	. 14	2. 83	1. 91	. 57	.00	. 07	. 14	100. 09
Go 7-1	48. 58	16. 53	3. 39	3. 74	8. 55	9. 88	2. 01	. 45	3. 95	1. 93	. 62	.00	. 09	. 13	99. 85
Dh 6-1b	55. 0	13. 8	3. 8	4. 0	9. 4	7. 9	2. 3	. 88	[1] 2. 6	------	. 34	$<$.05	. 07	. 11	[2] 100
Dh 6-1c	54. 2	14. 6	5. 1	3. 4	8. 0	7. 9	2. 4	1. 4	[1] 2. 9	------	. 36	$<$.05	. 08	. 12	[2] 101
B. Dikes cutting mafic flows and boulders in conglomerates and pyroclastic agglomerates															
Ie 2-1	55. 73	19. 50	2. 56	4. 59	1. 98	8. 03	3. 24	2. 14	0. 26	0. 75	0. 67	0. 02	0. 36	0. 15	99. 98
Go 10-2	65. 19	15. 65	2. 54	2. 04	2. 41	5. 36	3. 29	1. 04	. 72	1. 08	. 44	. 01	. 11	. 06	99. 94
If 6-1	60. 02	16. 74	3. 50	3. 31	2. 86	6. 67	3. 35	1. 52	. 65	. 30	. 56	. 01	. 19	. 13	99. 81
Ss 9-1	68. 89	13. 73	2. 59	1. 70	2. 11	4. 42	3. 50	1. 00	. 77	. 95	. 23	. 07	. 05	. 05	100. 06
Ch 4-3	51. 63	14. 10	2. 27	5. 93	9. 93	9. 47	2. 21	. 52	1. 84	1. 42	. 43	. 07	. 05	. 15	100. 02
Ch 4-4	53. 53	16. 28	2. 53	5. 24	5. 41	5. 59	5. 14	1. 77	1. 09	2. 45	. 60	. 11	. 08	. 12	99. 94
Gm 1-2	64. 49	14. 01	1. 62	2. 19	3. 23	7. 73	2. 65	. 80	. 86	. 69	. 39	. 94	. 08	. 08	99. 76
Gm 25-1	58. 43	14. 80	1. 82	5. 10	6. 58	7. 77	2. 57	. 54	. 73	. 93	. 50	. 02	. 08	. 14	100. 01
Go 6-1	69. 04	12. 71	3. 20	1. 03	1. 96	5. 79	2. 50	1. 00	1. 23	. 81	. 36	. 09	. 05	. 05	99. 82
Ie 3-1	51. 06	18. 05	3. 63	6. 08	4. 56	10. 09	2. 45	1. 02	. 81	. 71	. 73	. 15	. 22	. 20	99. 76
C. Tuffs and weathered tuffs															
Fm 2-1	73. 58	9. 68	1. 14	0. 14	0. 48	1. 98	1. 37	0. 82	4. 07	6. 16	0. 21	0. 01	0. 00	0. 02	99. 66
Gm 9-1	74. 09	10. 23	. 73	. 12	. 47	2. 94	1. 67	. 55	3. 77	5. 20	. 23	. 01	. 02	. 01	100. 04
Gm 21-1	70. 59	10. 05	1. 30	. 18	1. 38	2. 42	. 35	1. 12	4. 61	7. 47	. 39	. 01	. 01	. 01	99. 89
Gm 33-1	52. 88	23. 95	7. 76	. 00	1. 13	. 00	. 06	. 98	2. 73	9. 31	. 74	. 15	. 06	. 27	100. 02
Gm 5-1a	67. 10	13. 07	2. 34	. 64	1. 42	1. 63	1. 22	1. 19	3. 88	6. 74	. 21	. 00	. 20	. 05	99. 69
Gm 5-1b	74. 23	14. 36	1. 42	. 16	. 18	. 17	. 10	. 20	2. 50	5. 91	. 34	. 01	. 14	. 02	99. 74
Gm 5-1c	47. 78	26. 23	5. 43	. 07	2. 03	. 31	. 06	. 12	6. 59	10. 58	. 37	. 01	. 15	. 02	99. 75

[1] Total H_2O.
[2] Total as reported by the analysts.

Sample no.	DESCRIPTION OF SAMPLES
Ee 4-2c	Basalt lava flow near middle, above Umatac springs.
Fd 2-1b	Basalt lava flow near top, above Merizo dam.
Go 7-1c	Basalt lava flow near top, Spruance Drive roadcut.
Go 7-1d	Basalt lava flow near bottom, Spruance Drive roadcut.
Df 2-1	Mafic flow, old road to Umatac, west of Latti stones.
Ee 4-2	Mafic flow over pyroclastics, above Umatac springs.
Fd 2-1	Mafic flow 520 ft upstream from road above Merizo dam.
Fo 10-1	Mafic lava flow, Spruance Drive roadcut.
Go 7-1	Mafic lava flow, Spruance Drive roadcut.
Dh 6-1b	Mafic flow near base, slightly weathered, Lamlam roadcut.
Dh 6-1c	Mafic flow near top, slightly weathered, Lamlam roadcut.
Ch 4-3	2-ft dike cutting mafic flows, 3,600 ft northeast of Facpi Point.
Ch 4-4	4-ft dike cutting mafic flows, 3600 ft northeast of Facpi Point.
Gm 1-2	Mafic boulder, from pyroclastic conglomerate east of Mount Alutom.
Gm 25-1	Mafic boulder, pyroclastic conglomerate east of Mount Tenjo.

Sample no.	DESCRIPTION OF SAMPLES
Go 6-1	Mafic boulder, pyroclastic conglomerate, Spruance Drive.
Ie 3-1	Mafic boulder, Dandan area.
Ie 2-1	Mafic boulder pyroclastic conglomerate, Martinez Pasture, Dandan area.
Go 10-2	Mafic boulder, pyroclastic conglomerate, Spruance Drive.
If 6-1	Mafic boulder, Dandan Area.
Ss 9-1	Quartz porphyry, southeast slope Mount Santa Rosa.
Fm 2-1	Green water-laid tuff, Tenjo peak.
Gm 9-1	Brecciated silicified water-laid tuff, ridge southeast of road leading east from Tenjo Road between Alutom and Tenjo Peaks.
Gm 21-1	Green silicified water-laid tuff, Tenjo Road between Alutom and Tenjo Peaks.
Gm 33-1	Red and white clay altered from water-laid tuff, Tenjo Road between Alutom and Tenjo Peaks.
Gm 5-1a	Water-laid tuff (relatively unaltered), Tenjo Road between Comar Reservoir and Alutom turnoff.
Gm 5-1b	Water-laid tuff, green clay altered from Gm 5-1a.
Gm 5-1c	Water-laid tuff, pink clay altered from Gm 5-1b.

RESULTS OF ANALYSES

MECHANICAL COMPOSITION

The mechanical composition and pH of the soils on volcanic rocks and on limestones are given in table 3. The soils are generally clays or silty clays in recognition of which the textural term "clay" is used in the field descriptions. Table 3 shows that all the profiles of Atate clay contain similar amounts of clay ($<$0.002 mm), although the percentages vary in different parts of the profile. Shallower profiles of the Guam clay on limestones also show less variation. The average percentages of grades of silt and clay in the Atate clay and Guam clay profiles are given below.

Atate clay		*Guam clay*	
(7 profiles, 34 samples)		(5 profiles, 8 samples)	
Silt	Clay	Silt	Clay
23. 5	70. 7	33. 0	58. 5

TABLE 3.—*Mechanical composition, in percent, and pH of soils on volcanic rocks and on limestones*

[Analyst, P. D. Blackmon, U.S. Geological Survey; Tr., trace, <0.1 percent]

Description	Profile and sample No.	Horizon	Depth	pH	Gravel >2 mm	Very coarse sand 1-2 mm	Coarse sand 0.5-1 mm	Medium sand 0.25-0.5 mm	Fine sand 0.10-0.25 mm	Very fine sand 0.05-0.10 mm	Silt 0.002-0.05 mm	Clay <0.002 mm
Soils on volcanic rocks												
ATATE CLAY												
Red latosol on Alutom Formation.	S54-4-1	A	0-6 in.	5. 5	------	0. 1	0. 7	1. 5	4. 6	4. 2	32. 4	56. 5
	4-2	A	7-20 in.	5. 8	Tr.	. 3	. 3	. 3	. 6	. 7	14. 3	83. 5
	4-3	B	20-30 in.	6. 0	Tr.	. 4	. 5	. 5	. 6	. 7	12. 3	85. 0
	4-4	B	30-51 in.	5. 4	0. 1	. 1	. 2	. 3	. 5	. 5	22. 6	75. 7
	4-5	C	51-60 in.	5. 4	. 5	. 3	. 6	. 6	1. 5	1. 9	26. 0	68. 6
	S54-5-1	A	0-6 in.	5. 6	4. 0	2. 0	1. 9	1. 6	1. 4	1. 1	9. 9	78. 1
	5-2	B	6-18 in.	5. 1	1. 9	1. 0	. 7	. 6	1. 1	. 8	12. 9	81. 0
	5-3	B	18-53 in.	5. 3	2. 0	1. 0	. 7	. 9	2. 0	1. 5	14. 5	77. 4
	5-4	B	53-60+ in.	5. 2	1. 7	1. 2	1. 6	2. 4	2. 0	2. 8	25. 3	63. 0
	5-5	C	10. 0-10. 5 ft	4. 7	3. 8	2. 4	1. 7	1. 7	2. 1	1. 4	19. 2	67. 7
Red latosol on Bolanos Pyroclastic Member of Umatac Formation.	S54-6-1	A	0-2 in.	5. 1	. 2	. 3	. 2	. 4	1. 2	1. 2	20. 9	75. 6
	6-2	A	2-10 in.	5. 1	. 2	. 3	. 3	. 6	1. 9	1. 5	25. 6	69. 6
	6-3	B	10-16 in.	5. 1	------	. 1	. 1	. 4	1. 4	. 8	11. 7	85. 5
	6-4	B	16-32 in.	5. 0	. 2	Tr.	. 1	. 5	1. 5	. 9	24. 4	72. 4
	6-5	B	32-46 in.	4. 9	. 4	Tr.	. 1	. 3	. 8	. 8	27. 6	70. 0
	6-6	C	46-60 in.	4. 8	------	. 1	Tr.	. 2	1. 7	2. 1	33. 1	62. 8
	6-7	C	13. 5-14. 5 ft	4. 8	------	------	Tr.	. 5	6. 3	4. 5	50. 0	38. 7
	S54-10-1	A	0-3 in.	5. 6	. 1	. 1	. 2	. 8	2. 3	2. 1	30. 6	63. 8
	10-2	A	3-15 in.	5. 1	. 1	Tr.	. 2	. 9	2. 5	1. 9	16. 5	77. 9
	10-3	B	15-28 in.	5. 1	------	Tr.	. 1	. 9	2. 5	1. 7	22. 6	72. 2
Red latosol on Facpi Volcanic Member of Umatac Formation.	S54-12-1	A	0-6 in.	5. 3	. 1	. 1	. 1	. 3	1. 6	2. 5	28. 6	66. 7
	12-2	B	6-13 in.	5. 1	Tr.	. 2	. 3	. 3	. 8	1. 5	34. 3	62. 6
	12-3	B	13-40 in.	5. 3	------	. 1	. 2	. 2	. 5	. 5	10. 2	88. 3
	12-4	C	40-84+ in.	5. 4	------	. 1	Tr.	. 1	. 8	1. 2	19. 8	78. 0
	12-5	C	9. 0-10. 0 ft	5. 0	------	------	Tr.	. 4	2. 7	2. 9	30. 9	63. 1
	12-6	C	15. 0-16. 0 ft	4. 8	------	------	------	Tr.	. 5	1. 3	37. 1	61. 1
	12-8	C	22. 5-23. 0 ft	5. 0	------	------	Tr.	. 4	3. 2	3. 5	39. 8	53. 1
Red latosol on Alutom Formation.	S54-20-1	A	0-4 in.	6. 8	Tr.	. 1	. 1	. 4	1. 3	1. 1	13. 3	83. 7
	20-2	B	4-16 in.	5. 6	------	Tr.	Tr.	. 1	. 3	. 5	20. 3	78. 8
	20-3	B-C	16-36 in.	5. 5	------	------	Tr.	. 1	. 6	1. 1	20. 5	77. 7
	S54-21-1	A	0-16 in.	5. 4	------	. 1	. 1	. 3	3. 0	3. 0	24. 2	69. 3
	21-2	B	16-36 in.	5. 8	Tr.	Tr.	. 1	. 2	. 6	. 8	13. 3	85. 0
	21-3	C	36-66 in.	5. 6	------	Tr.	. 1	1. 2	8. 1	8. 6	23. 6	58. 4
	21-4	C	8. 0-9. 0 ft	5. 8	------	Tr.	. 1	. 9	6. 9	8. 2	30. 2	53. 7
ASAN CLAY												
Brown regosol on Alutom Formation.	S54-23-1	A	0-8 in.	5. 6	. 3	Tr.	. 1	. 3	2. 4	4. 2	31. 0	61. 7
Soils on limestone												
GUAM CLAY												
Red latosol on Barrigada Limestone.	S54-16-1	A	0-60 in.	6. 1	------	------	Tr.	0. 5	2. 7	5. 4	28. 8	62. 6
Red latosol on Mariana Limestone.	S54-17-1	A	0-3 in.	7. 8	Tr.	Tr.	. 3	1. 0	5. 2	5. 1	34. 9	53. 5
	17-2	B	3-24 in.	7. 9	------	------	Tr.	Tr.	. 6	1. 5	35. 4	62. 5
	S54-18-1	A	0-1 in.	7. 4	------	------	. 1	. 3	2. 7	3. 1	40. 6	53. 2
	18-2	B	1-15 in.	7. 4	------	Tr.	. 1	. 2	1. 5	2. 5	28. 3	67. 4
	S54-19-1	A	0-4 in.	7. 0	. 1	. 1	. 1	. 3	5. 9	9. 0	40. 1	44. 4
	19-2	B	4-12 in.	7. 8	2. 0	. 4	. 1	. 1	. 4	1. 6	44. 0	51. 4
FOSSIL SOIL												
Fossil red latosol	S54-24-1	------	(1)	7. 8	2. 0	2. 6	2. 3	2. 4	2. 7	2. 6	12. 4	73. 0

See footnote at end of table.

TABLE 3.—*Mechanical composition, in percent, and pH of soils on volcanic rocks and on limestones*—Continued

[Analyst, P. D. Blackmon, U.S. Geological Survey; Tr., trace, <0.1 percent]

Description	Profile and sample No.	Horizon	Depth	pH	Gravel >2 mm	Very coarse sand 1-2 mm	Coarse sand 0.5-1 mm	Medium sand 0.25-0.5 mm	Fine sand 0.10-0.25 mm	Very fine sand 0.05-0.10 mm	Silt 0.002-0.05 mm	Clay <0.002 mm
Soils on limestone—Continued												
CHACHA CLAY												
Brown silty clay on Agana Argillaceous Member of Mariana Limestone.	S54-1-1	A	0-6 in.	6. 5	1. 5	3. 4	3. 2	1. 5	0. 5	0. 7	2. 3	86. 9
	1-2	B	6-18 in.	5. 5	. 1	1. 2	1. 1	. 4	. 3	. 3	1. 1	95. 5
	1-3	B	18-32 in.	6. 5	------	Tr.	Tr.	Tr.	. 1	. 1	5. 6	94. 1
	1-4	B-C	32-46 in.	6. 9	------	Tr.	Tr.	Tr.	Tr.	Tr.	6. 9	93. 0

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[1] Sample obtained from 3-ft vertical channel in middle of 6-ft soil exposure on roadside steep cutbank.

Within each profile of Atate clay there are variations in amounts of both silt and clay, but there does not seem to be any regularity in this variation: for example, in profile S54-4 the lowest percentage of silt is in the B horizon, as it is in profiles S54-5, S54-6, S54-10 and S54-12; but in S54-20 the surface soil contains the least silt and the most clay. For nearly all these profiles the least clay content is in the C horizon and the maximum in the B horizon, although some of the A horizons also have a low percentage of clay. The shallow Guam clay on limestone contains less clay in the surface soil than at depth. The two brown soils, the Asan clay on the Alutom Formation and the Chacha clay on Mariana Limestone, differ from the other soils in being regosols or lithosols and hence differ in stage of development. The Chacha clay has a very high clay content, averaging 92 percent, with consequent low silt content. The surface of this soil, however, is much lower in clay than the remainder of the profile, but it has more coarse sand than the average soils analyzed. The surface Asan clay on the volcanic rocks has a higher clay content than the average clay in the latosols (Atate clay) developed on the same kinds of rocks.

All the soils contain small percentages of the sand grades. Profile S54-5 is the only one to show an appreciable quantity (10.2 percent) of gravel and sand grades; the highest percentage is at the surface and at a depth of 10 feet in the C horizon. Most of the soils reach maximum coarseness in the fine sand (0.10 to 0.25 mm) and very fine sand (0.10 to 0.05 mm) grades. Most profiles have a slightly greater percentage of sand at the surface and at the base of the profile in the C horizon where coarse material probably reflects the composition of the parent material. The weatherable nature of the underlying rocks is reflected in the quantities of the silt and clay grades.

SOIL REACTION

The pH of a 1:5 soil-water suspension for all the soils is given in table 3. The readings range from 4.7 at the base of profile S54-5 to 7.9 at the base of profile S54-17 on Mariana Limestone. All the profiles of Atate clay on the volcanic rocks have pH readings which average 5.3; the Guam clay profiles average 7.4. The Asan clay on volcanics has a pH of 5.6, but the brown soil on limestone, the Chacha clay, has an average pH of 6.3.

The lowest pH readings in the Atate clay profiles are in the dry upper parts of the C horizon, whereas the shallow Guam clay profiles show little variation in pH or an increase towards the underlying limestone.

CHEMICAL COMPOSITION

The major chemical constituents in 6 soil profiles of Atate clay, 5 soil profiles of Guam clay and 1 soil profile each of Asan clay and Chacha clay are given in table 4. The constituents of particular importance with regard to soil formation and mineralogy are silica, alumina, iron, and water.

ATATE CLAY ON VOLCANIC ROCKS

In each soil profile (table 4) the percent of SiO_2 in the Atate clay is less in the surface soil than in the C horizon. In some profiles there is a gradual change in quantity, but in others there is one soil horizon that is noticeably less siliceous than the others. In profile S54-4, the 20- to 30-inch horizon has 27.8 percent, whereas the horizon immediately above it has 28. 2 percent and the surface (0 to 6 in.), 36.6 percent SiO_2. In profile S54-5, the 53- to 60-inch horizon contains 30.3 percent SiO_2, whereas the 18- to 53-inch horizon contains 33 percent. In profile S54-12, the 13- to 40-inch horizon contains 22.4 percent SiO_2, whereas the horizon above and that below it contain 29.1 and 28.7 percent SiO_2, respectively.

In some profiles there is little variation in the amount of Al_2O_3; in others there is a slight accumulation, generally in the horizon that is somewhat depleted in SiO_2.

The total Fe_2O_3 content of the soils is variable; some of the Fe_2O_3 is in the free state (table 5; discussion on p. F11). In general, there is an accumulation

TABLE 4.—*Major chemical constituents, in percent, in samples of soil from 13 soil profiles on Guam*

[Analysts: P. L. D. Elmore, K. E. White, P. W. Scott. Total Fe as Fe_2O_3]

Description	Profile and sample	Horizon	Depth	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	H_2O	CO_2	Total	$\frac{SiO_2}{Al_2O_3+Fe_2O_3}$
Soils on volcanic rocks																	
ATATE CLAY																	
Red latosol on Alutom formation.	S54-4-1	A	0-6 in.	36.6	25.2	14.6	1.0	0.26	0.07	0.16	0.92	0.19	0.36	15.8	0.14	[1] 95	0.92
	4-2	A	6-20 in.	28.2	29.8	19.1	1.8	.09	.03	.17	1.1	.12	1.2	17.7	.24	100	.57
	4-3	B	20-30 in.	27.8	30.0	20.1	1.0	.10	.04	.15	1.2	.10	.96	17.4	.14	99	.55
	4-4	B	30-51 in.	30.4	29.6	19.3	.82	.13	.04	.06	.92	.09	.08	17.4	.09	99	.62
	4-5	C	51-60 in.	29.8	29.6	19.4	.82	.16	.02	.06	.84	.08	.03	18.2	.08	99	.61
	4-6	C	11.0-11.5 ft.	39.1	29.3	13.2	.83	.12	.03	.08	.77	.06	.10	16.6	<.05	100	.92
	4-7	C	12.5-13.0 ft.	40.6	26.7	14.0	1.1	.15	.05	.20	.74	.06	.20	16.0	<.05	100	1.0
	S54-5-1	A	0-6 in.	27.7	27.2	15.3	.39	.20	.06	.12	1.2	.12	.24	17.8	<.05	[1] 90	.65
	5-2	B	6-18 in.	32.0	31.5	15.4	.31	.12	.06	.08	1.1	.06	.02	18.3	<.05	99	.68
	5-3	B	18-53 in.	33.0	31.9	15.2	.42	.09	.08	.12	1.0	.07	.10	18.6	.08	101	.70
	5-4	B	53-60+ in.	30.3	31.8	16.9	.42	.14	.06	.19	1.1	.07	.12	19.1	.08	100	.62
	5-5	C	10.0-10.5 ft.	31.0	31.8	16.5	.48	.11	.04	.16	1.3	.08	.02	18.8	.08	100	.64
	5-6	C	28.5-29.0 ft.	46.3	18.7	8.7	2.8	.15	.04	.28	.64	.10	.02	21.6	.06	99	1.69
Red latosol on Bolanos pyroclastic Member of Umatac Formation.	S54-6-1	A	0-2 in.	35.0	23.0	12.8	1.0	.30	.02	.10	.92	.20	.18	17.5	<.05	[1] 91	.98
	6-2	A	2-10 in.	35.6	25.7	15.5	.82	.14	.04	.11	1.1	.14	.08	18.0	<.05	[1] 97	.86
	6-3	B	10-16 in.	35.7	27.2	14.6	.74	.12	.05	.08	.92	.13	.05	18.7	<.05	99	.85
	6-4	B	16-32 in.	37.6	27.6	13.2	.82	.09	.04	.07	.87	.12	.04	18.9	<.05	99	.92
	6-5	B	32-46 in.	38.2	27.2	12.6	1.1	.10	.06	.12	.88	.10	.06	19.4	<.05	100	.96
	6-6	C	46-60 in.	40.0	26.2	11.8	1.2	.12	.01	.12	.82	.10	.11	19.2	<.05	100	1.05
	6-7	C	13.5-14.5 ft.	40.8	26.8	11.2	1.2	.10	.03	.07	.78	.10	.12	18.4	<.05	100	1.07
	S54-10-2	A	3-15 in.	36.5	27.8	16.2	.54	.12	.03	.09	1.4	.14	.12	16.2	<.05	99	.83
	10-5	C	11.3-12.3 ft.	40.0	27.2	12.3	.87	.11	.04	.22	1.1	.12	.16	16.8	<.05	99	1.01
Red latosol on Facpi Volcanic Member of Umatac Formation.	S54-12-1	A	0-6 in.	28.4	27.2	18.1	.94	.17	.04	.14	.92	.18	.52	17.8	.14	[1] 95	.63
	12-2	B	6-13 in.	29.1	29.6	18.8	.59	.11	.03	.09	.96	.15	.32	18.2	<.05	[1] 98	.60
	12-3	B	13-40 in.	22.4	32.2	21.5	1.5	.06	.04	.17	1.2	.10	1.5	19.0	.18	100	.42
	12-4	C	40-84+ in.	28.7	31.1	20.4	.60	.13	.02	.07	.98	.08	.25	16.9	<.05	99	.56
	12-5	C	9.0-10.0 ft.	34.8	28.4	18.2	.61	.07	.03	.09	.87	.06	.10	16.0	<.05	99	.75
	12-8	C	22.5-23.0 ft.	34.2	28.8	18.2	.81	.08	.04	.11	.88	.08	.14	16.1	<.05	99	.73
Red latosol on Alutom Formation.	S54-20-2	B	4-16 in.	40.4	26.8	8.8	1.4	.52	.03	.10	.76	.08	.02	18.4	<.05	[1] 97	1.13
	20-3	B-C	16-36 in.	41.5	26.6	8.9	1.4	.46	.04	.13	.80	.06	.01	18.6	<.05	99	1.17
ASAN CLAY																	
Brown regosol on Alutom Formation.	S54-23-1	A	0-8 in.	43.7	17.2	10.0	3.6	.42	.08	1.1	.83	.09	.07	18.1	<.05	[1] 95	1.61
	23-2	C	8-36 in.	46.4	16.6	10.1	3.8	.48	.06	1.5	.74	.06	.16	19.1	<.05	99	1.74
Soils on limestone																	
GUAM CLAY																	
Red latosol on Barrigada Limestone.	S54-16-1	A	0-60 in.	1.2	41.1	22.6	0.74	0.40	0.03	0.08	2.2	2.2	0.84	25.4	0.19	[1] 97	0.02
Red latosol on Mariana Limestone.	S54-17-2	B	3-24 in.	1.1	42.6	22.1	1.2	.31	.03	.09	2.2	1.3	1.2	24.6	.26	[1] 97	.02
	S54-18-1	A	0-1 in.	.74	37.3	19.7	.23	.78	.07	.06	2.0	.82	.47	24.4	.20	[1] 87	.01
	18-2	B	1-15 in.	1.0	40.0	21.0	.16	.41	.06	.07	2.0	.68	.45	26.4	.50	[1] 93	.01
	18-3	D[2]	15+ in.	------	------	------	.45	54.0	------	------	------	------	------	------	------	------	------
	S54-19-1	A	0-4 in.	2.2	35.3	17.0	.47	1.0	.06	.12	1.8	2.5	.48	23.0	.24	[1] 84	.04
	19-2	B	4-12 in.	2.3	38.5	19.4	.50	2.0	.06	.14	1.8	2.4	.36	21.3	2.4	[1] 91	.04
	19-3	D[2]	12-20 in.	------	------	------	.58	54.5	------	------	------	------	------	------	------	------	------
FOSSIL SOIL																	
Fossil red latosol	S54-24-1	--------	(3)	22.4	38.6	15.3	.08	.36	.07	.04	1.0	.22	.04	20.4	.35	99	.41
CHACHA CLAY																	
Brown silty clay on Agana Argillaceous Member of Mariana Limestone.	S54-1-1	A	0-6 in.	26.8	24.8	19.0	.54	.62	.06	.10	.94	.89	.48	18.4	.12	[1] 93	.61
	1-2	B	6-18 in.	33.0	29.0	16.2	.66	.25	.07	.08	.84	.76	.09	18.4	.08	99	.73
	1-3	B	18-32 in.	34.2	30.4	14.6	.66	.21	.08	.08	.88	.60	.06	18.4	.09	100	.76
	1-4	B-C	32-46 in.	34.4	29.7	14.6	.71	.36	.08	.10	.82	.64	.06	18.5	.08	100	.78
	1-5	D[2]	46-52 in.	------	------	------	.67	54.3	------	------	------	------	------	------	------	------	------

[1] Organic matter present in appreciable quantity.

[2] D horizon is parent rock.

[3] Sample obtained from 3-ft vertical channel in middle of 6-ft soil exposure on roadside steep cutbank.

of Fe_2O_3 in the upper parts of the profiles; for example, profile S54–5 contains 8.7 percent in the C horizon and 15.3 percent Fe_2O_3 at the surface. Table 4 shows that Fe_2O_3 tends to accumulate in the B soil horizon.

The presence of organic matter in the surface soils makes the determination of total water difficult, and the resulting figure may be inaccurate. There is little variation in water content in the horizons in any one profile, the figure for H_2O for all profiles averaging 17.8 percent. The figures obtained range between 16.5 and 19.0 percent H_2O for profile averages.

The remaining oxides (table 4), MgO, CaO, Na_2O, K_2O, TiO_2, P_2O_5, MnO, and CO_2, can be regarded as the minor constituents of the soils. There is little variation in the percentage of most of these oxides in each profile, but TiO_2 and MnO show an increase, generally in the B horizon.

ASAN CLAY ON VOLCANIC ROCKS

The chemical composition of the Asan clay, a brown regosol developed on volcanic rocks, differs markedly from that of the red latosols (Atate clay). Silica is about 10 percent higher, but Al_2O_3 is about the same as the average figure for the Atate clay. Ferric iron is lower, but total water is about the same. The most striking difference is in the MgO and K_2O contents, which average 3.7 percent MgO and 1.3 K_2O in the Asan clay compared with an average of 0.88 percent MgO and 0.12 percent K_2O in the Atate clay profiles.

GUAM CLAY ON LIMESTONES

As the Guam clay is a shallow soil, variations in chemical composition within the profile are not noticeable. The SiO_2 content is very low, averaging 1.4 percent compared with an average of 35.5 percent for the soils developed on volcanic rocks. The Al_2O_3 content of the Guam clay averages 42.5 percent as against 28 percent in the Atate clays. The ratio between SiO_2 and Al_2O_3 is reflected in the kinds of clay minerals found in these soils. The Fe_2O_3 averages 20 percent; so $Al_2O_3+Fe_2O_3$ account for more than 60 percent of the soil substance. Much of the Fe_2O_3 is present as free iron oxide on the outside of other mineral grains. The total water is 24 percent, which, with the high Al_2O_3 content and low percentage of SiO_2, results in the presence of gibbsite in these soils (section on silt and clay minerals, p. F18–F24.

Of the remaining oxides given in table 4, CaO and TiO_2 deserve mention. In profile S54–19, 1 percent of CaO is present in the surface soil and 2 percent at depth, which is higher than for any other soil analyzed. The TiO_2 averages 2 percent, which is about twice as much as occurs in the soils developed from volcanic rocks and suggests an accumulation of TiO_2 during the formation of these soils on limestones.

FOSSIL RED LATOSOL

The fossil red latosol that has developed on limestone resembles in its SiO_2 content the Chacha clay on limestone, but its content of Al_2O_3 resembles that of the Atate clay. The content of Fe_2O_3 is approximately the same as the average for the Atate clay.

CHACHA CLAY ON LIMESTONE

The Chacha clay on limestone although classified as a silty clay, is actually a clay with less silt content than any of the other soils described. In chemical composition it resembles some of the Atate clay profiles. The SiO_2 ranges from 34 percent in the C horizon to 27 percent in the surface soil (average, 32.1 percent), and its distribution is similar to that in the Atate clay. The Al_2O_3 content is variable (average, 28.5 percent) with about 5 percent less in the surface soil than at depth. The highest concentration of Fe_2O_3, 19 percent, is at the surface, whereas the lowest soil horizon contains 14.6 percent (average, 16.1 percent). There is little variation in the other constituents throughout the profile; total water is 18.4 percent for each part of the profile. The TiO_2 content is similar to that in the Atate clay and shows very little concentration in any part of this profile.

CHEMICAL CHARACTERISTICS

Chemical differences between the soils developed on the volcanic rocks and those on the limestones are most marked in the Atate and Guam clays; although they are also apparent in the brown soils on these rocks, for which few samples are available for study. The principal differences are shown by the averages for the various soil types. These averages are perhaps more valid for the Atate clay than for the other soils because of the much larger number of samples. The average contents, in percent, for a number of chemical constituents in these soils follows.

Clay	Number of samples	SiO_2	Al_2O_3	Fe_2O_3	H_2O	TiO_2	MnO	P_2O_5
Atate	34	35.5	27.9	14.5	17.8	1.0	0.20	0.10
Asan	2	45.0	16.9	10.0	18.6	.78	.11	.07
Gnam	6	1.4	42.5	20.3	24.2	2.0	.63	1.6
Chacha	4	32.1	28.5	16.1	18.4	.87	.17	.72

FREE IRON OXIDE

The uncombined, easily removed ferric oxide of soils is generally referred to as the free iron oxide. Mineralogically it is geothite, hematite, or indefinite noncrystalline iron oxide, which is principally associated with the clay mineral particles to which it is firmly attached. It is considered that 75 percent of the free iron oxide of a soil is in the clay fraction.

The free iron oxide determined for these soils is given in table 5.

Within the individual profiles of the Atate clay there is a considerable variation in free iron oxide content, and in general the samples from the C horizon contain much less than those near the top of the profile. This is to be expected because the iron in the unweathered volcanic rocks is largely present as FeO in combination with alumina and silica in pyroxenes. The average free iron oxide in the Atate clay is 11.4 percent. The profile averages are 12.0, 13.2, 9.2, 11.7, 14.1, 4.1, and 11.1 percent, respectively. The reason for the low figure for profile S54–20 (4.1 percent) is not apparent; but this soil has a higher exchange capacity than most, and most of the iron may be in combination in a clay mineral, for some possible mixed-layered halloysite-montmorillonite is present in this profile.

TABLE 5.—*Organic carbon, free iron oxide. and ion-exchange capacity of soils on volcanic rocks and on limestones*

[Analysts, Dorothy Carroll and H. C. Starkey; n.d., not determined]

Description	Profile and sample	Horizon	Depth	Organic carbon (percent)	Free iron oxide (percent)	Ion-exchange capacity milliequivalents per 100 grams
Soils on volcanic rocks						
ATATE CLAY						
Red latosol on Alutom Formation.	S54-4-1	A	0-6 in.	2.9	10.8	11.4
	4-2	A	6-20 in.	.7	15.4	3.9
	4-3	B	20-30 in.	n.d.	17.7	4.8
	4-4	B	30-51 in.	n.d.	12.7	6.6
	4-5	C	51-60 in.	n.d.	10.8	6.6
	4-6	C	11.0-11.5 ft	n.d.	7.4	6.6
	4-7	C	12.5-13.0 ft	n.d.	9.5	9.6
	S54-5-1	A	0-6 in.	5.0	13.2	10.2
	5-2	B	6-18 in.	1.1	14.7	7.2
	5-3	B	18-53 in.	n.d.	15.4	8.1
	5-4	B	53-60+ in.	n.d.	[1] 20.4	8.0
	5-5	C	10.0-10.5 ft	n.d.	14.4	7.8
	5-6	C	28.5-29.0 ft	n.d.	1.5	33.6
Red latosol on Bolanos Pyroclastic Member of Umatac Formation.	S54-6-1	A	0-2 in.	4.3	12.7	17.1
	6-2	A	2-10 in.	1.8	8.4	13.8
	6-3	B	10-16 in.	2.2	10.8	35.1
	6-4	B	16-32 in.	.6	8.4	16.5
	6-5	B	32-46 in.	n.d.	10.8	19.5
	6-6	C	46-60 in.	n.d.	6.6	23.7
	6-7	C	13.5-14.5 ft	n.d.	6.6	23.4
	S54-10-1	A	0-3 in.	3.4	14.7	15.0
	10-2	A	3-15 in.	.5	10.8	11.1
	10-3	B	15-28 in.	n.d.	12.7	9.9
	10-4	C	28-60+ in.	n.d.	13.2	10.2
	10-5	C	11.3-12.3 ft	n.d.	7.4	11.7
Red latosol on Facpi Volcanic Member of Umatac Formation.	S54-12-1	A	0-6 in.	2.7	10.8	11.1
	12-2	B	6-13 in.	1.2	12.7	6.3
	12-3	B	13-40 in.	.3	19.8	3.0
	12-4	C	40-84+ in.	.5	19.8	5.7
	12-5	C	9.0-10.0 ft	.1	15.4	7.8
	12-6	C	---------------	n.d.	12.7	8.4
	12-7	C	---------------	n.d.	7.4	12.0
	12-8	C	22.5-23.0 ft	n.d.	14.0	16.0
Red latosol on Alutom Formation.	S54-20-1	A	0-4 in.	1.1	4.0	32.0
	20-2	B	4-16 in.	n.d.	4.3	31.2
	20-3	B-C	16-36 in.	.6	4.0	23.2
	S54-21-1	A	0-16 in.	2.5	13.2	20.8
	21-2	B	16-36 in.	.5	15.4	19.2
	21-3	C	36-66 in.	.1	7.3	27.2
	21-4	C	8.0-9.0 ft	.06	8.4	26.4
ASAN CLAY						
Brown regosol on Alutom Formation.	S54-23-1	A	0-8 in.	1.5	4.3	38.4
	23-2	C	8-36 in.	2.0	4.0	40.8
Soils on limestone						
GUAM CLAY						
Red latosol on Barrigada Limestone.	S54-16-1	A	0-60 in.	.1	14.0	4.5
Red latosol on Mariana Limestone.	S54-17-1	A	0-3 in.	5.9	17.7	35.2
	17-2	B	3-24 in.	.4	16.8	6.6
	S54-18-1	A	0-1 in.	4.4	20.4	26.4
	18-2	B	1-15 in.	2.5	20.4	17.6
	S54-19-1	A	0-4 in.	3.9	16.8	36.4
	19-2	B	4-12 in.	2.0	20.4	11.6
FOSSIL SOIL						
Fossil red latosol	S54-24-1	-------	---------------	.06	13.2	6.3
CHACHA CLAY						
Brown silty clay on Agana Argillaceous Member of Mariana Limestone.	S54-1-1	A	0-6 in.	3.3	4.0	13.5
	1-2	B	6-18 in.	1.1	7.4	11.4
	1-3	B	18-32 in.	n.d.	4.0	11.4
	1-4	B-C	32-46 in.	n.d.	8.4	15.0

See footnote at end of table.

[1] Percentage is high, probably because of organic matter.

The free iron oxide in the samples of Guam clay ranges from 16.8 to 20.4 percent with an average of 18.07 percent if S54–16 is included, which is nearly twice as high as the content of the Atate clay. All the figures obtained, with one exception, were higher than those for the Atate clay. The fossil red latosol on the Mariana Limestone, S54–24, has a free iron oxide content similar to those obtained for the Atate clay. The regosols, Asan clay (S54–23) and Chacha clay (S54–1), have low free iron oxide contents, the former averaging 4.1 and the latter 5.9 percent. The low figures are probably due to a shorter period of formation for these soils, as their color is brown and not red as in the latosols. The principal iron oxide mineral in the Chacha clay is goethite (table 7).

ION-EXCHANGE CAPACITY

The cation-exchange capacity of these soils is given in table 5. The figures obtained vary within each soil profile and between the different profiles and are a reflection of the kind of clay mineral present. The most completely weathered soils have the most uniform figures for ion-exchange capacity. In general, the figure for the surface soil is higher than for samples obtained in other parts of the profile, and this is most probably due to the organic matter present. Increase of ion-exchange capacity in the C horizon of profile S54–5 is due to variation in the type of clay mineral present, for it has been found (table 7) that montmorillonite occurs in the weathered rock constituting the C horizon, whereas the clay mineral in the upper parts profile is halloysite.

In the Atate clay, the ion-exchange capacity varies. Averages for the profiles are 7.0, 8.2 (33.6 at base), 21.4, 11.6, 8.8, 28.8, and 24 milliequivalents per 100 grams. The relationship between clay minerals and ion-exchange capacity of the Atate clay is shown by considering tables 5 and 7.

The surface soils of the Guam clay have a high ion-exchange capacity which is due to their high content of organic matter. The average for soil material without organic matter is 5.8 milliequivalents per 100 grams, which is consistent with their clay mineralogy.

The brown regosols, Asan clay and Chacha clay, on volcanic rocks and on limestone, respectively, differ considerably. The Asan clay has an average ion-exchange capacity of 39 milliequivalents per 100 grams, which includes the exchange due to organic matter. The Chacha clay averages 12 milliequivalents per 100 grams (also including organic matter). The ion-exchange capacity reflects essential differences in the mineralogy of these soils.

ORGANIC MATTER

As a measure of the amount of organic matter present in the surface samples of these profiles the organic carbon was determined (table 5). The average for the upper 6 inches of all these soils is 3.4 percent organic carbon equivalent to approximately 5.8 percent organic matter. In the lower parts of the soil profiles organic matter is present in small quantities, but it was not determined for all profiles. An Atate clay profile S54–12 (table 5) has 0.1 percent at a depth of 10 feet, and another profile, S54–21, has a small quantity at 8 to 9 feet in the C horizon. The quantity of organic matter is higher in the Guam clays than in the Atate clays, but in the latter it may be more closely associated with the clay minerals and therefore more difficult to determine. The organic matter in the surface soils has resulted in low totals for the chemical analyses (table 4).

MINERALOGICAL COMPOSITION

SAND FRACTIONS

The minerals identified in the sand fractions are listed in table 6. As the soils on volcanic rocks average 94 percent silt and clay, and the soils on limestones average 91 percent silt and clay (table 3), only a small quantity of material coarser than 50 microns is present in any sample. The scarcity of coarse grains in the volcanic rocks has reduced the occurrence of sand-sized minerals in the soils. The fine sand (0.25 to 0.10 mm) and the very fine sand (0.10 to 0.05 mm) fractions were separated in bromoform to obtain the heavy minerals.

The quantity of heavy residue in these sand fractions varies within each soil profile and from profile to profile; this variation is apparently the end result of differences in parent material weathering under similar climatic conditions. Calculation of the amount of heavy residue in the whole soil shows that the maximum amount is 3.5 percent in profile S54–10–1 to 10–5, Atate clay on the Bolanos Pyroclastic Member of the Umatac Formation, but many soils contain only a trace (<0.1 percent) of heavy minerals. The soils overlying the limestones have a heavy-mineral content similar to that of soils on the volcanic rocks. Some profiles, notably S54–4–1 to 4–7, S54–5–1 to 5–6, and S54–10–1 to 10–5, have an enrichment in heavy minerals in the surface horizon, a feature that has been noted elsewhere in old soil profiles; that is, in soils which have remained in place and have been subjected to soil-forming processes without disturbance for long periods.

The minerals present in the heavy residues are, in order of abundance, magnetite, other opaque grains (indefinite iron oxides and ilmenite), augite, hypersthene, greenish-brown and brown amphiboles. Zircon, sphene, and rutile occur sporadically in very small quantities.

Magnetite.—Table 6 shows that magnetite is the most abundant of the heavy minerals and that it commonly makes up about three-quarters by weight of the heavy residue. It occurs in small octahedra and in irregular grains. Magnetite seems to be resistant to weathering under the conditions in which these soils are forming, but some of the goethite and hematite occurring as red and brown opaque grains probably has been derived from magnetite. Magnetite is a constituent of many of the lavas and tuffs on Guam, and it is therefore a residual mineral in these soils. Magnetite has, however, often been found in bands or layers in the weathered rock material, which suggests that there has been movement of material and that any concentration of magnetite in a surface soil may not be derived from the rock now immediately beneath the soil.

Ilmenite.—The black opaque less strongly magnetic grains in the residues are ilmenite. Many are irregular in shape, but others are well crystallized with tabular rhombohedral crystals generally lying on the base *c* (0001) and showing rhombohedral faces. The presence of titanium was confirmed spectroscopically. Ilmenite occurs in much smaller quantities than magnetite and, as it is relatively resistant to weathering, has become concentrated in the surface soils. Many crystals have sharp-edged faces and do not have leucoxenic alterations, but in parts of some profiles, notably in the weathered rock at the base of S54–12, many ilmenite grains show corrosion pits. Such pitting indicates removal of part of the ilmenite by solution. It is probable that some of the parent rocks contain ilmenite that is well crystallized, whereas in other rocks the

TABLE 6.—*Heavy minerals (sp gr >2.8) in the sand fractions (0.25–0.10 mm and 0.10–0.05 mm) of soils from Guam*

[H. R., heavy residue, including magnetite; Mag. Fr., strongly magnetic fraction in sand; Tr., trace, <0.1 percent; n.d., not determined; A, major constituent; ++, present in large amounts; +, present]

Profile and sample	Horizon	Depth	0.25–0.10 mm		0.10–0.05 mm		Total in soil [1]		Minerals						
			H. R. (percent)	Mag. Fr. (percent)	H. R. (percent)	Mag. Fr. (percent)	H. R. (percent)	Mag. Fr. (percent)	Ilmenite	Opaque red, brown	Augite	Hypersthene	Amphibole		Others
													Green	Brown	
Atate clay															
S54-4-1	A	0-6 in.	11.6	9.2	38.0	26.4	2.7	1.9	A	+	+	++	------	------	------
4-2	A	6-20 in.	9.2	4.4	60.8	17.4	.7	.2	A	+	------	------	------	------	------
4-3	B	20-30 in.	10.5	7.4	25.4	7.9	.5	.2	A	A	------	------	------	------	------
4-4	B	30-51 in.	5.5	.9	33.3	8.3	.3	Tr.	A	A	------	------	------	------	------
4-5	C	51-60 in.	3.8	.3	16.6	4.1	.5	.1	+	A	------	------	------	------	------
4-6	C	11.0-11.5 ft	23.1	19.1	48.3	45.0	------	------	+	A	------	------	------	------	------
4-7	C	12.5-13.0 ft	13.5	4.2	31.4	17.6	------	------	+	A	------	------	------	------	------
S54-5-1	A	0-6 in.	3.4	.3	7.8	.4	.6	Tr.	+	------	A	A	------	------	------
5-2	B	6-18 in.	.3	Tr.	.9	Tr.	Tr.	Tr.	+	------	++	+	------	------	------
5-3	B	18-53 in.	.2	.1	1.1	.5	Tr.	Tr.	A	+	+	------	------	------	------
5-4	B	53-60+ in.	.5	.2	1.7	.2	.1	Tr.	A	++	+	------	+	------	------
5-5	C	10.0-10.5 ft	Tr.	Tr.	.7	Tr.	Tr.	Tr.	A	++	+	------	+	------	------
5-6	C	28.5-29.0 ft	1.1	1.0	7.8	6.2	------	------	A	------	+	------	+	------	------
S54-6-1	A	0-2 in.	23.1	18.8	52.6	42.8	1.3	1.0	A	+	++	+	+	------	+
6-2	A	2-10 in.	56.4	30.1	37.0	32.9	2.2	1.5	A	+	+	------	+	------	+
6-3	B	10-16 in.	12.9	10.9	32.4	26.7	.6	.5	A	+	+	------	------	------	+
6-4	B	16-32 in.	17.0	13.5	43.4	37.5	.9	.8	+	A	------	+	------	------	+
6-5	B	32-46 in.	18.9	14.8	57.9	55.2	.9	.8	++	A	------	------	------	------	+
6-6	C	46-60 in.	8.9	8.1	56.6	51.6	1.3	1.2	++	A	+	------	------	------	+
6-7	C	13.5-14.5 ft	9.2	8.2	36.0	34.9	2.5	2.4	A	++	------	------	------	------	+
S54-10-1	A	0-3 in.	54.6	46.3	70.5	61.3	3.5	3.0	++	A	+	+	+	------	------
10-2	A	3-15 in.	53.3	49.5	51.6	49.0	2.9	2.7	++	A	------	------	------	------	------
10-3	B	15-28 in.	26.3	20.7	36.9	31.3	1.6	1.3	+	A	------	------	------	------	+
10-4	C	28-60+ in.	37.9	34.1	49.0	42.8	------	------	+	A	------	------	------	------	------
10-5	C	11.3-12.3 ft	5.8	5.8	15.1	15.1	------	------	++	++	------	------	------	------	+
S54-12-1	A	0-6 in.	.9	Tr.	5.9	Tr.	.1	Tr.	A	+	++	+	------	------	------
12-2	B	6-13 in.	.6	Tr.	17.9	Tr.	.3	Tr.	+	A	------	------	------	------	------
12-3	B	13-40 in.	3.1	Tr.	12.1	Tr.	.1	Tr.	++	++	+	------	------	------	------
12-4	C	40-84+ in.	3.0	Tr.	8.3	Tr.	.1	Tr.	+	A	------	------	------	------	------
12-5	C	9.0-10.0 ft	3.2	Tr.	11.4	Tr.	.4	Tr.	+	A	------	------	------	------	------
12-7	C	13.4-13.9 ft	2.1	Tr.	.6	Tr.	------	------	++	++	------	------	------	------	+
12-6	C	15.0-16.0 ft	1.0	Tr.	7.5	Tr.	Tr.	Tr.	+	A	------	------	------	------	------
12-8	C	22.5-23.0 ft	0.3	Tr.	1.1	Tr.	Tr.	Tr.	++	+	------	------	------	------	+
S54-20-1	A	0-4 in.	3.1	1.5	2.7	1.5	Tr.	Tr.	A	+	++	+	+	------	------
20-2	B	4-16 in.	Tr.	Tr.	.6	.3	Tr.	Tr.	+	+	+	------	+	------	+
20-3	B-C	16-32 in.	Tr.	------	.8	.4	Tr.	Tr.	++	+	------	------	------	------	------
S54-21-1	A	0-16 in.	.6	Tr.	.9	Tr.	Tr.	Tr.	+	+	A	A	------	------	------
21-2	B	16-36 in.	.1	Tr.	1.5	Tr.	Tr.	Tr.	A	A	+	+	------	------	------
21-3	C	36-66 in.	.1	Tr.	1.3	Tr.	.1	------	+	A	------	------	------	------	------
21-4	C	8.0-9.0 ft	.3	.1	2.8	2.1	.2	------	+	A	------	------	------	------	------
Asan clay															
S54-23-1	A	0-8 in.	3.1	2.7	13.1	11.5	0.6	0.5	++	+	A	+	+	+	------
23-2	C	8-36 in.	.5	------	5.5	5.0	------	------	+	+	+	------	------	------	------
Guam clay															
S54-16-1[2]	------	0-60 in.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	------	------	------	------	------	------	------
S54-17-1	A	0-3 in.	7.0	3.5	n.d.	n.d.	.4	.2	+	A	++	------	------	------	------
17-2[2]	B	3-24 in.	n.d.	Tr.	n.d.	n.d.	------	------	------	------	------	------	------	------	------
S54-18-1	A	0-1 in.	39.1	13.0	n.d.	n.d.	1.2	.4	A	+	+	+	------	+	+
18-2	B	1-15 in.	35.7	7.1	n.d.	n.d.	.7	.1	A	+	+	+	------	------	+
S54-19-1	A	0-4 in.	8.3	Tr.	n.d.	n.d.	------	------	+	+	A	+	------	------	------
19-2	B	4-12 in.	40.0	30.0	n.d.	n.d.	.9	.7	+	++	A	+	------	------	------

See footnotes at end of table.

TABLE 6.—*Heavy minerals (sp gr >2.8) in the sand fractions (0.25–0.10 mm and 0.10–0.05 mm) of soils from Guam*—Continued

[H. R., heavy residue, including magnetite; Mag. Fr., strongly magnetic fraction in sand; Tr., trace, <0.1 percent; n.d., not determined; A, major constituent; ++, present in large amounts; +, present

Profile and sample	Horizon	Depth	0.25–0.10 mm		0.10–0.05 mm		Total in soil [1]		Minerals						
			H. R. (percent)	Mag. Fr. (percent)	H. R. (percent)	Mag. Fr. (percent)	H. R. (percent)	Mag. Fr. (percent)	Ilmenite	Opaque red, brown	Augite	Hypersthene	Amphibole		Others
													Green	Brown	
							Fossil soil								
S54–24–1	------	Composite sample.	4.7	3.8	22.7	18.2	2.0	1.6	+	A	------	------	------	------	------
							Chacha clay								
S54–1–1	A	0–6 in.	13.6	1.0	n.d.	n.d.	0.7	Tr.	A	+	+	+	------	------	------
1–2	B	6–18 in.	10.3	.5	n.d.	n.d.	.2	Tr.	A	A	+	------	------	------	------
1–3	B	18–32 in.	.2	Tr.	n.d.	n.d.	Tr.	------	A	A	------	------	------	------	------
1–4	B–C	32–46 in.	9.0	Tr.	n.d.	n.d.	Tr.	------	+	A	+	+	------	------	------

[1] Total found in 0.25–0.10 and 0.10–0.05 mm grades recalculated for whole soil; the figure will be slightly less than the true amount present because of small quantities probably present in other sand grades and silt.

[2] Sand fractions too small in quantity for bromoform separation.

ilmenite was originally irregular in shape. It is the irregular grains, probably more poorly crystallized, that are strongly corroded and pitted.

Red and brown opaque grains.—Red and brown opaque grains are commonly present in all the heavy residues (table 6) where they represent alteration of magnetite and ilmenite to hematite and goethite. Many have a core of a black opaque mineral. These opaque grains are not dissolved by 1+1 HCl to any great extent. In some residues these opaque grains are more abundant than ilmenite.

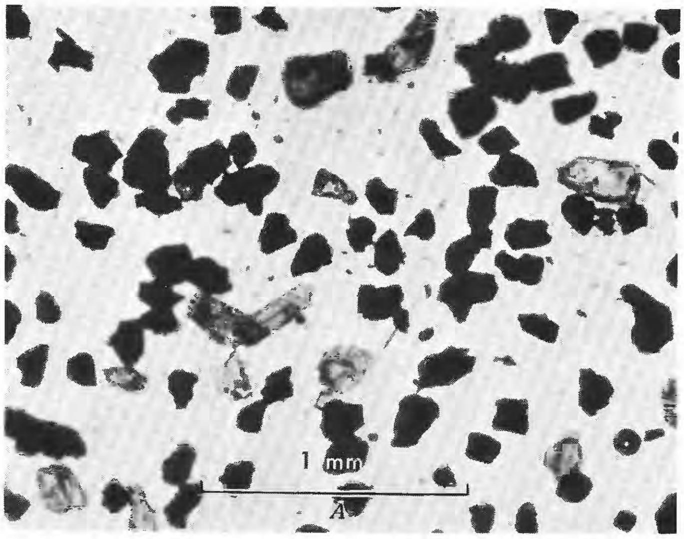
Augite.—Augite in the soil heavy residues is similar to that described from the insoluble residues of the limestones (Hathaway and Carroll, 1963), but in the soils many of the grains are very strongly corroded. Figure 4 shows fresh and corroded augite. The most strongly corroded grains occurred in the Asan clay on the Alutom Formation (S54–23).

Augite is the major ferromagnesian mineral in the andesites, dike rocks, and tuffs of Guam. It has been incorporated in the limestones; so it may be present in a residual soil developed from a limestone. It is noteworthy that augite, together with hypersthene and in places amphibole, is of more common occurrence in the surface soils than in the subsoils and weathered rocks. Mohr and Van Baren (1954, p. 215) describe accumulation in soils in Indonesia and explain it as due to a late fall of volcanic ash. The senior author, from experience with many residual soils, believes that accumulation of magnetite, ilmenite, zircon, tourmaline, and other resistant minerals is due to the age of the soil in its present position, unless it can be proved that such minerals have been added from another source. It has been observed on many occasions that initial weathering of ferromagnesian minerals produces clay minerals, whereas those slightly more resistant minerals will show etched surfaces and no chemical alteration. There is a stage in the corrosion of such grains at which the optical properties change and the mineral can no longer be considered the same as it was originally; at this stage the mineral will lose chemical elements by solution and will eventually disappear.

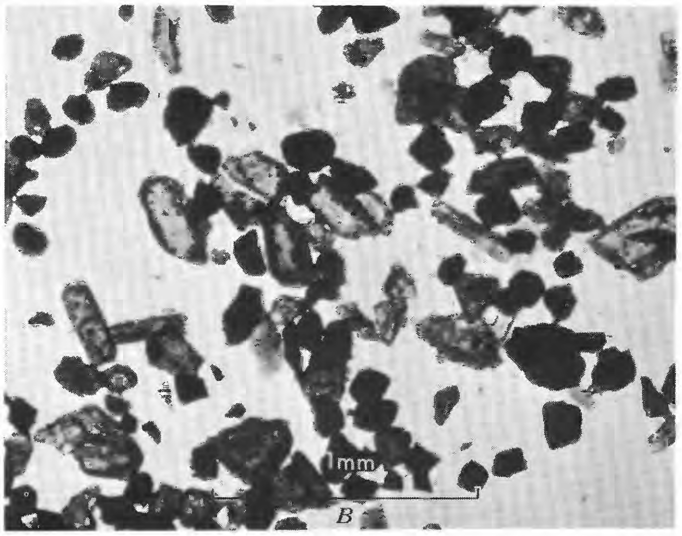
Hypersthene.—The hypersthene, where it is present in these soil heavy residues, is also similar to the grains observed in the insoluble residues of limestones. Generally, hypersthene is subordinate to augite in quantity, but in S54–5 it is equal in amount to augite. Many hypersthene grains are in stout prismatic euhedra which have been very little modified by weathering, although some corrosion is noticeable. Hypersthene is less corroded than augite and appears to be more resistant to leaching. In the parent rocks hypersthene is generally less plentiful than augite; so equal amounts in a heavy residue would suggest differential removal of augite.

Amphibole.—Only negligible amounts of amphibole, principally a brownish-green variety, were observed. The grains are fresh and noncorroded. Amphibole is not at all abundant in the volcanic rocks of Guam, although some of the limestones contain appreciable quantities (Hathaway and Carroll, 1963).

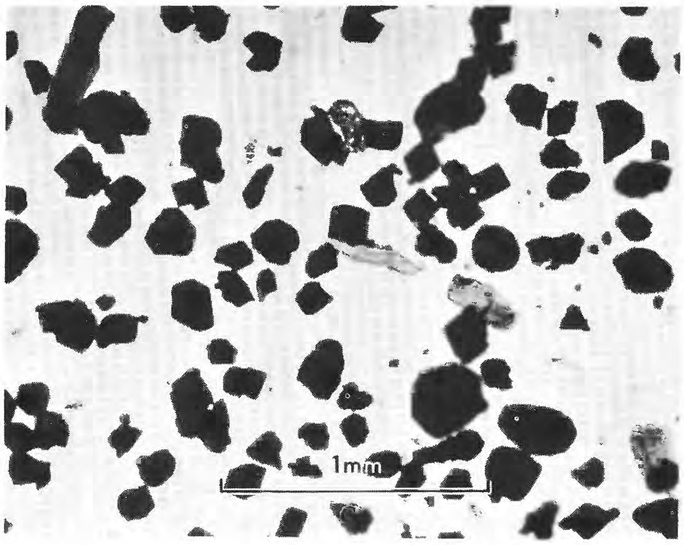
Of the remaining heavy minerals listed, zircon, sphene, and rutile are very scarce. Minor amounts of zircon were observed in samples S54–5–3 and 5–4, and S54–6–1 to 6–7, S54–18–1, and S54–20–2. The zircon is either euhedral or rounded; the rounding, however, is not considered to be the result of erosion and redeposition, but to be an inherent characteristic. Sphene was observed in samples S54–1–1, S54–5–2, S54–18–2, and S54–20–1. Rutile is even scarcer than sphene. It is



A. Atate clay, 0 to 6 inches, on Alutom Formation. Surface soil from profile S54-4, dark-reddish-brown clay. Fraction plus 140 (0.25 to 0.10 mm) nonmagnetic × 35. Opaques, augite, hypersthene.

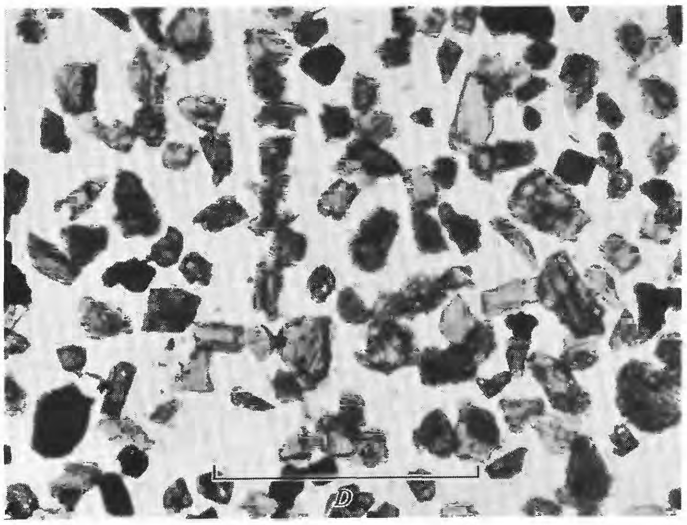


B. Atate clay, 0 to 6 inches, on Alutom Formation. Surface soil from profile S54-5 dark-reddish-brown clay. Fraction plus 140 (0.25 to 0.10 mm) nonmagnetic × 35. Augite, hypersthene, opaques.

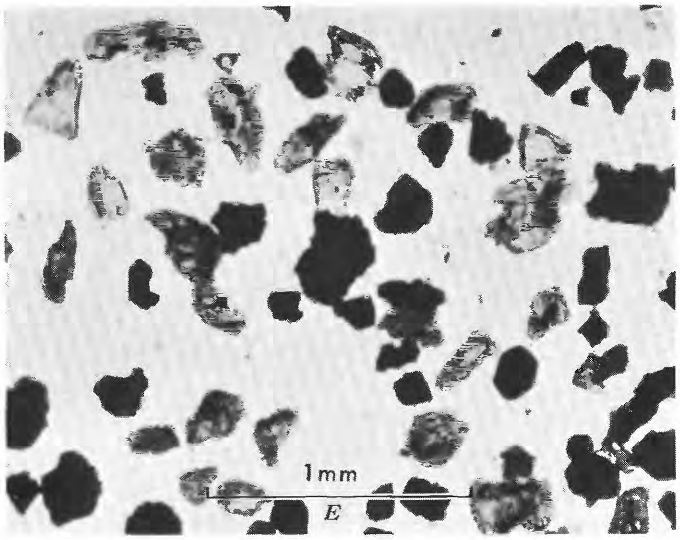


C. Atate clay, 28.5 to 29 feet, soft weathered tuff, Alutom Formation, profile S54-5, the parent material of this soil, mottled white with yellow and red clay. Fraction plus 140 (0.25 to 0.10 mm), nonmagnetic × 35. Opaques, augite, altered hornblende.

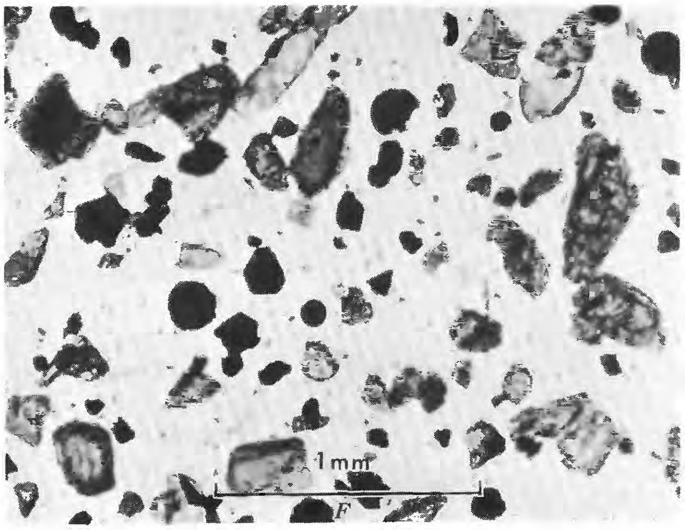
FIGURE 4. Heavy residues of



D. Atate clay, 0 to 16 inches, on Alutom Formation. Surface soil from profile S54-21, dark-reddish-brown clay. Fraction plus 140 (0.25 to 0.10 mm), nonmagnetic × 35. Augite, hypersthene, opaques. Both augite and hypersthene are corroded.



E. Asan clay, 0 to 8 inches, on Alutom Formation. Surface soil from profile S54-23, dark-grayish-brown clay. Fraction plus 140 (0.25 to 0.10 mm), nonmagnetic × 35. Opaques, augite (strongly corroded).



F. Guam clay, 0 to 4 inches, on Mariana Limestone. Surface soil from profile S54-19, yellowish-red-clay. Total heavy residue, nonmagnetic × 35. (All less than 0.25 mm.) Augite, hypersthene, opaques.

sand fractions of soils on Guam.

apparently not formed authigenically from the alteration of ilmenite, which itself is not very plentiful in these residues or in the volcanic rocks. Anatase was not seen under the microscope, although X-ray diffraction charts indicated its presence in samples S54–17 and S54–19.

CLAY AND SILT FRACTIONS

The minerals identified by X-ray examination are listed in table 7. Estimates of the amounts of the various minerals in the samples are derived from the relative intensities of the diffracted lines. Because in addition to quantity of a mineral, many factors, such as variations in degree of preferred orientation, difference in degree of crystallinity, and variations in isomorphous substitution, affect diffraction intensity, these estimates can give only a general indication of the relative amounts of the minerals present.

TABLE 7.—*Mineralogy of the clay and silt fractions of soils*

[Estimated amounts given as parts in ten; Tr., trace, <0.1 part; where a question mark precedes or replaces an estimate of quantity the identification of the mineral is doubtful; where a question mark follows an estimate of quantity the identification is reasonably certain, but the estimated amount is doubtful]

A. ON VOLCANIC ROCKS

Description	Profile and sample	Depth	Fraction	Halloysite	Goethite	Hematite	Magnetite	Gibbsite	Quartz	Alpha-cristobalite
Atate clay										
Red latosol on Alutom Formation.	S54-4-1	0–6 in	Clay	6	1	1	--------	--------	--------	--------
		0–6 in	Silt	5	1	1	Tr	--------	Tr.	1
	4-2	6–20 in	Clay [1]	6	Tr.	2	--------	Tr.	--------	--------
		6–20 in	Silt [1]	4	Tr.	2	--------	Tr.?	Tr.	1
	4-3	20–30 in	Clay [1]	6	Tr.	2	--------	1	Tr.	--------
		20–30 in	Silt [1]	4	Tr.	2	Tr.	Tr.	Tr.	Tr.
	4-4	30–51 in	Clay	5	1	2	--------	Tr.	--------	--------
		30–51 in	Silt	4	1	2	--------	3	--------	--------
	4-5	51–60 in	Clay	5	2	1?	--------	--------	--------	--------
		51–60 in	Silt	3	2	1?	--------	3	--------	--------
	4-6	11. 0–11. 5 ft	Clay	7	Tr.?	--------	--------	--------	--------	--------
		11. 0–11. 5 ft	Silt	6	1	--------	Tr.	?Tr.	--------	--------
	4-7	12. 5–13. 0 ft	Clay	7	--------	1	--------	--------	--------	?Tr.
		12. 5–13. 0 ft	Silt	6	--------	2	Tr.	--------	--------	1
	S54-5-1	0–6 in	Clay	5	2	2	--------	--------	--------	--------
		0–6 in	Silt	3	1?	2	--------	1	2	Tr.
	5-2	6–18 in	Clay	6	2	1	--------	--------	--------	--------
		6–18 in	Silt	4	1	3	--------	Tr.	Tr.	Tr.
	5-3	18–53 in	Clay	6	3	Tr.	--------	--------	--------	--------
		18–53 in	Silt	3	2	1	--------	1	Tr.	Tr.
	5-4	53–60+ in	Clay	6	2	1	--------	--------	--------	--------
		53–60+ in	Silt	4	1	2	--------	2	Tr.	Tr.
	5-5	10. 0–10. 5 ft	Clay	5	1	3	--------	--------	--------	--------
		10. 0–10. 5 ft	Silt	3	Tr.	3	--------	2	Tr.	--------
	5-6	28. 5–29. 0 ft	Clay [2]	Tr.	--------	--------	--------	--------	--------	?Tr.
		28. 5–29. 0 ft	Silt [2]	--------	--------	--------	--------	--------	Tr.	?Tr.
Red latosol on Bolanos Pyroclastic Member of Umatac Formation.	S54-6-1	0–2 in	Clay	8	Tr.?	1	--------	--------	--------	--------
		0–2 in	Silt	6	1?	1	Tr.	--------	Tr.	--------
	6-2	2–10 in	Clay	7	2	Tr.	--------	--------	--------	--------
		2–10 in	Silt	6	1	1	1	--------	Tr.	--------
	6-3	10–16 in	Clay	7	2	Tr.	--------	--------	--------	--------
		10–16 in	Silt	5	1	1	1	--------	1	--------
	6-4	16–32 in	Clay	7	2	Tr.	--------	--------	--------	--------
		16–32 in	Silt	5	1	Tr.	?	--------	Tr.	--------
	6-5	32–46 in	Clay [3]	6	1	2	--------	--------	--------	--------
		32–46 in	Silt	5	Tr.	1	Tr.	--------	1	--------
	6-6	46–60 in	Clay [3]	5	1	Tr.	--------	--------	--------	--------
		46–60 in	Silt	5	Tr.	1	1	--------	1	--------
	6-7	13. 5–14. 5 ft	Clay [3]	7	1	Tr.	--------	--------	--------	--------
		13. 5–14. 5 ft	Silt	7	Tr.	Tr.	Tr.	--------	--------	--------
	S54-10-1	0–3 in	Clay	6	2	1	--------	--------	--------	--------
		0–3 in	Silt	5	1	1	?Tr.	--------	1	Tr.
	10-2	3–15 in	Clay	6	2	1	--------	--------	--------	--------
		3–15 in	Silt	6	1	1	Tr.	--------	Tr.	--------
	10-3	15–28 in	Clay	7	1	1	--------	--------	--------	--------
		15–28 in	Silt	7	--------	1	Tr.	--------	Tr.	--------
	10-4	28–60+ in	Clay	7	1	1	--------	--------	--------	--------
		28–60+ in	Silt	7	1	1	Tr.	--------	Tr.	--------
	10-5	11. 3–12. 3 ft	Clay	8	Tr.	1	--------	--------	--------	--------
		11. 3–12. 3 ft	Silt	8	--------	1	Tr.	--------	Tr.	--------

See footnotes at end of table.

TABLE 7.—*Mineralogy of the clay and silt fractions of soils*—Continued

A. ON VOLCANIC ROCK—Continued

Description	Profile and sample	Depth	Fraction	Halloysite	Goethite	Hematite	Magnetite	Gibbsite	Quartz	Alpha-cristobalite
Atate clay—Continued										
Red latosol on Facpi Volcanic Member of Umatac Formation.	S54-12-1	0-6 in	Clay	7	1	1	--------	Tr.	--------	--------
		0-6 in	Silt	6	Tr.	1	1	1	--------	--------
	12-2	6-13 in	Clay	6	1	2	--------	Tr.	--------	--------
		6-13 in	Silt	5	1	2	1	Tr.	--------	--------
	12-3	13-40 in	Clay	5	Tr.	3	--------	1	--------	--------
		13-40 in	Silt	3	1	3	Tr.	2	--------	--------
	12-4	40-84+ in	Clay	6	Tr.	2	--------	Tr.	--------	--------
		40-84+ in	Silt	4	Tr.	3	Tr.	2	--------	--------
	12-5	9. 0-10. 0 ft	Clay	7	1	1	--------	--------	--------	--------
		9. 0-10. 0 ft	Silt	5	1	Tr.	1	--------	--------	--------
	12-6	15. 0-16. 0 ft	Clay	8	1	Tr.	--------	--------	--------	--------
		15. 0-16. 0 ft	Silt	5	Tr.	2	1	--------	--------	--------
	12-8	22. 5-23. 0 ft	Clay	8	1	--------	--------	--------	--------	--------
		22. 5-23. 0 ft	Silt	5	Tr.	2	Tr.	--------	--------	--------
Red latosol on Alutom Formation.	S54-20-1	0-4 in	Clay [4]	8	Tr.	--------	--------	--------	--------	--------
		0-4 in	Silt [5]	6	--------	Tr.	--------	--------	--------	1
	20-2	4-16 in	Clay [4]	8	Tr.	Tr.	--------	--------	--------	--------
		4-16 in	Silt [4]	8	--------	Tr.	--------	--------	--------	?
	20-3	16-36 in	Clay [4]	8	--------	Tr.	--------	--------	Tr.	--------
		16-36 in	Silt [4]	8	--------	1	--------	--------	Tr.	Tr.
	S54-21-1	0-16 in	Clay	8	Tr.	1	--------	--------	--------	--------
		0-16 in	Silt	7	Tr.	1	1	Tr.	Tr.	Tr.
	21-2	16-36 in	Clay	7	Tr.?	2	--------	--------	--------	--------
		16-36 in	Silt	7	--------	1	1	--------	Tr.	Tr.
	21-3	36-66 in	Clay [6]	--------	--------	Tr.	--------	--------	--------	--------
		36-66 in	Silt [4]	7?	--------	1	Tr.	--------	--------	--------
	21-4	8. 0-9. 0 ft	Clay [6]	--------	--------	Tr.	--------	--------	--------	--------
		8. 0-9. 0 ft	Silt [4]	7?	--------	Tr.	1	--------	--------	Tr.
Asan Clay										
Brown regosol on Alutom Formation.	S54-23-1	0-8 in	Clay [2]	--------	--------	--------	--------	--------	--------	--------
		0-8 in	Silt [2]	--------	--------	--------	--------	--------	Tr.	--------

B. ON LIMESTONES

Description	Profile and sample	Depth (inches)	Fraction	Halloysite	Goethite	Hematite	Gibbsite	Boehmite	Quartz
Guam clay									
Red latosol on Barrigada limestone.	S54-16-1	0-60	Clay	--------	2	1	6	--------	--------
		0-60	Silt	--------	2	1	6	--------	--------
Red latosol on Mariana Limestone.	S54-17-1	0-3	Clay [7]	--------	Tr.	2	5	2	--------
		0-3	Silt [7]	--------	Tr.	2	5	2	--------
	17-2	3-24	Clay [7]	--------	Tr.	2	5	1	--------
		3-24	Silt [7]	--------	Tr.	2	5	1	--------
	S54-18-1	0-1	Clay	--------	Tr.	2	7	--------	--------
		0-1	Silt	--------	Tr.	2	7	--------	--------
	18-2	1-15	Clay	--------	Tr.	2	7	--------	--------
		1-15	Silt	--------	Tr.	2	7	--------	--------
	S54-19-1	0-4	Clay [7]	--------	Tr.	1	4	3	--------
		0-4	Silt [7]	--------	Tr.	1	4	3	--------
	19-2	4-12	Clay [7]	--------	Tr.	1	4	3	--------
		4-12	Silt [7]	--------	1	1	4	3	--------
Fossil soil									
Fossil red latosol [8]	S54-24-1	--------	Clay	5	1	1	2	--------	--------
		--------	Silt	4	1	1	3	--------	--------

See footnotes at end of table.

TABLE 7.—*Mineralogy of the silt and clay fractions of soils*—Continued

B. ON LIMESTONES—Continued

Description	Profile and sample	Depth (Inches)	Fraction	Halloysite	Goethite	Hematite	Gibbsite	Boehmite	Quartz
Chacha clay									
Brown silty clay on Mariana Limestone.	S54–1–1	0–6	Clay	7	2				
		0–6	Silt [7]	1	1				3
	1–2	6–18	Clay	7	2	Tr.			
		6–18	Silt	1	2	Tr.			4
	1–3	18–32	Clay	6	2	Tr.			Tr.
		18–32	Silt	6	2	Tr.			Tr.
	1–4	32–46	Clay	6	2				
		32–46	Silt	4	2	1			Tr.

[1] Contains chromite.
[2] Principal clay mineral is montmorillonite.
[3] Contains a little montmorillonite.
[4] Contains a little mixed-layer montmorillonite-halloysite.
[5] Contains weddelite.
[6] Principal clay mineral is mixed-layer montmorillonite-halloysite.
[7] Contains anatase.
[8] Sample obtained from a 3-ft vertical channel in middle of 6-ft soil exposure on roadside steep cutbank.

The most abundant minerals are halloysite, goethite, hematite, and gibbsite with lesser amounts of montmorillonite, magnetite, boehmite, quartz, and alpha-cristobalite. One or two samples contain traces of anatase, chromite, or weddelite [1] (a hydrated calcium oxalate). Material that is probably randomly mixed layered halloysite-montmorillonite occurs in at least two of the samples.

Although no particles of tubular shape were observed in electron micrographs of two of the samples, the kaolinite-group mineral revealed by the X-ray diffraction patterns was identified as halloysite rather than kaolinite or "fire clay" mineral on the basis of the following criteria:

1. Broad diffuse 00*l* peaks near 7.5A.
2. Broad poorly resolved *hk* bands, particularly those in the region 2.3A to 2.5A, of greater intensity than the 00*l* peaks.
3. Failure of the 00*l* reflections to show distinctly higher intensity in oriented aggregates.

Halloysite occurs primarily in the soils developed on volcanic rocks, whereas gibbsite together with some boehmite is dominant in the soil developed on relatively pure limestone. This relationship is brought out by figure 5, which shows a weighted estimate of the amounts of these minerals in each profile. Profile S54–23 is omitted because it contained neither halloysite nor gibbsite and boehmite. The normative amounts of halloysite and gibbsite calculated from the average chemical composition for each profile are shown for comparison. Profile S54–21 is omitted because chemical analyses were not made.

Differential-thermal-analysis curves (fig. 6 and table 8) made by George T. Faust, U.S. Geological Survey, lend support to the identification of halloysite in samples S54–24–1, S54–1–2, S54–4–2 and 4–5, in view of the high slope ratio due to asymmetry of the endothermic peak near 600° C. According to Bramao and others (1952), a high slope ratio does not exclude kaolinite, but its presence in conjunction with the X-ray characteristics mentioned above strongly suggests halloysite. Interpretation of the various thermal peaks is given in table 8.

TABLE 8.—*Interpretation of thermal reactions shown by differential thermal analysis curves in figure 6.*

Sample	Temperature (° C)	Endothermic	Exothermic
S54–17–2	140	Adsorbed water	
	360	Gibbsite	
	542	Boehmite	
	875		?.
18–2	140	Adsorbed water	
	362	Gibbsite	
	471		Organic matter.
24–1	144	Adsorbed water	
	338	Gibbsite	
	608	Halloysite	
	972		Halloysite.
1–2	141	Adsorbed water	
	324	Gibbsite	
	344	Goethite	
	597	Halloysite	
	945		Do.
4–2	151	Adsorbed water	
	330	Gibbsite	
	602	Halloysite	
	962		Do.
4–5	151	Adsorbed water	
	314	Gibbsite?	
	377	Goethite?	
	604	Halloysite	
	961		Do.
23–1	160	Interlayer water (montmorillonite)	
	361		Organic matter.
	588	Montmorillonite	
	868	do	
	922		Montmorillonite.

Montmorillonite was dominant in only two samples, both overlying volcanic rock. One of these (S54–23–1) was collected from a roadcut in the Asan clay, a sapro-

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[1] The samples containing weddelite were collected from pasture land; therefore, this mineral may be of animal origin.

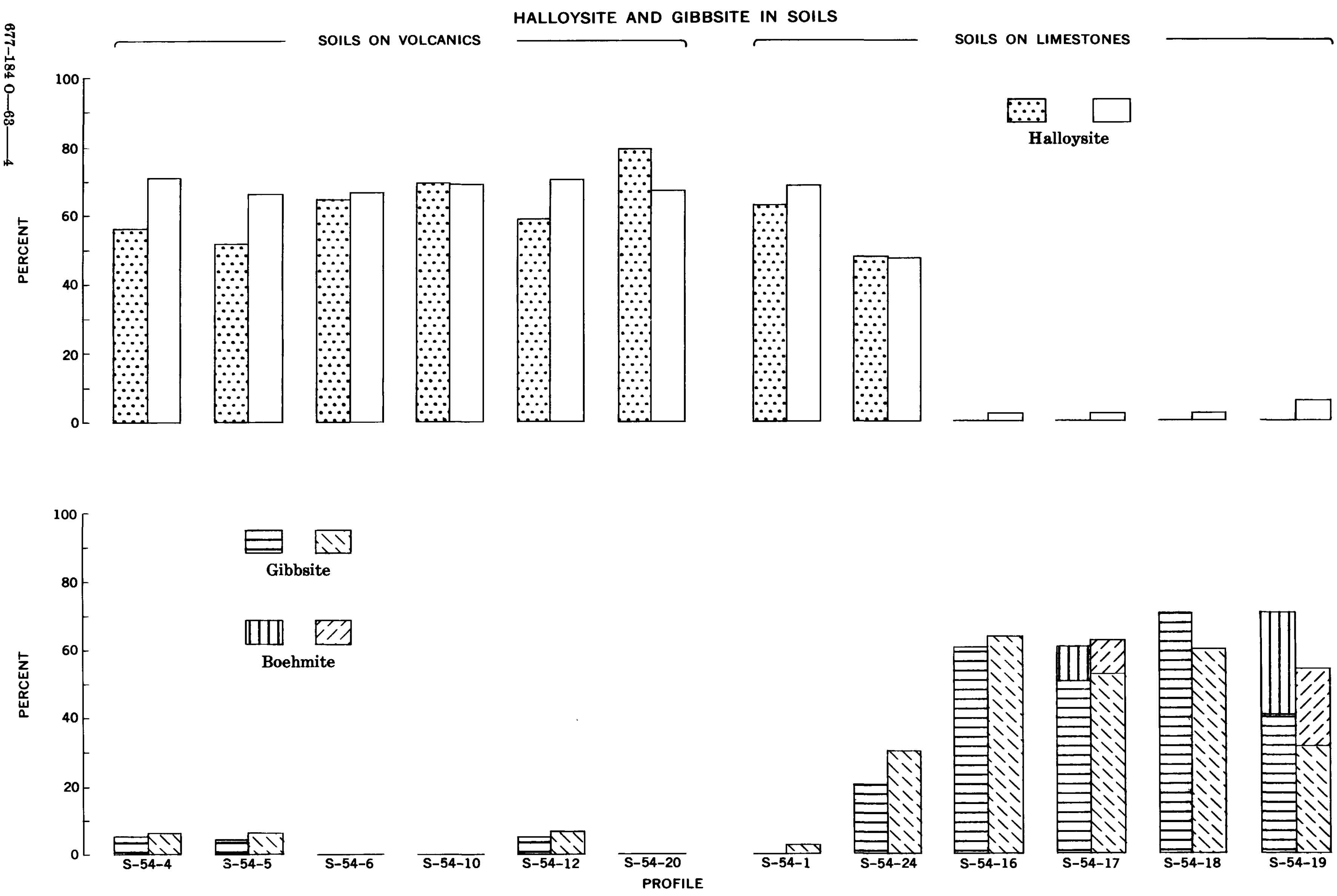

FIGURE 5.—Diagram showing proportion of halloysite to gibbsite and boehmite in the various soil profiles. Stippling and horizontal and vertical lines represent weighted averages of amounts estimated from X-ray analyses. No pattern and broken diagonal lines represent normative amounts calculated from the average chemical composition of each profile.

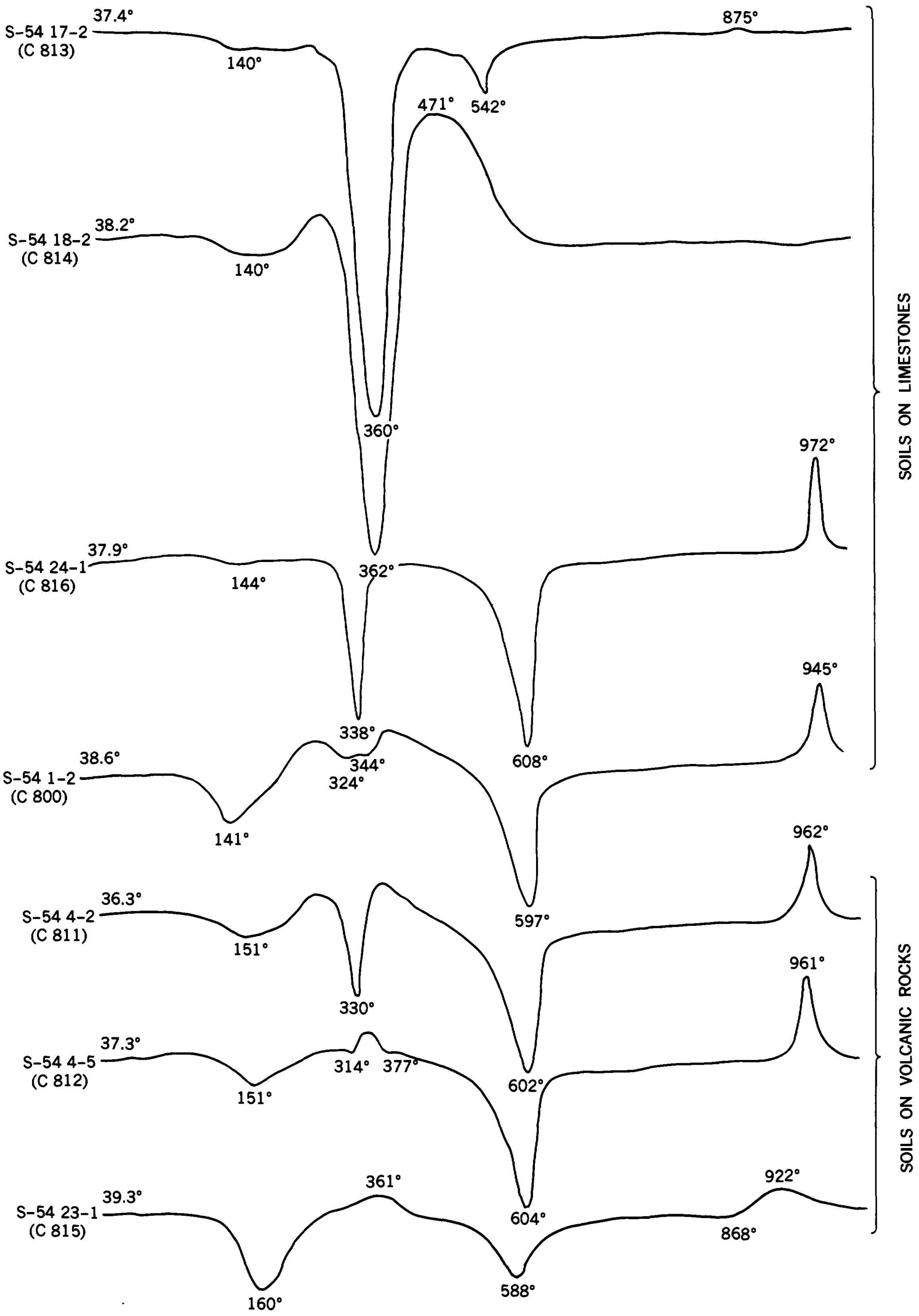

FIGURE 6.—Differential-thermal-analysis curves of the clay (<2 μ) fraction of soils developed on limestones and on volcanic rocks. The analyses were made by George T. Faust, U.S. Geological Survey, who also assisted in their interpretation. Numbers in parentheses are laboratory numbers. Sample S54 17-2, Guam clay, on Mariana Limestone, detrital facies. 3 to 24 inches. S54 18-2, Guam clay on Mariana Limestone, molluscan facies. 1 to 15 inches. S54 24-1, Fossil latosol on Alifan Limestone. S54 1-2, Chacha clay on Agana Argillaceous Member of the Mariana Limestone. 6 to 18 inches. S54 4-2, Atate clay, on Alutom Formation. 7 to 20 inches. S54 4-5, Atate clay, on Alutom Formation. 51 to 60 inches. S54 23-1, Asan clay, on Alutom Formation. 0 to 8 inches.

litic soil younger than the other soils sampled; the other (S54–5–6) sample collected at a depth of 29 feet is a highly weathered tuff from asmall mesita of Atate clay. As very little other than montmorillonite was revealed by X-ray examination, structural formulas were calculated from the chemical analyses (table 4) by the method of Marshall (1949, p. 58). Ferrous iron was not determined in these samples because of the presence of organic matter. Calculation of the formula for S54–5–6, assuming that all the iron is in the ferrous state, was also made. It is probable that the true formula lies between these extremes near the ferric end, for the material occurs in an oxidized zone. In both calculations the sum of octahedrally coordinated cations indicates that the minerals are dioctahedral. This agrees with the X-ray diffraction data that show 060 spacings in the region of 1.50 A, characteristic of dioctahedral montmorillonites.

The structural formulas calculated for the three samples are given below.

S54–25–1, Asan clay, 0 to 8 inches

$$[\underbrace{(Al_{1.14}Fe^{+3}_{.60}Mg_{.43}Ti_{.05}Mn)}_{2.22}(Si_{3.51}Al_{.49})O_{10}(OH)_2](K_{.11}Na_{.01}Ca_{.03})$$

S54–5–6, Atate clay, 28.5–29 feet

[Iron calculated as ferric iron]

$$[\underbrace{(Al_{1.33}Fe^{+3}_{.51}Mg_{.32}Ti_{.04}Mn)}_{2.20}(Si_{3.61}Al_{.39})O_{10}(OH)_2](K_{.03}NaCa_{.01})$$

S54–5–6, Atate clay, 28.5–29 feet

[Iron calculated as ferrous iron]

$$[\underbrace{(Al_{1.46}Fe^{+2}_{.52}Mg_{.33}Ti_{.04}Mn)}_{2.35}(Si_{3.69}Al_{.30})O_{10}(OH)_2](K_{.03}NaCa_{.01})$$

Goethite and hematite are present in most of the soils, and their variation in abundance is shown in figure 7. The normative amounts of these minerals were calculated from the chemical analyses, assuming the ratio of goethite to hematite suggested by the X-ray data. In weighting the estimated amounts from table 7, estimates indicated as "trace" (Tr.) are arbitrarily assigned a value of 0.2 part in ten. The water in excess of that required for the formation of normative halloysite, gibbsite, boehmite, and goethite in these soils is also shown in figure 7.

Total water only was determined in the chemical analyses because of the interference of organic matter. The excess water shown in figure 3 therefore includes adsorbed water and water contained in the organic matter in the sample. In general, the excess water amounts to about 6 percent, except in profiles S54–24 and S54–16 where it is about 2 percent. As both of these profiles contain practically negligible amounts of organic carbon (table 5) compared with the other profiles, this lower amount of excess water is probably a reflection of low content of organic matter.

Profiles S54–20 and S54–19 show amounts of excess water somewhat higher than the average. As none of the samples in these profiles show excessive amounts of organic carbon (table 5), water contained in the organic matter of the samples is not responsible for the excess. It is significant in profile S54–20 that 9.5 percent excess silica results in the calculation of its normative composition. As mixed layered halloysite-montmorillonite is present in this profile (table 7), the "excess" water and silica probably occur in montmorillonite layers randomly interstratified with halloysite. Comparison of the estimated and calculated amounts of halloysite shown in figure 2, together with the amounts of "excess" silica and water, suggests that 10 to 15 percent of the material estimated as halloysite is montmorillonite randomly interstratified with the remaining halloysite.

Profile S54–10, on the other hand, contains no excess silica, but underestimation of the amount of gibbsite relative to boehmite would be revealed as excess water in the calculation. It is therefore possible that the estimate for the amount of boehmite in profile S54–19 is high by a factor of about 2. Recalculation would then yield about 5.5 percent excess water, which would correspond more closely to the average "excess" water in the various profiles.

The only other substantial overestimate occurs in profile S54–5; the estimated goethite and hematite exceed the normative amounts of these minerals by a factor of about 2. In the rest of the profiles, the X-ray and chemical data are in good agreement when the limitations inherent in quantitative estimations by X-ray methods are considered.

Together, the two sets of data indicate that a high halloysite-low gibbsite content is usually associated

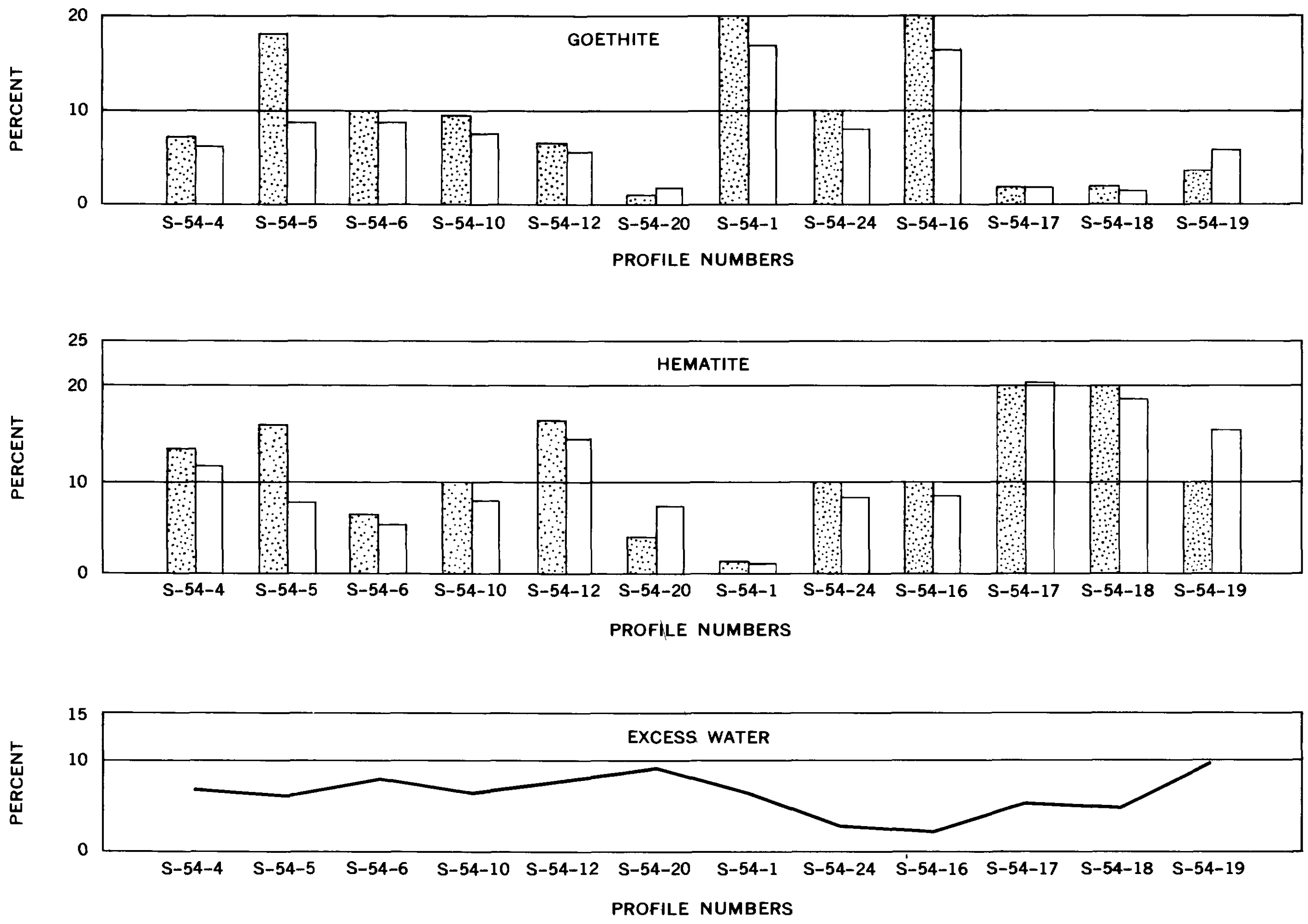

FIGURE 7.—Diagram showing percentage of goethite and hematite in the various soil profiles and water in excess of that required to form normative halloysite, gibbsite, and goethite. Stippled columns represent weighted averages of amounts estimated from X-ray analyses. Open columns represent normative amounts calculated from the average chemical composition of each profile using the goethite : hematite ratio suggested by the X-ray data.

with soils developed on the volcanics, whereas high gibbsite-low halloysite soils are restricted to the nonargillaceous limestone areas. Two limestone soil profiles do, however, contain major amounts of halloysite. It may be significant that both of these occur in the outcrop area of the Agana argillaceous Member of the Mariana Limestone, which had been shown (Hathaway and Carroll, 1963) to contain a noncarbonate fraction resembling the volcanic soils in mineralogic composition.

SOIL GENESIS

EVIDENCE FROM CHEMICAL COMPOSITION

The chemical composition of the soils shown in tables 4 and 10 indicates that there is a striking difference in the latosols developed on the volcanic rocks (Atate clay) and those on the relatively pure limestones (Guam clay); the single profiles of supposedly younger soils, the Asan clay (on volcanic rocks) and the Chacha clay (on argillaceous limestone), show fewer differences.

Following the method of Hough and others (1941) in assessing the gains and losses of chemical constituents in soil profiles developed on the basaltic rocks of the Hawaiian Islands, the chemical analyses of the presumed parent rocks (table 2) of the Guam soils on volcanics were averaged and then recalculated on a water-free basis with the results shown in table 9. Then the analyses of samples from the soil profiles were recalculated on a water-free basis, and a weighted average composition for each profile was calculated. The weighting was done by considering a section of the soil 1 inch thick as a unit. Thus, an A horizon from 0 to 6 inches thick is considered as 6 units. Table 4 shows that 4 of the profiles were sampled to a depth of 60 inches; in addition, there are samples of highly weathered rocks that are considered representative of the C horizon. Table 10 gives the weighted average composition of 9 of the profiles on a water-free basis.

SOILS ON VOLCANIC PARENT ROCKS

Each profile for which there is adequate chemical information can now be compared with its presumed parent rock based on field descriptions and locality. Unfortunately, fresh rocks could not be collected be-

TABLE 9.—*Average chemical composition of three groups of volcanic rocks that are parent materials of soils on Guam*

[A, complete analysis; B, analysis recalculated on a water-free basis. Figures in parentheses are number of analyses averaged. Analyses of the rocks are given in table 6]

	Basalt (11)		Dikes (10)		Tuffs (4)		Average volcanic material	
	A	B	A	B	A	B	A	B
SiO_2	51.76	54.09	59.80	61.35	71.34	78.83	60.96	64.75
Al_2O_3	15.24	15.92	15.55	15.95	10.75	11.88	13.84	14.58
Fe_2O_3	3.73	3.90	2.62	2.68	1.37	1.51	2.57	2.69
FeO	5.20	5.43	3.72	3.81	.25	.27	3.05	3.17
MgO	7.05	7.36	4.10	4.20	.93	1.03	4.02	4.19
CaO	9.08	9.49	7.09	7.27	2.24	2.47	6.13	6.41
Na_2O	2.32	2.42	3.09	3.17	1.15	1.27	2.18	2.28
K_2O	.65	.68	1.13	1.16	.92	1.01	.90	.95
$H_2O\pm$	4.05	--------	2.63	--------	10.47	--------	5.71	--------
TiO_2	.65	.68	.49	.50	.26	.28	.46	.48
CO_2	.07	.07	.14	.14	.007	.007	.07	.07
P_2O_5	.14	.14	.12	.12	.05	.05	.10	.10
MnO	.15	.14	.10	.10	.02	.02	.08	.08

neath the soil profiles as the weathering processes have penetrated to average depths of 50 feet. However, comparison with the composition of average basalt, dike rock, or tuff will give some indication of the movement of constituents within the profile. In making these comparisons, it is assumed that silica and bases have been removed and that alumina, iron, and titania have accumulated.

Atate clay, profile S54-4.—This profile, from 0 to 60 inches, is on the volcanic conglomerate, tuff, and coarse-grained pyroclastic material of the Alutom Formation. The parent material is considered to be the tuffs of table 9. The relationship between the parent rock and the soil is shown in table 11.

The chemical composition of samples from the weathered rocks at the base of this profile, at a depth of 11 to 11.5 feet and 12.5 to 13 feet, were averaged and recalculated to a water-free basis and then compared with the part of the profile from 0 to 60 inches, as shown in table 11.

TABLE 10.—*Average chemical composition (water-free basis), in percent, of soil profiles developed on volcanic rocks and on limestones from Guam*

Soil type	Profiles developed on volcanic rocks					Profiles developed on limestone			S54-1 (0-46 in)
	S54-4 (0-60 in)	S54-5 (0-60 in)	S54-6 (0-60 in)	S54-12 (0-84 in)	S54-23 (0-36 in)	S54-16 (0-60 in)	S54-18 (0-15 in)	S54-19 (0-12 in)	
	Atate clay				Asan clay	Guam clay			Chacha clay
SiO_2	36.80	39.63	47.26	32.87	57.87	1.68	1.46	3.47	41.00
Al_2O_3	36.0	39.13	33.45	38.29	21.13	57.58	61.55	57.34	36.16
Fe_2O_3	23.20	19.16	16.46	25.22	12.73	31.67	31.29	28.54	19.37
MgO	1.34	.50	1.21	1.12	4.73	1.03	.24	.74	.81
CaO	.16	.13	.13	.12	.58	.56	.64	2.55	.39
Na_2O and K_2O	.48	.22	.16	.15	1.74	.14	.16	.29	.18
TiO_2	1.21	1.29	1.11	1.28	.90	3.08	3.00	2.76	1.05
P_2O_5	.13	.08	.14	.11	.07	3.08	1.02	3.72	.85
MnO	.63	.11	.08	.84	.16	1.18	.66	.60	.14

TABLE 11.—*Chemical composition, in percent, of parent rock and soil profile, Atate clay on Alutom Formation*

[Profile S54-4]

	Average tuff	Presumed losses from (a)	Remainder in profile	Remainder recalculated to 100 percent	Whole profile weighted average	Difference (e−d)	Weathered average rock, 11 to 13 feet	Difference	
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(e−g)	(d−g)
SiO_2	78.8	0	78.8	85.0	36.8	−48.2	47.6	+10.8	−37.4
Al_2O_3	11.8	0	11.8	12.7	36.0	+23.3	33.4	−2.6	+20.7
Fe_2O_3	1.5	0	1.8	1.9	23.2	+21.3	16.2	−7.0	+14.3
FeO	.3								
MgO	1.0	1.0	0	0	1.3	+1.3	1.1	+.2	−1.1
CaO	2.5	2.5	0	0	.1	+.1	.1	0	−.1
Na_2O	1.3	1.3	0	0	.5	+.5	.2	+.3	−.2
K_2O	1.0	1.0	0	0					
TiO_2	.3	0	.3	.3	1.2	+.9	.9	+.3	−.6
MnO	.1	0	.1	.1	.6	+.5	.1	+.5	0

The principal differences are that the weathered rock contains nearly 11 percent more SiO_2, 2.6 percent less Al_2O_3, and 7 percent less Fe_2O_3 than the average for the whole soil from 0 to 60 inches, which suggests that the soil-forming processes are active at this depth and that the principal changes take place or are initiated in the weathered rock.

Atate clay, profile S54–5.—This profile, from 0 to 60 inches, is on the Alutom Formation, a bedded fine- to coarse-grained sandy tuff, weathered to a depth of 50 feet or more.

Samples of highly weathered rocks were collected at depths of 10 to 10.5 feet and 28.5 to 29 feet. The analyses of these materials were recalculated to a water-free basis and then compared with the soil from 0 to 60 inches, as shown in table 12. The weathered rock at 10 to 10.5 feet is practically identical in chemical composition with that of the weighted average soil from 0 to 60 inches. Differences, however, are apparent between the weathered rock at 28.5 to 29 feet and that at 10 to 10.5 feet; there is a decrease of 19 percent in SiO_2, an increase of 15 percent in Al_2O_3, an increase of 9 percent in Fe_2O_3, a decrease of 2.8 percent in MgO, and an increase of 0.7 percent in TiO_2. Na_2O and K_2O in the weathered rock at 10 to 10.5 feet are one-half the quantity present in the weathered rock at 28.5 to 29 feet.

This profile, therefore, shows a reduction in SiO_2, MgO, CaO, Na_2O, and K_2O, but increases in Al_2O_3, Fe_2O_3, and TiO_2. If the analysis of average tuff is compared with that of the saprolitic rock at 28.5 to 29 feet, it is seen that SiO_2 has decreased and that Al_2O_3 and Fe_2O_3 have increased, pointing to the mobilization of SiO_2 at a very early stage in rock weathering.

Atate clay, profile S54–6.—This profile, from 0 to 60 inches, is on the Bolanos Pyroclastic Member of the Umatac Formation, a fine- to coarse-grained tuff mostly weathered to a depth of 65 feet. Samples of weathered rocks from 13.5 to 14.5 feet were collected for comparison with the soil. The chemical analysis of this material was recalculated to a water-free basis in table 13. There is very little difference in chemical composition between the weathered rock at 13.5 feet and the weighted average for the soil from 0 to 60 inches.

Atate clay, profile S54–12.—This profile, from 0 to 84 inches, is on pillow basalt of the Facpi Volcanic Member of the Umatac Formation weathered to a depth of 75 feet or more (table 14). Comparison of the chemical composition at 9 to 10 feet with that at 22.5 to 23 feet indicated that there are only negligible differences. The average composition of the weathered rock is different from that of the weighted average of the whole soil at 0 to 60 inches. This profile has lost only a small percentage of its SiO_2 between the weathered rock and the profile as a whole; there is a small increase in Al_2O_3, Fe_2O_3, and TiO_2.

Asan clay, profile S54–23.—This profile, from 0 to 36 inches, is on the massive lapilli pyroclastic material of the Alutom Formation. As no samples of weathered rock were collected below this profile, no comparison of weathered rock and average profile composition is made. This profile has A and C horizons only, and the 8- to 36-inch horizon is of weathered rock or saprolite (table 15) and therefore comparable with Atate clay sample S54–5 at 28.5 to 29 feet (table 12).

A consideration of the information in tables 11 through 15 shows that the principal process in the formation of these soils is the removal of silica from the profile. This results in a relative accumulation of alumina and ferric iron. The volcanic rocks consist almost entirely of weatherable minerals that release silica readily. Some minerals, such as zeolites and volcanic glass of intermediate or mafic composition, alter rapidly to clay minerals of the montmorillonite group.

TABLE 12.—*Chemical composition, in percent, of parent rock and soil profile, Atate clay on Alutom Formation*

[Profile S54–5]

	Average tuff	Presumed losses from (a)	Remainder in profile	Remainder recalculated to 100 percent	Whole profile weighted average	Difference (e−d)	Weathered rock		Difference		
							10 to 10.5 feet	28.5 to 29 feet			
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(g−h)	(d−g)	(d−h)
SiO_2	78.8	0	78.8	85.0	39.6	−45.4	36.9	56.0	−19.1	+48.1	+29.0
Al_2O_3	11.8	0	11.8	12.7	39.1	+26.4	37.8	22.6	+15.2	+25.1	−9.9
Fe_2O_3	1.5	0	1.8	1.9	19.1	+17.2	19.6	10.5	+9.1	−17.7	−8.6
FeO	.3										
MgO	1.0	1.0	0	0	.5	+.5	.6	3.4	−2.8	−.6	−3.4
CaO	2.5	2.5	0	0	.1	+.1	.1	.2	−.1	−.1	−.2
Na_2O	1.3	1.3	0	0	.2	+.2	.2	.4	−.2	0	0
K_2O	1.0	1.0	0	0							
TiO_2	.3	0	.3	.3	1.3	+1.0	1.5	.8	+.7	+.2	−.5

TABLE 13.—*Chemical composition, in percent, of parent rock and soil profile, Atate clay on Bolanos Pyroclastic Member of the Umatac Formation*

[Profile S54-6]

	Average tuff	Presumed losses from (a)	Remainder in profile	Remainder recalculated to 100 percent	Whole profile weighted average	Difference	Weathered rock 13.5 to 14.5 feet	Difference	
	(a)	(b)	(c)	(d)	(e)	(e−d)	(f)	(e−f)	(d−f)
SiO_2	78.8	0	78.8	85.0	47.2	−37.8	48.1	−0.9	+36.9
Al_2O_3	11.8	0	11.8	12.7	33.4	+20.7	31.6	+1.8	−18.9
Fe_2O_3	1.5	0	1.8	1.9	16.5	+14.6	13.2	+3.3	−11.3
FeO	.3								
MgO	1.0	1.0	0	0	1.2	+1.2	1.4	−.2	−1.4
CaO	2.5	2.5	0	0	.1	+.1	.1	0	−.1
Na_2O	1.3	1.3	0	0	.1	+.1	.1	0	−.1
K_2O	----------	----------	----------	0					
TiO_2	.3	0	.3	.3	1.1	+.8	.9	+.2	−.6

TABLE 14.—*Chemical composition, in percent, of parent rock and soil profile, Atate clay on pillow basalt of the Facpi Volcanic Member of the Umatac Formation*

[Profile S54-12]

	Average basalt	Presumed losses from (a)	Remainder in profile	Remainder recalculated to 100 percent	Whole profile weighted average	Difference	Weathered rock 9 to 10 feet and 22.5 to 23 feet	Difference	
	(a)	(b)	(c)	(d)	(e)	(e)—(d)	(f)	(e)—(f)	(d)—(f)
SiO_2	54.1	0	54.1	67.0	32.8	−34.2	40.1	−7.3	+26.9
Al_2O_3	15.9	0	15.9	19.7	38.3	+18.6	33.0	+5.3	−13.3
Fe_2O_3	3.9	0	9.9	12.2	25.2	+13.0	21.1	+4.1	−8.9
FeO	5.4								
MgO	7.3	7.3	0	0	1.1	+1.1	.8	+.3	−.8
CaO	9.5	9.5	0	0	.1	+.1	+0	+.1	0
Na_2O	2.4	2.4	0	0	.1	+.1	.1	0	−.1
K_2O	.6	.6	0	0					
TiO_2	.7	0	.7	.8	1.3	+.5	1.0	+.3	−.2
P_2O_5	.1	.1	0	----------	----------	----------	----------	----------	----------
MnO	.1	0	.1	.1	.8	+.7	0	+.8	+.1

TABLE 15.—*Chemical composition, in percent, of parent rock and soil profile, Asan clay on Alutom Formation*

[Profile S54-23]

	Average volcanic rock	Presumed losses from (a)	Remainder in profile	Remainder recalculated to 100	Whole profile weighted average	Difference
	(a)	(b)	(c)	(d)	(e)	(e−d)
SiO_2	64.7	0	64.7	75.14	57.8	−17.3
Al_2O_3	14.6	0	14.6	16.9	21.1	+4.2
Fe_2O_3	2.7	0	6.2	7.2	12.7	+5.5
FeO	3.2					
MgO	4.2	4.2	0	----------	4.3	+4.3
CaO	6.4	6.4	0	----------	.6	+.6
Na_2O	2.3	2.3	0	----------	1.7	+1.7
K_2O	.9	.9	0			
TiO_2	.5	0	.5	.6	.9	+.3
P_2O_5	.1	0	.1	.1	----------	----------

SILICA REMOVAL

In the latosols (Atate clay) the weighted average soil shows a loss of 34 to 48 percent SiO_2 from that in the presumed parent rock, when compared on a water-free basis. Table 4 and figure 8 show that there is a progressive loss of silica towards the top of the profiles, the top containing the least silica. This is a gradual loss, which indicates that there is no sharp differentation into horizons such as have been described for some Australian laterites (Carroll and Woof, 1951). The field descriptions of the Guam soils made by Stensland (p. F43–F49 also indicate that there is little development of distinct horizons in these soils, although the weathered rock (C horizon) often is mottled red or yellow and white.

The profile of Asan clay, a brown regosol on saprolitic volcanic rocks (table 15), differs from profiles of the latosols in that is has lost only 17 percent of SiO_2 during profile development, suggesting that this is a younger soil than the latosols.

ALUMINA ACCUMULATION

In the latosols, alumina accumulation ranges between 18 and 26 percent more than that in the parent rocks and has an average of 22 percent. The accumulation starts in the highly weathered rocks with the removal of SiO_2; for example, in table 11, there is an accumulation of 20 percent for samples at depths of 11 to 13 feet, only differing by 2.6 percent from the alumina in the soil. Weathered rock between 28.5 and 29 feet (table 12) shows an accumulation of 10 percent Al_2O_3 more than that in the presumed parent rock. The Al_2O_3 content in weathered rock at 10 to 10.5 feet is approximately the same as that in the soil profile. Figures for alumina for weathered rocks at about this depth in other profiles are of the same order of magnitude.

The accumulation of alumina in the Asan clay only amounts to 4 percent, which is about one-fifth of that found in the latosol profiles.

FERRIC OXIDE

The parent rocks do not contain much iron. The average basalt has about 4 percent Fe_2O_3 and 5.5 percent FeO; the average tuff has much less, with 1.5 percent Fe_2O_3 and 0.3 percent FeO. The average for all the volcanic rocks for which analyses are available is 2.7 percent Fe_2O_3 and 3.2 percent FeO. Ferrous iron present in pyroxenes, amphiboles, and volcanic glass is changed in the early stages of rock weathering to ferric oxide, which may be hematite, goethite, or indefinite iron oxides that become intimately associated with the clay minerals. No figures for ferrous iron were obtained for the soil samples because of the presence of organic matter and the consequent inaccuracy imparted to the FeO determinations.

Ferric oxide has accumulated in all the profiles examined. The increase in Fe_2O_3 ranges from 13 to 21 percent for the latosols (Atate clay), but is only 5.5 percent in the Asan clay.

In the soil descriptions (p. F43–F49) there is mention of iron concretions, but these are insignificant when compared with the amount of ferric oxide held in intimate association with the clay and silt minerals. The size distribution of the soil material (table 3) shows that there is a small amount of coarse material which would include any of these small iron concretions. There is no conspicuous layer of iron concretions in these soils similar to those in fossil laterites in Australia (Prescott, 1931), where their presence is thought to indicate seasonal movements of the level of the ground water owing to periodic wet and dry seasons.

TITANIA

The average TiO_2 content of these groups of volcanic rocks (table 9) is 0.46 percent (0.48 percent on a water-free basis), whereas the average for the upper part of the soils on these rocks is 1.16 percent (water-free basis). This is an accumulation of TiO_2 amounting to more than twice the content of the parent rocks in which titanium is present as a constituent of ilmenite, titaniferous magnetite, and possibly of the pyroxenes.

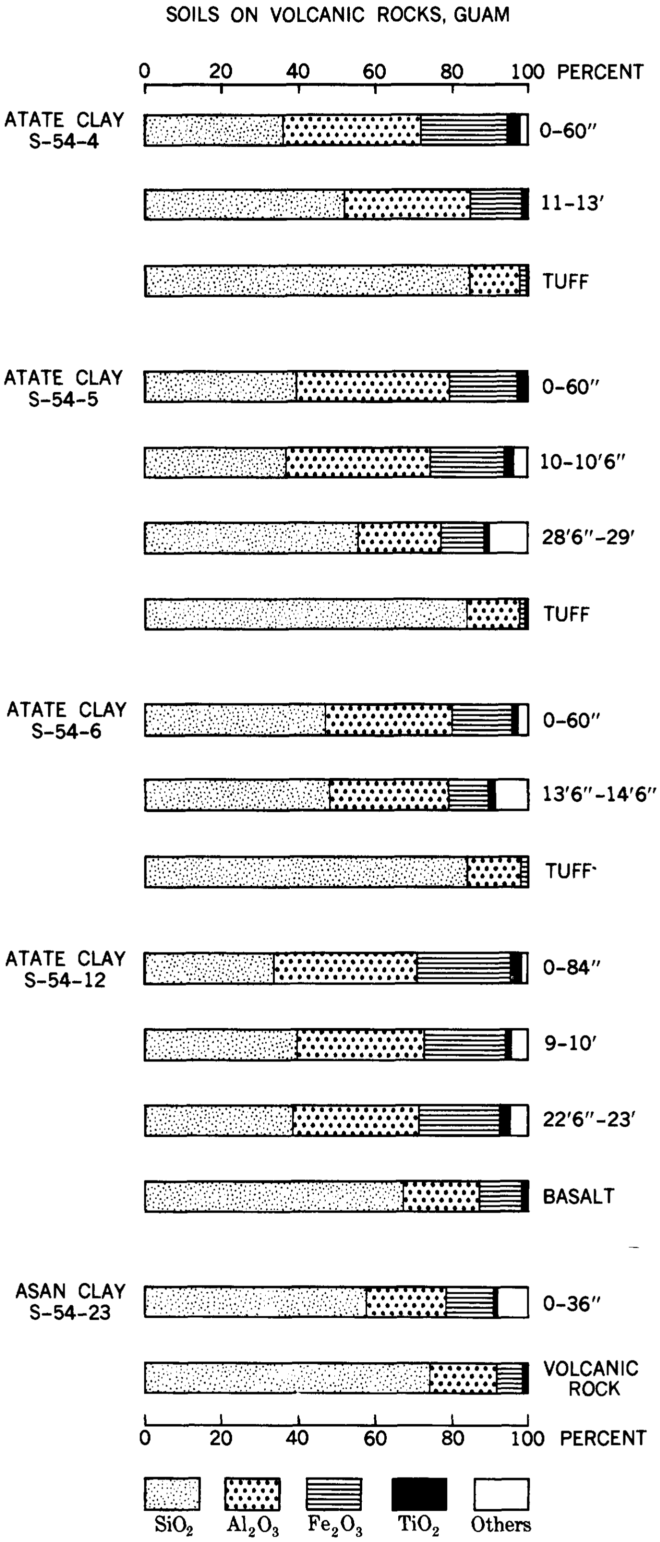

FIGURE 8.—Chemical composition of four profiles of Atate clay and one profile of Asan clay on volcanic rocks. The analyses were recalculated to a water-free basis. The figures used are in tables 11 to 15 for the soils and in table 9 for the average composition of the tuffs and basalts. The diagrams represent average amounts of SiO_2, Al_2O_3, Fe_2O_3, and TiO_2 weighted for the thickness of the soil horizons analyzed. No fresh rocks were obtainable beneath these soils. The composition of the presumed parent rocks of the soils are the averages for the different kinds of rocks. The kind of parent rock that probably underlies the soil profiles is that indicated by field occurrence and the geologic map.

The accumulation of TiO_2 is a feature of weathering and soil formation in tropical climates that has been noted many times (Hough and others, 1941; Sherman and others, 1948). Bauxite and laterites generally show an accumulation of TiO_2, which must therefore be regarded as inert or an almost insoluble oxide at the pH values found in most soils. Allen (1948, p. 621) records an increase in TiO_2 in bauxite developed from basalt in Oregon; Gordon and Tracey (1952, p. 26) record a similar accumulation in the Arkansas bauxite; and Mohr and Van Baren (1954, chap. 4) quote numerous analyses of parent rocks and the laterites derived therefrom in which there is also an accumulation of TiO_2.

The Atate clay profiles described herein have a greater TiO_2 content than that found in the single profile of Asan clay, which suggests that the Asan clay is at a younger stage of profile development than the Atate clay.

WATER

The presence of water is essential for the formation of the clay minerals and of gibbsite. Table 4 gives the quantity of water in these soils. The average for the soils of volcanic parent material is 17.95 percent. This water can be used to calculate the normative clay minerals present in the soils in the same way as the normative mineral compositions of igneous rocks are calculated. The normative clay minerals are kaolinite or halloysite ($2SiO_2 \cdot Al_2O_3 \cdot 2H_2O$) and gibbsite ($Al_2O_3 \cdot 3H_2O$), together with goethite ($Fe_2O_3 \cdot H_2O$) and (or) hematite (Fe_2O_3), and ilmenite ($FeO \cdot TiO_2$). Any silica not used for normative kaolinite or halloysite in these normative calculations is assigned to to normative quartz. The Guam soils, however, do not contain sufficient silica to form normative quartz.

The normative compositions of 1 Atate clay profile, 2 Guam clay profiles, 1 fossil red latosol, and 1 Chacha clay profile are shown in table 16.

The dominant clay minerals identified by X-ray diffraction in the upper parts of these soils were halloysite in the soils developed from volcanic rocks and on argillaceous limestone, and gibbsite in the soils developed on relatively pure limestone. The origin of the clay minerals is discussed on pages F30–F36.

SOILS ON LIMESTONES

The soils on the limestones are very similar in appearance to those on the volcanic rocks, but they differ in chemical composition (tables 4, 10). The most conspicuous difference is the low silica content. The principal soil type is the red latosol known as Guam clay, but brown soils also occur in smaller areas. A profile of the latter type, Chacha clay, was also examined.

TABLE 16.—*Normative clay mineral composition, in percent, calculated from chemical analyses, of soil profiles on volcanic rocks and on limestones*

[Ferric oxide calculated as geothite unless X-ray analyses showed only traces present. Low summations indicate that appreciable organic matter was in the samples. Sample S54-24-1 was obtained from 3-ft vertical channel in middle of 6-ft soil exposure on roadside steep cutbank. Sample S54-5-6 is predominately montmorillonite]

Sample	Depth	Halloysite	Gibbsite	Goethite	Hematite	Excess H_2O	All others	Total
Atate clay on Alutom formation								
S54-5-1	0-6 in	59.6	5.6	16.9	--------	5.9	2.3	90
5-2	6-18 in	68.9	6.5	17.1	--------	4.7	1.8	99
5-3	18-53 in	71.0	5.9	16.9	--------	4.9	1.8	101
5-4	53-60+in	65.1	9.4	18.8	--------	4.9	2.2	100
5-5	10-10.5 ft	66.6	8.4	18.3	--------	4.7	2.3	100
5-6	28.5-29 ft	--------	--------	--------	--------	--------	--------	------
Chacha clay on Mariana limestone								
S54-1-1	0-6 in	57.6	3.1	21.1	--------	7.1	3.8	93
1-2	6-18 in	71.0	1.4	17.9	--------	6.4	2.8	99
1-3	18-32 in	73.6	2.0	16.2	--------	5.8	2.7	100
1-4	32-46 in	73.8	.8	16.2	--------	6.3	2.9	100
Fossil red latosol								
S54-24-1	--------------	48.2	29.9	17.1	--------	1.6	2.2	99
Guam clay on Mariana limestone								
S54-18-1	0-1 in	1.5	56.1	--------	19.7	4.7	4.6	87
18-2	1-15 in	2.1	59.8	--------	21.0	5.4	4.3	93
Guam clay on Mariana limestone								
S54-19-1	0-4 in	4.9	51.0	--------	17.0	4.7	6.7	84
19-2	4-12 in	4.9	56.0	--------	19.4	1.2	9.7	91

The Guam clay is similar in appearance and mineralogical composition to the red earthy deposits that overlie limestones in the Mediterranean regions and elsewhere and are known as terra rossa. Limestone areas in which terra rossa develops are all characterized by rapid drainage through the rocks, but few rivers are present. Many Pacific islands that have a core of volcanic rocks surrounded by limestones also have red soils on the limestones. Volcanic ash may have been deposited on these limestones during their deposition, as is known to have occurred in the Mariana and other limestones on Guam. Such limestones are impure and, on weathering, leave residual deposits that are very different from those on islands composed of coralline material alone.

The average chemical composition of the Guam clay is SiO_2, 1.4; Al_2O_3, 39.13; Fe_2O_3, 20.30; TiO_2, 2.0; H_2O, 24.18 percent. The analyses indicate normative gibbsite and a little halloysite, the percentages of which have been calculated and are given in table 16.

SILICA

The low figures for silica in all the analyses of these soils (table 4) suggest that, if silica were originally present in greater quantities, it has been removed during soil-forming processes in which leaching is a major factor. It was noted that silica was removed from the Atate clay on the volcanic rocks, but the process has not been nearly so active as in the Guam clay. Some insight into the process may be obtained by comparing the chemical composition of one profile of Chacha clay (S54–1, table 10) with those of the Guam clays. The Chacha clay is a brown soil developed on argillaceous Mariana Limestone. The Chacha clay has 41 percent SiO_2 (Guam clay, average 1.4 percent), 36 percent Al_2O_3 (Guam clay, average 39.1 percent), 19 percent Fe_2O_3 (Guam clay, average 20.9 percent), 1 percent TiO_2 (Guam clay, average 2.0 percent). In chemical composition the Chacha clay more closely resembles the Asan clay and the Atate clays on volcanic rocks than it does the Guam clay. It may be presumed that the first soil formed on argillaceous limestones will be like the Chacha clay, and on this presumption the changes in chemical composition during the development of the Guam clay are shown in table 17.

Table 17 indicates that silica has been lost and that the other constituents have increased, pointing to the fact that although conditions were favorable for the removal of silica, they were not favorable for the removal of iron from the Guam clay.

TABLE 17.—*Changes in chemical composition, in percent, of the Guam clay (average), presuming that it developed from material similar to the Chacha clay*

[Major constituents on a water-free basis]

	Guam clay (average, 3)	Chacha clay (single analysis)	Gain or loss in Guam clay
SiO_2	2.3	41.0	−38.7
Al_2O_3	58.8	36.0	+22.8
Fe_2O_3	30.5	19.0	+11.5
TiO_2	2.9	1.0	+1.9

ALUMINA

The alumina content of the Guam clays averages 39 percent. If it is assumed that the clay material in these soils was originally similar to that in the Atate clay derived from volcanic rocks, then removal of silica would cause increase in the percentage of alumina from 28 percent (Atate clay) to 39 percent (Guam clay; average for all samples). Silica can be removed in the slightly alkaline environment of the limestone soils in which the average pH is 7.4. Silicate minerals in such an environment will become corroded if they are fairly resistant to alteration, but less stable minerals may be completely decomposed.

FERRIC OXIDE

The iron oxide in the Guam clay averages 20.9 percent, which is higher than that in the Atate clay, 15.8 percent. It is present largely as free iron oxide (table 5) and is closely associated with the clay minerals, using this term in a wide sense to include the aluminous oxides, gibbsite and boehmite. In limestones that contain detrital soil material, such as the Agana Argillaceous Member of the Mariana Limestone, the iron oxide is already associated with the clay minerals, and on soil formation it remains in the same position. The chemical environment of weathering is such that iron oxide cannot be removed by leaching surface waters because the pH is too high.

In ferric oxide content the Guam clay is similar to the average low-silica bauxite developed above limestones in central Europe as described by De Weisse (1948). The ferric oxide in 128 samples of such bauxites averages 22.9 percent. The presence of free iron oxide in terra rossa soils has been shown to have a relationship to the porosity of these soils (McIntyre, 1956, p. 305), and its presence may have an important bearing on the removal of silica by leaching, leading to accumulation of alumina and subsequent formation of gibbsite and boehmite.

TITANIA

The Guam clay contains approximately twice as much TiO_2 as the Atate clay and Asan clay formed from volcanic rocks, and the content of these rocks is quite low (0.5 percent TiO_2). Accumulation of TiO_2 is a common feature of lateritic weathering, particularly in tropical soils as described for the Hawaiian Islands by Hough and others (1941) and more generally by Mohr and van Baren (1954). Titania, like alumina, is not readily removed from soils by leaching, so if SiO_2 and bases are removed by soil-forming processes, titania automatically increases. Bauxites developed on limestones all show about 2 percent TiO_2, which is the average for the Guam clay. The form in which titania is present may be as ilmenite, anatase, or as indefinite hydrous titanium oxide ($TiO_2 \cdot nH_2O$) associated with the clay minerals. The conditions for the recrystallization of the anatase-brookite-rutile group of minerals are not well understood, but anatase is the mineral which most commonly crystallizes authigenically.

PHOSPHATE

Some of the limestones contain apatite that replaces shell fragments (Schlanger, 1963). The Guam clay contains 1.65 percent P_2O_5 compared with 0.1 percent P_2O_5 in the Atate clay. The phosphate in the Guam clay can probably be best explained as a residual consitituent of the limestones that is not removed by leaching at pH 7 and therefore accumulates in the soils.

EVIDENCE FROM MINERALOGICAL COMPOSITION

SOILS ON VOLCANIC ROCKS

Chemical analyses of the various soils developed on the volcanic rocks indicate that silica is removed by the soil-forming processes and that alumina, ferric iron, and titania show a relative increase.

The parent rocks—basalts, mafic dikes, and tuffs—contain variable quantities of minerals that can be altered by weathering and soil-forming processes. These rocks vary in coarseness of grain size and in texture (figs. 1, 2). The total effect of weathering processes may be complete removal of a mineral, a reduction in the amount present, or a change of the original mineral into clay minerals and iron oxides. Some of the minerals are resistant to weathering and persist in the resulting soil. The weatherability of a rock can be diagnosed from a consideration of the kinds of minerals present or from a chemical analysis. One way to estimate the weatherability is to use the Weathering Potential Index (WPI) as suggested by Reiche (1950). This is the mol percentage ratio of the sum of the alkalis and alkaline earths, less combined water, to the sum of the total mols exclusive of water; or

$$\frac{100\times\text{mols}\ (K_2O+Na_2O+CaO+MgO-H_2O)}{\text{Mols}\ (SiO_2+Al_2O_3+TiO_2+Fe_2O_3+FeO+CaO+MgO+Na_2O+K_2O)}$$

This Weathering Potential Index is based on the observation that the order of loss of cations from rocks undergoing weathering appears to be Na, Ca, Mg, K, Si, Fe, Al, and Ti. This is probably true for the initial stages of weathering, but silica and ferric oxide accumulate with little loss under some conditions, although they are mobilized under others. In the normal process of lateritic soil formation SiO_2 is removed and Fe_2O_3 accumulates. Alumina is the inert oxide under these conditions.

The Guam volcanic rocks include basaltic andesites, tuffs and coarser pyroclastics, and agglomerates. The principal minerals are plagioclase feldspars, pyroxenes (augite and hypersthene) with a little scattered olivine and quartz. Accessory minerals are magnetite, hornblende, biotite, and alkalic feldspar, together with glass in the matrix. The tuffs generally contain zeolites. All these, with the exception of quartz, are weatherable minerals so that, except for secondary silicification of some of the tuffs, the volcanic rocks contain only weatherable minerals.

The Weathering Potential Index of certain minerals is given by Reiche (1950) as follows: olivine, 54, augite, 39, hornblende, 36, biotite, 22, labradorite, 20. The WPI of the Guam volcanic rocks, using the average chemical composition of table 9, is 14, which suggests that the rock as a whole is not more weatherable than oligoclase. However, Reiche's WPI is too narrow a concept of weathering for soil formation studies where silica and iron oxides are also important.

The Weathering Potential Index of the weathered rocks beneath the soils, computed in the same manner, is nil, which indicates that no bases remain. This means that the initial weathering removes all the readily mobilized elements, and subsequent soil-forming processes affect only the least readily removable elements, silicon, iron, and aluminum. The chemical analyses of the soils show this (table 4). In the agricultural use of these soils, deficiency of bases for plant nutrition would seem to constitute a problem. The low pH and generally low figures for ion-exchange capacity also point to a deficiency of bases.

The minerals present in the rocks, weathered rocks, and soils are shown in table 18.

TABLE 18.—*Weathering sequence of minerals in rocks and soils of Guam*

Minerals in rocks	Weathering potential index	Cations removed	Minerals in weathered rocks	Minerals in soil, final product
Feldspar	17	Ca, Na	Montmorillonite,[1] feldspar(?).	Halloysite.
Augite	40	Ca, Mg	Montmorillonite, augite.	Halloysite, augite.
Hypersthene	30	Mg, Fe	Hypersthene	Halloysite, hypersthene.
Olivine	50	Mg, Fe	Montmorillonite	Halloysite.
Magnetite			Magnetite	Magnetite.
Ilmenite			Ilmenite	Ilmenite.
Hornblende	36	Ca, Mg, Fe, Na.	Hornblende, montmorillonite(?).	Halloysite, hornblende.
Biotite	22	K, Mg, Fe	Montmorillonite	Halloysite.
Quartz			Quartz	Quartz.
Zeolite	50	Ca, K, Na	Montmorillonite	Halloysite.
Glass	50	Mg, Fe, Ca	do	Do.

[1] In the presence of weathering pyroxenes, montmorillonite forms from plagioclase feldspar with magnesium being contributed by the pyroxene.

Examination of the sand-sized minerals (table 6) shows that magnetite is the dominant residual mineral in all the soils developed on volcanic rocks and that generally it is more abundant in the surface soil than in the deeper layers. The maximum quantity varies, the highest figure being 3 percent by weight of the soil. There are more than 4½ pounds of magnetite per cubic foot of surface soil of profile S54-10 (Atate clay). This fact, coupled with the depletion in SiO_2 and increase of Al_2O_3 and Fe_2O_3 (fig. 4), indicates that the increase in quantity of resistant minerals is the natural result of soil-forming processes that have been in operation for considerable periods of time. If augite, hypersthene, and hornblende are present, a similar accumulation is shown in spite of the fact that these are generally considered as weatherable minerals.

It is probable that in certain soil horizons alteration takes place more readily than in others, as suggested by Carroll (1953, p. 100); if a mineral survives alteration in such a zone, it may not again be subjected to conditions that would cause its removal. Furthermore, there are two ways in which minerals are affected by weathering processes; the mineral may be completely replaced by a clay mineral, for example, augite may be replaced by montmorillonite in a weathered rock which remains saturated with water; however, with free drainage, augite may retain its identity and optical properties although at the same time its substance is slowly removed by ionic solution. An indication of slow solution is the etching of grain surfaces shown in figure 4. It is commonly observed in deeply weathered rocks that zones or channels are developed through which water moves more readily than in other parts of the rock. Chemical elements are more easily removed from minerals adjacent to these channels than from those in other parts of the rock. The relatively undrained parts of a weathering rock are saturated with water containing chemical elements removed from the individual minerals present. This condition of the rock is conducive to the formation of alteration products of the original minerals. Clay minerals, sericite or other types of secondary mica, and crystallized titanium minerals, such as anatase or rutile, are commonly found.

Examples of the early stages in the alteration of rocks of Guam are illustrated in figure 1C. Little loss of material has taken place, the principal change being the devitrification of glassy material and alteration to zeolites and montmorillonite. A more advanced stage is represented by figure 1D. In figure 2A and B clay minerals are present in considerable abundance, but the mineral assemblage—celadonite, saponite, and plagioclase—suggests that intense weathering or leaching has not yet been effected. A highly weathered saprolite is represented by sample S54–5–6 (table 7) in which the earlier alteration products as well as the parent minerals have largely disappeared. The weathering process to this stage has been—

1. Transformation of unstable minerals to more stable phases without the loss of much material through leaching.
2. Development of dioctahedral montmorillonite as the dominant phase by the leaching of bases and silica from the earlier alteration products and remaining primary minerals. A feature of this stage is the retention of magnesium and loss of silica (table 12). The probable explanation is that little magnesium in excess of the amount necessary for the formation of montmorillonite is present in the parent rock, whereas the amounts of silica and alkalies exceed requirements and occur in glass or relatively easily soluble minerals.

The Asan clay, represented by sample S54–23–1, has reached this stage of weathering and soil development.

Montmorillonite is replaced by halloysite ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$), which may actually be endellite ($Al_2O_3 \cdot 2SiO_2 \cdot 4H_2O$) within the soil and weathered rock. This transformation takes place in a random manner among the layers in montmorillonite, as shown by X-ray diffraction patterns indicative of a random interstratification of montmorillonite and halloysite layers. The lower horizons of profile S54–21 contain much interstratified montmorillonite and halloysite. Sampling was apparently not deep enough in the other profiles to show this transition, although small amounts of montmorillonite appear below 32 inches in profile S54–6. After this transformation of halloysite other changes take place only slowly, and all the profiles show a fairly uniform composition. One of the changes is the development of small amounts of gibbsite in the soils formed on the volcanic rocks. The normative amount does not exceed 7 percent in the profiles analyzed. The changes in mineral composition with soil development of these soils and some from other localities are summarized in graphical form in figure 9.

The vertical direction represents increasing degrees of soil development; the horizontal represents the composition of the soil at any given stage of development. The arrows indicate the transformations that the various minerals undergo. Nicolls and Tucker (1956, p. 116) indicate that feldspar persists through the montmorillonite stage and then alters to halloysite. As no feldspar of significant quantity was noted in the montmorillonitic stage (Asan clay) of the soils of Guam, the location of the feldspar-montmorillonite boundary is doubtful. As the decomposition products of feldspar alone would be inadequate to form montmorillonite of the composition of the Asan clay, the contribution of magnesium from the ferromagnesians would be required. For this reason the ferromaganesian-montmorillonite and feldspar-montmorillonite boundaries are given approximately the same shape.

On figure 9 a dashed line is given as the boundary between montmorillonite and halloysite because of the presence of mixed layering between the two in the Guam soil, making the boundary gradational. The gradual transformation of goethite to hematite shown in the diagram is not evident in the Guam soils, but it occurs in some of the other localities shown. Because of such variations among the localities, no attempt is made to quantify the diagram; therefore a schematic relationship only is shown.

SOILS ON LIMESTONES

The limestones on Guam vary from almost pure calcium carbonate (table 1) to argillaceous limestones, and some contain phosphate. Magnesium carbonate is generally less than 3.0 percent in the samples analyzed. An examination of the insoluble residues,

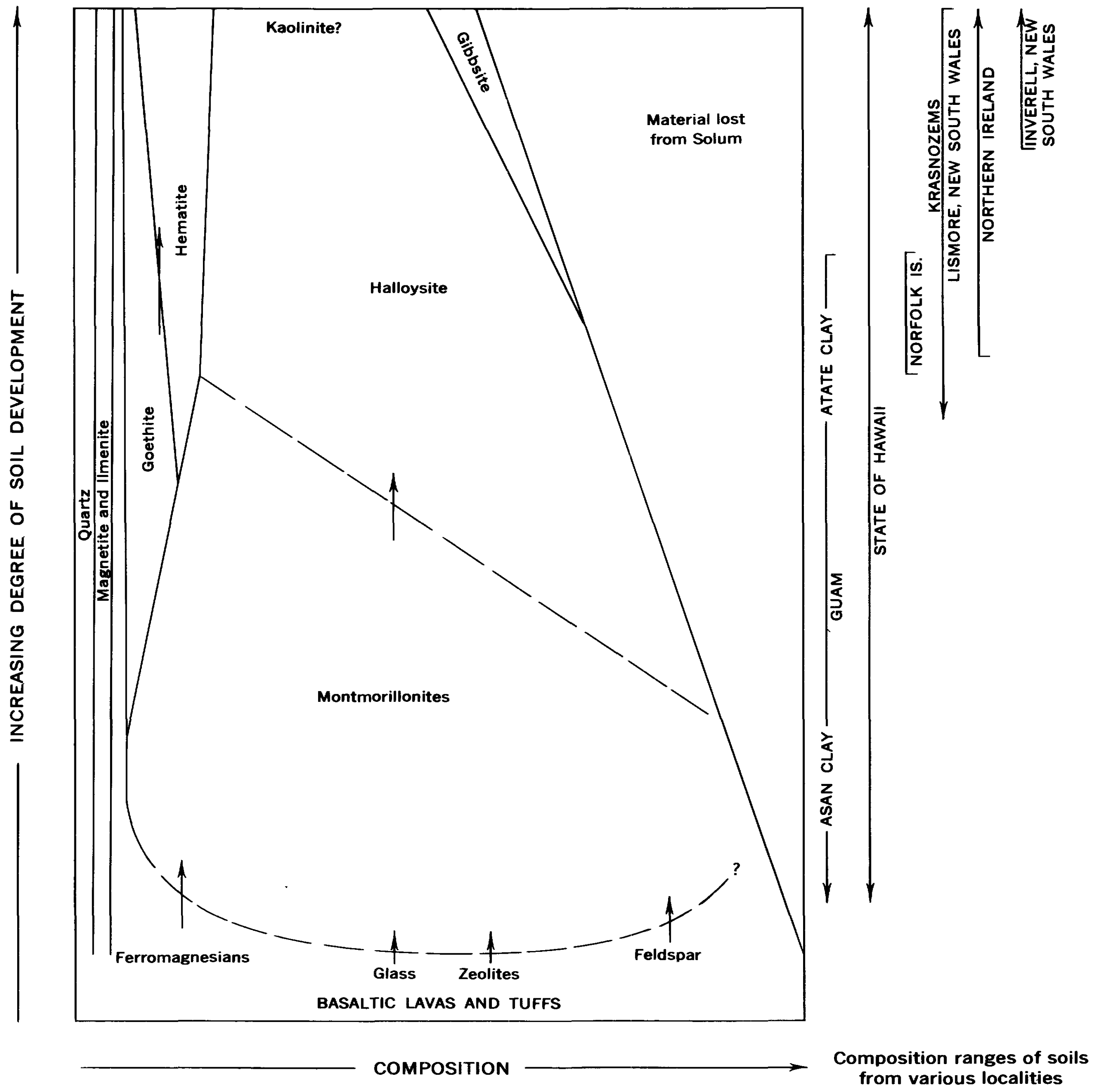

FIGURE 9. Diagram modified after Nicolls and Tucker (1956, p. 116) showing the mineralogical relation of soils developed on basaltic materials in various localities. Upward progression in the diagram indicates increasing degree soil development. Horizontal lines drawn across the diagram at various levels would indicate the composition of individual samples.

as reported by Hathaway and Carroll (1963), has shown that volcanic ash and argillaceous materials, derived from soils by erosion, have been added to the limestones during deposition. The volcanic ash contributed plagioclase feldspar, pyroxenes and amphiboles, magnetite, zeolites, and a little quartz; the eroded soil material contributed clay minerals and iron oxides, largely goethite.

The amount of material removed from limestones by solution by drainage waters depends on the purity of the limestones; in pure limestones the weathering potential index is 100, but with increase in insoluble residues this figure decreases. The quantity of insoluble residue in the Mariana Limestone varies as shown in table 1, but as explained on page F2, these samples may not be representative. However, it is probable that the average insoluble content in the Mariana and Barrigada Limestones is about 0.1 percent. The insoluble residue of the Alifan Limestone averages about 4 percent by weight. The other limestones listed in table 1 are not parent materials of soils of significant area. The amount of insoluble residues in the limestones examined shows considerable variation.

The insoluble residues of some Guam limestones contain variable quantities of silica in four forms: (1) as a constituent of halloysite, (2) as beta-cristobalite, (3) as a constituent of zeolites, and (4) as a constituent of montmorillonite. In addition there are scattered small euhedral quartz crystals. Minor quantities of silica are present in augite, hypersthene, and hornblende. Ferric oxide is also a constituent of these limestones. It is closely associated with halloysite where it forms a coating on individual mineral platelets. This iron oxide has been carried into the deposition area as part of the eroded soil material, as explained by Hathaway and Carroll (1963).

The Guam clay associated with the Mariana Limestone is characterized by a very low silica content (average, 1.4 percent) and by high alumina and ferric oxide. The minerals in the insoluble residues of the limestones have been recognized in the sand, silt, and clay grades of the soils. In the sands (table 6) these minerals account for a maximum of 1.2 percent by weight (profile S54–18). Generally the quantity is less than 1 percent. In some of the soils examined there are practically no residual minerals that could be related to minerals of a weathered rather than to a fresh volcanic-ash assemblage. The least weatherable minerals in the soils associated with limestones are indistinguishable from those developed on the volcanic rocks, although the quantities of such minerals are generally smaller. Where present, magnetite is the dominant mineral, but ilmenite, augite, hypersthene, and amphiboles are also present. In addition to the individual heavy minerals, composite grains of augite and feldspar also occur in these soils. Feldspar and quartz grains are present in some of the sand grades.

Gibbsite is the most abundant mineral in the Guam clay associated with the Mariana and Barrigada Limestones. Some boehmite is present in two of the profiles and minor quantities of other minerals occur. Only minor amounts of gibbsite and boehmite occur either in the soils on volcanic rocks or in the insoluble residues of limestones. It seems apparent that gibbsite is formed by alteration of minerals, largely though not entirely clay minerals, in the chemical environment of limestone weathering. The process is one of leaching by solutions formed principally from rainwater, but which also contain organic acids and compounds. The minerals that are leached may be present as impurities in the limestones, or they may have been added to the limestone surfaces from outside sources. The deposit that results is known as terra rossa; in places it is associated with hard limestones that have good drainage.

Small quantities of silica (<6 ppm) are soluble in water at all pH values (Correns, 1949, p. 210; Krauskopf, 1956, p. 1). Amorphous silica is many times more soluble than crystalline silica (100–140 ppm). Silica is more soluble at higher than at lower pH values. Alumina is soluble below pH 4 and above pH 8; between pH 4 and pH 8 it is insoluble and is not present in soil solutions (Magistad, 1925, p. 193). Silica is therefore removed preferentially to alumina between these pH values, that is, at the usual pH values for soils. Leaching by solutions within these values will remove silica from easily weatherable minerals. If sufficient SiO_2 is removed from clay minerals, their structure may break down and release Al_2O_3 that can crystallize as gibbsite or boehmite. All clay minerals, however, do not alter in such a way that silica is added to the soil solution (Siever, 1957, p. 828). The change from a montmorillonite to a micaceous clay mineral does not involve a reduction in the amount of silica present.

The pH of the soils (table 3) show that this is the important factor in the decomposition of halloysite to gibbsite. Most of the soils developed on the volcanic rocks fall in the range of pH 4.8 to 5.8, in which silica goes into solution and alumina accumulates. The amount of silica removed depends on the quantity of rainwater percolating through the soil and saprolitic rock. The better the drainage the greater the possibilities for removal of SiO_2. The soils associated with limestones have pH values that range from 6.1 to 7.9. At these values silica is dissolved more readily than at pH 4.8 to 5.8, but the soils are not sufficiently alkaline to remove Al_2O_3. The Chacha clay (profile S54–1) developed on the Agana Argillaceous Member of the Mariana Limestone illustrates the effect of quantity of material to be leached. The insoluble residue of the Agana Member consists of halloysite and goethite and a trace of gibbsite. The soil contains a maximum of 3 percent gibbsite, whereas the Guam clay contains between 50 and 60 percent gibbsite (table 16).

That pH is not the only factor is illustrated by a soil collected from a small depression on the limestone ridge of Mount Lamlam that forms the highest point on the present-day island. X-ray examination by the methods described above shows that this soil contains principally montmorillonite and minor amounts of goethite and, in the upper 16 inches, minor amounts of gibbsite and boehmite. The horizons below 16 inches contain major amounts of silt-sized calcite.

The soil at Mount Lamlam is developed on Alifan Limestone which contains a considerable amount of montmorillonite, although it also contains an erosional or weathered assemblage of nonclay minerals (Hathaway and Carroll, 1963). The presence of considerable silt-sized calcite in the lower horizons suggests a poorly drained relatively unleached soil. This lack of leaching accounts for the persistence of montmorillonite in the soil. The occurrence of gibbsite and boehmite in small amounts in the upper horizons suggests a development toward a high-alumina mineral composition without the intermediate formation of halloysite. This would suggest that a highly gibbsitic soil, such as the Guam clay, could form directly from a montmorillonitic noncarbonate residue in the limestone, if the drainage were good enough to provide strong leaching and the pH remains below 8. The Mariana Limestone on which the Guam clay most commonly occurs is for the most part highly porous and permeable and thereby provides very good internal drainage for the overlying soil. This limestone also has only a small insoluble content, and therefore it does not present at the weathering limestone surface a thick mass of residual clay particles which could retard drainage during the soil-forming period. Gibbsite cannot form in the presence of a sufficiently high concentration of silica in solution in soil water or in ground water.

As the Mariana Limestone contains an insoluble residue having both weathered and volcanic-ash mineral assemblages (Hathaway and Carroll, 1963), it is likely that the origin of at least part, if not most, of the Guam clay is the almost complete desilication of volcanic ash released from the limestone by solution and weathered under conditions of strong leaching and relatively high pH. The Chacha clay developed on the more highly argillaceous limestones, such as the Agana Member, which contain an erosional or weathered assemblage, tend to maintain a lower pH. This soil is subjected to less effective leaching, owing either to an abundance of clay that forms a relatively impervious blanket on release from the limestone or to the density of the underlying limestone. As a result, removal of silica takes place more slowly and the soil formed resembles the highly halloysitic Asan-type clay that was incorporated in the Agana during deposition.

On the question of the source of the insoluble content of the Alifan Limestone, the presence of iron oxides and nordstrandite and the absence of feldspars or zeolites (Hathaway and Carroll, 1963) suggest that a soil of the composition of the Asan clay, highly montmorillonitic, but a weathered soil material and not volcanic ash, was the contributing source. The montmorillonite could have been eroded from the volcanic areas in the early stages of weathering, during which montmorillonite was the dominant alteration product; or it could have been eroded after much longer weathering but from an area previously stripped by erosion of its halloysitic upper horizons.

Although means have been discussed whereby the noncarbonate minerals of the Mariana Limestone could alter to form the Guam clay, it is of course possible that this soil could have formed from materials derived from sources other than the underlying limestone. Zans (1952) proposed an alluvial origin for the Jamaican bauxites, suggesting that the material is eroded from soils on the volcanic areas of Jamaica and carried by the numerous streams draining these areas onto the limestones. This material may be deposited directly on the limestones or carried into solution channels or caves in the limestones. It may later be deposited on the floors of sinks and depressions if the water emerges as "boiling" springs.

The present topography of Guam is such that it is doubtful that any material from the volcanic parts of the island could reach the northern limestone plateau by river drainage. Any drainage to the north is intercepted by the Pago and Agana Rivers and carried to the eastern and western shores, respectively, close to the boundary between the volcanic rocks and limestone. Drainage from the limestone areas near this boundary is toward these rivers and away from the central parts of the limestone plateau. However, in the past, the limestone plateau was below sea level, and volcanic-rock weathering products undoubtedly were moved toward it.

The possibility that the limestone soils represent volcanic ash that fell on the limestone surface after its emergence must be considered. Such falls must have occurred even after the cessation of volcanic activity on Guam itself in Miocene time because of the presence of volcanic mineral assemblages in the Barrigada and Mariana Limestones. These ash falls must have originated from volcanic activity in places other than the present island of Guam. If the ash falls occurred after the emergence of the present limestones and during the present period of soil formation, evidence of the falls might be expected on the volcanic parts of the island in the form of repetitions of profile development. In particular, the more weatherable minerals should show sudden increases near the surface; however, such increases were not found in the soils developed on the volcanic areas.

It is also possible that windblown soil material from the volcanic soils was deposited on the limestone surface of the northern plateau. This soil material would become incorporated into the weathering products of the limestones. The prevailing winds of today are the Northeast trade winds. Soil material transported by them would be largely moved away from the island and deposited in the ocean. However, it has been noted that soil material is moved by breezes and winds from other directions, and it could contribute to the deposits on the limestone plateau.

COMPARISON OF SOILS OF GUAM WITH THOSE OF SIMILAR PARENTAGE IN OTHER SELECTED AREAS

The soils of Guam, with their parent rocks of basalt, tuffs, and limestones, are similar in appearance to those on the same kind of rocks undergoing weathering under tropical climates in various geographical locations. Many Pacific Ocean islands consist of a volcanic core flanked by limestone, and the soils on these islands are apparently similar to those of Guam, although, except for the islands of Hawaii, little detail is available. The West Indian islands of Jamaica and Hispaniola (Dominican and Haitiian Republics) have gibbsitic soils on limestones comparable with those of Guam.

VOLCANIC ROCK SOILS

HAWAIIAN ISLANDS

The soils of the Hawaiian Islands have been described in considerable detail chemically, and many mechanical analyses have been published (Hough and Byers, 1937; Hough and others, 1941; Sherman and others, 1948). The basalts of the Hawaiian Islands differ in chemical composition from the basaltic andesites and tuffs of Guam in containing less silica but more titania (table 19). The soil profiles have developed under rainfall ranging from 18 to 273 inches (Hough and others, 1941, p. 1), and exceedingly young, young, and old soils have been recognized. The chemical composition of the soils reflects that of the rocks. The silica is combined in the various minerals in the rocks and consequently is more easily removed than if it were partly present as quartz. Accumulation of TiO_2 is a characteristic feature, as it is in the Guam soils; but as the original rocks of Guam contain only 0.5 percent TiO_2, compared with 2.3 percent in the basalts of the Hawaiian Islands, the TiO_2 content is never as great.

Hough and others (1941, p. 32) found that two kinds of soil profiles are developed on the basaltic rocks of the Hawaiian Islands: a uniform profile in which SiO_2, Al_2O_3, Fe_2O_3 and TiO_2 do not vary more than 5 percent in the different soil horizons; and a podzolic profile in which the soil horizons are of different composition, with concentrations of TiO_2, Fe_2O_3, and Al_2O_3 in the upper part, with a consequent loss of SiO_2. It is considered that the podzolic profile, which has also been described by Sherman and his coworkers (1948) as a ferruginous latosol, is an older and more mature profile than the uniform profile. The podzolic profile may develop from the uniform profile with time.

Of the Guam soil, the Atate clay apparently is comparable with the uniform profile. Analyses (tables 11–14) show that SiO_2 has been removed, and that Al_2O_3, Fe_2O_3, and TiO_2 accumulate toward the surface; but there is a gradual change, and no very marked horizons, such as occur in podzols, are present.

The Asan clay of Guam can probably be compared with the young uniform soils of the Hawaiian Islands. One of the principal differences between the Asan clay and the Atate clay is that the former has recognizable grains of heavy minerals throughout the profile, whereas the Atate clay shows a marked surface accumulation of magnetite and other opaques. This is a result of long-continued soil-forming processes and is a feature of old soils. The Asan clay has montmorillonite as its principal clay mineral, whereas the Atate clay has halloysite or mixed-layered halloysite-montmorillonite and a little gibbsite.

The chemical composition of the colloidal fraction ($<2\mu$) of the Hawaiian Islands soil profiles that developed under different rainfall conditions varies in the SiO_2-Al_2O_3 ratio (Hough and others, 1941; Tanada, 1951), which indicates a change in clay minerals as follows:

$$\text{montmorillonite} \longrightarrow \text{halloysite} \longrightarrow \text{gibbsite}$$

As SiO_2 is removed, montmorillonite is unable to retain its lattice structure and its place is taken by halloysite; the alumina released from halloysite by further depletion of SiO_2 results in the presence of gibbsite or other aluminum oxide.

Both pH and organic matter content of the Guam soils have a trend similar to those of the Hawaiian Islands.

The clay minerals present in mature soils of the Hawaiian Islands belong to the kaolinite group (Dean, 1947, p. 102) and the differential thermal analysis curves strongly suggest halloysite, although Dean (p. 104) has not identified this mineral. In a study of the weathering of olivine basalt by Sherman and Uehara (1956) the differential thermal analysis curves of the soil adjacent to the basalt also suggest halloysite. In situations where the removal of bases is slow or restricted, the first weathering product of olivine is a member of the montmorillonite group. The weathering rock at the base of profile S54–21 has mixed-layered montmorillonite-halloysite, and the Asan clay S54–23–1 contains montmorillonite.

NORFOLK ISLAND

Norfolk Island which is in the south Pacific Ocean (lat 29°3′45″ S. and long 167°56′29″ E.) has an area of 8,500 acres. It consists of a core of basalts and tuffs surrounded by limestone similar to Guam. The soils (Hutton and Stephens, 1956) have been described as krasnozems, and many soil types are distinguished, varying from dark red (2.5YR 4/4) to chocolate overlying a deep subsoil of red (10YR 4/5–4/6) (Munsell Color Co., Inc., 1954), compact but friable granular

TABLE 19.—*Comparison of soils developed on basalt and volcanic ash from various selected localities*

Soil description	Type of profile	Rainfall (inches per year)	Temperature, mean (°F)	Humidity (percent)	pH	Cation-exchange capacity (milliequivalents per 100 grams)	Sum of exchangeable bases	Chemical composition (percent)						Grain size (percent)			
								SiO_2	Al_2O_3	Fe_2O_3	Free Fe_2O_3	TiO_2	H_2O	Sand	Silt	Clay	Clay minerals
GUAM																	
Lateritic, Atate clay	Uniform	89	80	81	5.3	14.0	1.2	33.9	28.4	15.6	11.6	0.9	17.8	5.8	23.5	70.7	Halloysite, gibbsite, montmorillonite.
Others, Asan clay	do	89	80	81	7.4	----	5.5	45.0	16.9	10.0	4.1	.8	18.6	7.3	31.0	61.7	Montmorillonite.
HAWAIIAN ISLANDS																	
Lateritic	Uniform and podzolic.	[1] 100	75	68	----	----	.7	22.2	24.1	25.8	----	5.5	17.6	13.6	40.3	43.0	Kaolinite-group mineral, montmorillonite.
NORFOLK ISLAND																	
Krasnozem,[2] several soil types.	Uniform	53	66	80	6.4	13.7	----	15.4	21.9	29.7	----	7.3	----	8.5	15	70	Kaolinite-group mineral, gibbsite.
LISMORE, NEW SOUTH WALES, AUSTRALIA																	
Krasnozem,[2] Alphadale clay loam.	do	55	67	----	5.3	22.5	----	----	----	----	14.3	----	----	11	14	72	Kaolinite, halloysite, montmorillonite.
INVERELL, NEW SOUTH WALES, AUSTRALIA																	
Fossil laterite	Podzolic	----	----	----	----	----	----	16.9	49.2	19.6	10.6	10.6	20.6	----	----	----	Kaolinite, gibbsite.
NORTHERN IRELAND																	
Fossil laterite	do	----	----	----	----	----	1.8	20.7	26.8	28.3	----	3.5	13.3	----	----	----	Halloysite, chamosite, gibbsite, chlorite-type mineral.

[1] Rainfall in the different islands is variable; it also varies from windward to leeward side and with elevation.

[2] Krasnozem is a red loam, generally termed a "latosol" in the United States.

EXPLANATION

Guam soils:

Data for the Atate clay are averages obtained from 29 samples (6 profiles) for chemical analyses and 33 samples (6 profiles) for mechanical analyses.

Data for the Asan clay are averages obtained from 2 samples (1 profile).

Hawaiian Islands:

Data are from Hough and Byers (1937) for the mechanical analyses (29 samples from 6 profiles) and from Hough and others (1941) for the chemical analyses (45 samples from 11 profiles). The profiles are described as "young profiles" and "old profiles." The rainfall under which they have developed ranges from 20 to 273 in., average 99 in. per year.

Norfolk Island:

Data are from Stephens and Hutton (1954) and Hutton and Stephens (1956). Mechanical analyses are for 22 samples from 6 profiles developed on basalt; greatest depth of profile is 72 in. The chemical data are derived from those given by Hutton and Stephens (1956, p. 261) and are for 6 samples of 3 soil types to a depth of 38 in. on basalt.

Lismore, New South Wales, Australia:

Data are from Nicolls and Tucker (1956). No chemical analyses are available, but the figures for mechanical analyses are averaged from 19 samples (3 profiles), 2 of which are to depths of 72 and 82 in., respectively, and the third to a depth of 189 in. (15.75 ft).

Inverell, New South Wales, Australia:

Data are from Carroll and Woof (1951) from a single old or "fossil" laterite profile which was sampled to a depth of 23 ft. Chemical analyses are averages of 8 samples to this depth.

Northern Ireland:

Data are from Eyles (1952) for the interbasaltic laterite which developed as a typical podzolic type of profile. The figures for the chemical analysis quoted were averaged from those quoted on page 14 (idem.) for a set of samples illustrating the lithomarge and laterite from basalt. The material at the surface of the old profile contains sufficient iron for it to be used as an iron ore.

clay to a depth of 60 inches. Other soils are brown, dark brown, or black, depending on topography and drainage. The rocks on which the soils have developed are not very deeply weathered. The recalculated chemical analyses (table 19) from Hutton and Stephens (1956, p. 261) show their similarity in development to the soils of Guam.

The soils of Norfolk Island are depleted in calcium, magnesium, and silica, with accumulation of iron and titanium to a depth of 30 inches. These soils have pH averaging 6.4, which is higher than that for the Atate clay (5.3). The incomplete rainfall records suggest that for several months during the year on the island there is an excess of rainfall over evapotranspiration (Hutton and Stephens, 1956, p. 262); so considerable leaching of the soils occurs.

The minerals in the clay fraction, to a depth of 30 inches, are kaolin, goethite, hematite, and a little gibbsite; quartz and rutile were found in one sample. Gibbsite may be considered the principal mineral in the coarser fractions (Hutton and Stephens, 1956, p. 263), for it is the dominant mineral identified in the concretionary material in many of the soil types. Mechanical analyses given by Stephens and Hutton (1954, p. 14–19) show that the surface soils in general contain a greater quantity of sand grades (2 to 0.2 mm) than the surface soils of Guam. The total cation-exchange capacities are very similar to those for the soils of Guam with calcium as the dominant exchangeable cation.

LISMORE, NEW SOUTH WALES

The soils developed on basalt in the Lismore district in the northern part of New South Wales, Australia, have been described by Nicolls and Tucker (1956). The area is near the coast and is part of an extensive basalt plateau in an advanced stage of dissection. The four residual soils on basalt are krasnozems, which are reddish-brown deep soils considered to be at an advanced stage of weathering which results in the production of kaolin minerals, goethite, and gibbsite. They have developed under a yearly rainfall of 55 to 60 inches, mostly in summer. The sand fractions, as in the Guam soils, are small and variable, and the reaction is acid, averaging 5.3. The pH at the surface is higher than at depth, one profile having pH 4.2 at 96 to 108 inches. The clay content is high but variable, and an accumulation of coarser particles may be in the surface soil.

The clay minerals of these soils have been examined in considerable detail by Norrish [1] as quoted by Nicolls and Tucker (1956, p. 51).

> the silicate clay minerals of these krasnozems belong to the kaolin group and make up 70 to 95 percent of the clay mineral assemblage. In the deeper horizons the kaolin mineral is halloysite. Towards the surface the kaolin structure becomes increasingly well ordered, approaching that of kaolinite. The remainder of the clay consists of hematite and ilmenite (together 5 to 15 percent of the clay) with a little gibbsite in the surface horizons and occasionally some quartz.

An interesting relation between free iron oxide and drainage has been noted by Nicolls and Tucker (1956, p. 115) who state, "The separation of iron (from the original minerals) as the free oxide is very important in maintaining the free internal drainage of the krasnozems" and hence favors their continued development.

In mechanical composition all the soils formed on basalt in the Lismore area have a large proportion of clay and, according to Nicolls and Tucker (1956, p. 116),

> this is most apparent in the krasnozems where all but the most resistant primary minerals have weathered to clay minerals. The smaller amounts of clay at the surface of the soils are probably due to a change in composition of the clay minerals rather than to movement of clay particles by eluviation. In the Caniaba series (pedocalcic black soils, residual on basalt) this change is from montmorillonites to kaolinite group minerals, and in the krasnozems it is from kaolinite group minerals to gibbsite; both these changes involve a loss of silica from the clay fraction.

A diagrammatic representation of the mineralogical changes accompanying the development of the various soils of the Lismore area (Nicolls and Tucker, 1956, fig. 21, p. 116) has been adapted to show the relationship of the soils of Guam to the soil-forming processes as indicated by the chemical analyses (fig. 9). The positions of the soils of Guam to the soils of Hawaii, Norfolk Island, Lismore, Northern Ireland, and Inverell, New South Wales are shown.

INVERELL, NEW SOUTH WALES

A single profile of a laterite on basalt was described by Carroll and Woof (1951). It is an example of a podzolic profile in which there is a sharp contrast in chemical composition and mineralogy in the different horizons between the weathered parent rock and the bright red ferruginous soil. The normative composition of the fine earth (<2 mm) from each horizon shows that kaolinite ranges from 72 percent in the red and white mottled zone (12.75 to 16.25 ft) to 6 percent in the bauxitic horizon just above it (11.5 to 12.75 ft), which contains 90 percent of gibbsite. X-ray examination confirms the calculations from the chemical analyses. Calculations show that a loss of 90 percent of the silica originally present in the parent basalt would produce a profile having approximately the composition that was found for the weighted average of the samples. Hematite is the principal iron oxide, but a little goethite also occurs. A marked concentration of TiO_2 occurs in most horizons; it is largely present in ilmenite, but anatase is also present and is recorded by X-ray diffraction. The parent rock contains 1.13 percent TiO_2. Maghemite, a magnetic hematite developed from magnetite, was found in the lower part of the profile; a similar occurrence of maghemite is recorded (Eyles, 1952, p. 34) for the laterites of Northern Ireland, which can be considered comparable in many ways.

ANTRIM, NORTHERN IRELAND

The chemical composition and mineralogy of the laterites of the Interbasaltic Horizon among the Tertiary basalt flows of County Antrim, Ireland, have been described in detail by Eyles (1952). The interval between basalt flows was sufficiently long to enable the lower basalts to weather to laterites and bauxites. Later, the weathered surface was covered by another flow of basalt.

Analysis are given (Eyles, 1952, table 1, p. 14) that show a progressive loss of SiO_2 and an accumulation of Al_2O_3, Fe_2O_3, and TiO_2 in the weathering products of the basalt. The mineral composition calculated from the analyses gives about 70 percent kaolinite in what is described as basaltic lithomarge, and less than 2 percent kaolinite in red ferruginous bauxite containing 66 percent of gibbsite. Some of the weathered material contains sufficient iron to be used as

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[1] Norrish, Keith, 1952, A study of the mineralogy of some Australian soils formed from basic igneous rocks: Unpub. Ph. D. thesis (pt. 1), Univ. London.

an iron ore, the iron-bearing minerals being hematite, goethite, and magnetite. The material high in iron oxide forms an upper crust just above the bauxite horizon. Thus, this profile may be described as a podzolic one from the original description of Hough and others (1941, p. 34). It is similar to the laterites which have been described from India (Fox, 1932) and the "fossil" laterites from Australia (Carroll and Woof, 1951; Prescott and Pendleton, 1952). Such lateritic profiles are characterized by morphological, chemical, and mineralogical distribution of their constituents in different easily recognizable horizons.

The process of removal of SiO_2 and bases, leaving an accumulation of Al_2O_3, Fe_2O_3, and TiO_2 is similar to that of the soils of Guam, but the Antrim laterites are considered to be at a later stage of development.

X-ray examination of the Antrim laterites and bauxites has confirmed the presence of a kaolin-type mineral, gibbsite, goethite, boehmite, hematite, a chlorite-type mineral, anatase, rutile, and maghemite. The kaolin-type mineral is halloysite, $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$. Endellite, $Al_2O_3 \cdot 2SiO_2 \cdot 4H_2O$, was recognized in many of the samples investigated. Thus, the principal clay mineral of the soils of Guam is the same as that in the Antrim laterites.

Other similarities are the presence of hematite as the principal iron oxide, of gibbsite, and of small quantities of goethite and boehmite. Most of the magnetite in the Antrim laterites has been altered to hematite and some to maghemite, the latter not having been recognized in the soils of Guam.

Chamosite (Eyles, 1952, p. 47), a clay mineral with the composition of a ferruginous kaolinite $(Al, Fe^{3+}, Fe^{2+}, Mg)_3(Si, Al)_2O_3 \cdot 2H_2O$, was found as a secondary alteration product in some parts of the Antrim laterites where downward-leaching water has reduced ferric to ferrous iron. Swampy conditions on the land surface are considered responsible for the leaching water.

The examples given above have been used to compare with the soils of Guam because considerable chemical and mineralogical detail are available. Many other soils developing on mafic rocks under warm temperatures and high rainfall conducive to rapid leaching and weathering show the same processes, namely, the removal of SiO_2 and the accumulation of Al_2O_3, Fe_2O_3, and TiO_2. Descriptions in the literature indicate that there are many stages in the genesis of lateritic profiles. As the process continues, the pH decreases to a minimum determined by the environment, exchangeable cations are removed, and simpler clay minerals replace the more complex ones.

SOILS ON LIMESTONES

Red soils associated with limestones are a common feature in many places. Such soils vary in character from strongly podzolized red soils to true laterites and from strongly acid soils to those high in free calcium carbonate (Baldwin and others, 1938, p. 991). Silica-alumina ratios vary from considerably more than two to much less than one. These red soils have been termed "terra rossa."

Red soils associated with limestones occur on a number of islands in the Pacific Ocean, on Jamaica and Hispaniola in the West Indies, and on islands in the Bahama group. Many of these islands have a central core of volcanic rocks that is flanked by limestone, but some, such as the Bahamas and Miyako and Aguiguan in the Pacific, do not.

Many of the limestones associated with terra rossa deposits of soillike and bauxitic material contain small quantities of volcanic-ash minerals and clay minerals derived from the weathering of volcanic rocks. These impurities are released as a residual deposit if the limestone is removed by solution during weathering. As most of the limestones are relatively pure, however, insoluble material apparently is insufficient to form thick deposits. It seems, therefore, that soil material of similar composition has been added from outside sources. Mineralogical examination of the limestones and the bauxitic soils of Jamaica by Hartman (1955) has shown that both limestones and soils contain the same suite of minerals. The aluminous lateritic soil of the Dominican Republic contains accessory minerals that are characteristic of volcanic material (Goldich and Bergquist, 1947, p. 77). These soils are derived wholly or in part from the solution of limestone.

The terra rossa type of bauxites are well known in southern France, Italy, Greece, Yugoslavia, and elsewhere (De Weisse, 1948; Harder, 1949). Similar types of bauxite deposits associated with limestone occur in the Valley and Ridge province of the southeastern United States.

The chemical composition of these bauxitic soils from different localities is rather similar. Marshall (1930) described red soils on the karstlike irregular surface of the makatea on Atiu Island, and similar soils are found on Mangaia Island. Analyses given below show typical features in a low percentage of silica and high percentages of alumina and ferric oxide.

	Taunganui, Atiu Island (percent)	*Mangaia Island (percent)*
SiO_2	9.80	8.84
Al_2O_3	23.85	19.70
Fe_2O_3	25.13	31.71
CaO	2.75	1.60
TiO_2	5.42	5.10
P_2O_5	2.55	2.48
Ignition loss	30.60	30.80
	100.10	100.23

The formation of bauxite from clay and argillaceous terra rossa is shown by the following analyses (in percent) from Zans (paper presented at the Internat. Geol. Cong., 20th, Mexico City 1957).

	1	2	3	4	5
SiO_2	55.6	5.0	11.4	1.4	0.4–3.5
Al_2O_3	12.2	45.3	46.4	49.2	46.4–50.3
Fe_2O_3	6.1	19.7	19.3	17.8	17.5–22.8
TiO_2	1.0	1.9	2.3	1.7	2.4–2.6
H_2O	9.0	23.4	19.5	24.1	26.0–27.0

NOTE.—Minor elements are omitted.

1. Clay.
2. Bauxitic terra rossa or low-grade bauxite.
3. Bauxitic terra rossa or low-grade bauxite, about 1,000 ft above sea level.
4. Red bauxite, about 700 ft above sea level.
5. Red bauxite, average of commercial bauxite of Jamaica from higher limestone plateaus.

In discussing the origin of the bauxite of Jamaica, Zans points out the importance of the drainage through the limestone, and the height above the water table.

The aluminous lateritic soil in the Aceitillar area, Dominican Republic, analyzed by Goldich and Bergquist (1947, p. 65) has the following composition (average of 10 samples): SiO_2, 2.45; Al_2O_3, 47.61; Fe_2O_3, 19.86; TiO_2, 2.64; loss on ignition, 25.8 percent.

The principal mineral of the bauxite of the Dominican Republic is gibbsite, as it is in the bauxite of Jamaica and in the Guam clay on limestone. Boehmite and kaolinite are also present. Hematite is the chief iron mineral, but a little goethite is also present (Goldich and Bergquist, 1947, p. 68–69). The accessory minerals are quartz, zircon, and magnetite or ilmenite, and these accessories are similar to those in the aluminous lateritic soil from Haiti and from Jamaica. In another area (Bucan Polo) the silica content of these soils is higher and normative kaolinite or halloysite, ranging from 18 to 27 percent, has been calculated (p. 71). Although not completely identified, it is suggested that this clay mineral is halloysite.

Kaolinite and halloysite are the principal clay minerals in the Jamaica bauxite, according to Hill (1955, p. 680). Similarity between the mineralogy of the acid insoluble residue in the White Limestone and the bauxite suggests (p. 684) that this limestone is the immediate source of the bauxite even though this residue amounts to only one-half of 1 percent of the rock. The constituents in this residue are Al_2O_3, Fe_2O_3, SiO_2, TiO_2, and P_2O_5. Hartman (1955), from his study of the insoluble residues of limestone and bauxite, is of the same opinion as to its origin.

Soils considered to be terra rossa have recently been studied in Israel (Barshad and others, 1956) and in Australia (Norrish and Rogers, 1956; Stace, 1956; and McIntyre, 1956). The clay content of these soils is high (average of 5 samples is 47.6 percent, Stace, 1956, p. 292) and the clay minerals are the same as those in the underlying limestone, although montmorillonite, where present, has been replaced by kaolinite and (or) vermiculite (Norrish and Rogers, 1956, p. 296). Free iron oxide is a major constituent of these soils, as it is of the Guam clay. It causes aggregation of the grains, thereby increasing the porosity and the passage of water through the soil material. This effect is not completely understood (McIntyre, 1956, p. 304). The aggregation may be due to iron oxide alone or to an iron-organic matter complex binding the particles together. Apparently organic matter is quickly broken down in this type of soil, and organic compounds are added to the soil solution.

In summary, the Guam clay, a red soil associated with the Barrigada and the Mariana Limestones, is similar to some other red soils occurring in comparable geologic environments. Chemically and mineralogically it resembles the bauxites of Jamaica, the aluminous laterites of the Dominican Republic, and the red soils of Atiu and Mangaia Islands in the Pacific Ocean.

Several different kinds of soil are associated with different kinds of limestone on Guam. Some, such as the Agana Argillaceous Member of the Mariana Limestone, contain large quantities of clay derived from the weathering of volcanic rocks. In the rather pure Mariana Limestone, however, there are only very small quantities of clay minerals and of volcanic-rock minerals. Leaching of both types of minerals by surface waters at pH values a little below pH 7 removes silica preferentially to alumina, particularly from the clay minerals. Gibbsite therefore forms if the drainage is sufficiently good to transport silica away from altering clay minerals (largely halloysite). The iron oxide originally attached to the halloysite particles also accumulates because it cannot go into solution at neutral to slightly alkaline pH values. Gibbsite forms only very slowly in the relatively impermeable soils associated with the argillaceous limestones. The clay mineral in these limestones is also halloysite. The argillaceous limestones weather in a similar manner to the volcanic rocks. A saprolite forms first, and then in its upper surface a soil develops. The amount of gibbsite in the soil on argillaceous limestone is comparable in amount to that in the soils formed from volcanic-rock materials.

CONCLUSIONS

The data from the mineralogical and chemical investigation of selected soil profiles on the volcanic rocks and on the limestones of Guam show that two distinct kinds of soils are associated with these rocks. The Atate clay on the volcanic rocks consists principally of halloysite, iron oxides, and a little gibbsite. The most widespread soil on the Mariana limestone, the Guam clay, consists principally of gibbsite, iron oxides, and a little boehmite and halloysite. The Guam clay is similar mineralogically and chemically to the terra rossa type of bauxite found in Jamaica.

The principal process of formation of both types of soil is the removal of silica by percolating waters. This is a lateritic type of weathering. Silica in the volcanic rocks is present in plagioclase feldspars, zeolites, glass, and pyroxenes. These minerals are all weatherable, and consequently the volcanic rocks are weathered to considerable depths (more than 50 ft in places). Comparison of chemical analyses of fresh rocks and of saprolite many feet below the surface shows that silica has been removed. The average pH of the Atate clay is 5.3; the pH is lower at depth. Silica goes into solution at all pH values, but alumina and iron do not. They accumulate in the weathering rocks and soils.

The first mineralogical changes in the weathering of the volcanic rocks are feldspars, pyroxenes, glass, and zeolites to montmorillonite. Continued leaching of bases causes the montmorillonite structure to break down, and montmorillonite is replaced by halloysite. Ferric oxide is produced by the oxidation of ferrous iron in pyroxenes; ferric oxide coatings on clay and other mineral particles results. Continued leaching removes silica from halloysite and gibbsite is produced.

Comparison of the mineralogy and chemical composition of the Atate clay on Guam with lateritic soils developed on similar types of rock in other countries shows that various stages of development can be recognized. Sufficient climatic data are not available to assess the leaching factor that is responsible for the development of the Atate clay, but comparison with the lateritic soils (latosols) of the Hawaiian Islands indicates that the Atate soil is similar to the uniform profile soils. The relative accumulations of Al_2O_3, Fe_2O_3, and TiO_2 occur in both types. The volcanic rocks of Guam, however, contain somewhat more silica, and less iron and titania than the Hawaiian basaltic rocks. The rocks of Guam are more andesitic in character.

The presence of gibbsite in the red soils (Guam clay) associated with the Mariana Limestone is considered to be due to the removal of silica from clay minerals, such as halloysite and montmorillonite, by leaching with water at almost neutral pH. The average pH of these soils is 7.4. Ferric oxide, alumina, and titania are insoluble at this pH.

The insoluble residues of the limestones vary in quantity and in mineralogy. In some limestones the residue consists of volcanic minerals, such as augite, hypersthene, magnetite, feldspars, and zeolites. These minerals seem to come from volcanic ash falls over the area in which calcium carbonate was being deposited. In other limestone beds clay minerals and iron oxides were deposited. These minerals came from the erosion of a land surface and were transported to the area of carbonate deposition. This material is similar to that in the deeply weathered volcanic rocks on Guam.

The volcanic minerals in these limestone remain unaltered until calcium carbonate is removed by solution. Alteration of glass and zeolites to clay minerals takes place if calcium carbonate is removed. The grain size of the Guam clay is coarser than that of the Atate clay, and the sand fractions contain volcanic minerals and some composite unweathered rock fragments. Mineralogical examination of a limestone soil on Mount Lamlam shows that the original detrital volcanic minerals alter first to montmorillonite. Silica is then removed and gibbsite forms without an intermediate halloysite stage. This suggests that, although the amount of fresh detritus in the Mariana Limestone is generally small, it contributes to the gibbsite present in the Guam clay. The scattered distribution of the detrital minerals in the limestone enhances their chances of rapid change to montmorillonite and then to gibbsite. In the argillaceous limestones, on the other hand, the clay minerals form thick beds that are less permeable to water, and the alteration proceeds slowly, as in the Atate clay associated with the volcanic rocks. The Asan clay on the Agana Argillaceous Member of the Mariana Limestone is an example of this type of development.

The small quantity of detrital material, both fresh volcanic minerals and clay minerals, makes it difficult to explain the amount of red soil that is associated with the Mariana Limestone. It is probable that soil material from the weathered volcanic rocks on Guam has been deposited on the surface of the northern limestone plateau. This material together with that in the limestones has been leached in a porous near-neutral environment to produce the red gibbsitic deposits. The fact that the titania content of these soils and of bauxites on limestones from many widely separated areas is about 2 percent indicates that the processes operating on residual material in the limestones, or associated with the limestones, must be similar, and that the material has a narrow range of composition. The composition may be characteristic of an "average clay."

The following schematic sequence of events is suggested as an explanation of clay mineral development in the soils associated with limestones:

Detrital volcanic minerals ⟶ montmorillonite ⟶ gibbsite ⟶ boehmite
Incorporated soil minerals ⟶ halloysite ⟶ gibbsite ⟶ boehmite

The change from gibbsite ($3H_2O$) to boehmite (H_2O) is thought to be due to the periodic desiccation of these soils, as drainage is rapid even after heavy falls of rain.

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DESCRIPTION OF SOIL PROFILES [1]

By Carl H. Stensland

SOILS OF VOLCANIC ROCKS

Profile S54–4. *Atate clay, on Alutom Formation*

Location.—About 1 mile southwest of ComNavMar headquarters (lat 13° 27′ 21″ N., long 144°42′18″ E.), at a point near south-center of a fairly large mesita, about 500 ft northeast of junction of El Patio Road with Spruance Drive.

Topography.—Upland flat (alt about 390 ft) rising 10 to 50 ft above surrounding terrain, about half an acre in area. Surface gradient across sampling area is about 1 percent.

Vegetation.—Sword grass (*Miscanthus floridulus*) and scattered clumps of *Casuarina equisetifolia;* some *Dimeria* and other grasses and small shrubs.

Sample	*Depth*	*Description*
S54–4–1	0–6 in.	Dark-reddish-brown (5YR 3/3 [2] dry, to 2/4 moist) clay; strong fine granular to medium granular in upper half-inch of soil and medium granular below (granules are hard when dry, and water-stable); friable to firm and only slightly sticky; moderate plasticity; pH 6.0.[3]
4–2	6–20 in.	Dark-reddish-brown (4YR 3/4 dry, 2.5YR 2/4 moist) clay; structure and consistency same as sample 4–1; contains roots and rootlet channels; pH 5.7. The lowest 4 in. is gradational to the horizon below and was omitted from the sampling.
4–3	20–30 in.	Dark-reddish-brown (2.5YR 3/4, moist) clay, similar to sample 4–2 in structure; pH 6.0 to 6.5. Grades into underlying horizon.
4–4	30–51 in.	Dark-red (2.5YR 3/6, moist) clay; contains yellowish-red spots (5YR 5/6) that increase in number and size with depth; firm, with a few pinholes and small fractures, but less porous than upper horizons; pH about 6.
4–5	51–60 in.	Red to reddish yellow (2.5YR 4/6 to 5YR 6/6 moist) clay; less firm and more friable than upper horizons; pH 5.5 to 6.0.
S54–4–6	11.0–11.5 ft	Varicolored soft porous clay, predominantly pinkish-white, with yellowish brown staining (the inside of each particle is mostly white, and the outside coating is pinkish); contains a few small hard vitreous granules; pH 5.0.
4–7	12.5–13.0 ft	White to pale-yellow clay; soft porous coarse granular pyroclastic material (volcanic agglomerate and tuff), weathered to clay with bedding and structure preserved (saprolite); contains much red and pale-red material with bluish, greenish, and yellowish brown staining, the latter accumulated in individual particles in some places; pH less than 5.0. (Samples 4–6 and 4–7 were collected from one side of the scarp surrounding the mesita.)

Profile S54–5. *Atate clay, on Alutom Formation*

Location.—About 2 miles northwest of center of Yona village (lat 13°25′20″ N., long 144°44′49″ E.), on highest small mesita 300 ft northwest of jeep road to dismantled radio station, 2,500 ft southwest of station site.

Topography.—Small upland flat (alt about 450 ft) with slightly convex surface sloping northwestward at about 3 to 5 percent gradient; bounded by scarps 10 to 30 ft above the surrounding terrain.

Vegetation.—*Miscanthus floridulus* and scattered *Casuarina equisetifolia.*

Sample	*Depth*	*Description*
S54–5–1	0–6 in.	Dark-reddish-brown (5YR 3/3, dry) clay; very fine grained, subangular blocky; very hard; noncalcareous; some "bauxitic" concretions (rounded to angular, pitted, pinkish-white fragments, 2 to 10 mm diameter) and some fine egg-shaped black pellets (iron, manganese or both, less than 1 mm diameter), and a few very fine threads or fibers of a glassy mineral; porous; many small roots; pH 5.5 to 6.0. The lowest 3 in. is irregularly transitional to the horizon below.
5–2	6–18 in.	Red (10R 5/6 to 2.5YR 3/5, dry) clay; moderately fine, blocky; firm; slightly sticky; contains some irregularly pitted concretions (1 to 10 mm) of a whitish mineral that becomes more abundant in the lower part of this horizon; contains a few small pinholes and root hairs; pH 5.0.

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[1] The field positions of the profiles are shown on figure 3.

[2] Color according to the Munsell Soil Color Chart, Munsell Color Co., Inc. (1954).

[3] All pH values in these descriptions were determined in the field.

Profile S54-5—Continued

Sample	*Depth*	*Description*
S54-5-3	18–53 in.	Similar to overlying horizon, but whitish concretions comprise as much as 5 percent of volume.
5-4	53–60+ in.	Red (10R 3/6, dry) moderately fine clay; finely mottled with light gray and bright yellow; very few concretions; fine tubes numerous; pH 5.0.
5-5	10. 0–10. 5 ft	Red (7.5R 4/6, dry) clay; strong, fine subangular blocky to coarse granular or nutty; hard; plastic; sticky; porous, with numerous cracks and fractures; contains a few distinct fine white mottles; pH 4.5 to 5.0.
5-6	28. 5–29. 0 ft	Soft highly weathered tuff; white in a 2-mm layer bordering joints or fractures, and reddish-yellow (7.5YR 7/6, dry) clay; each fracture zone is coated with weak-red (10R 4/4, dry) material. The weathered tuff breaks readily into angular blocks, but is very hard when dry; pH 4.5 to 5.0. The underlying rock is tilted bedded fine- to coarse-grained "sandy" tuff, weathered to clay to depths of 50 ft or more. It is stained red almost throughout to depths of 6 to 10 ft and is red in bands along bedding planes and fractures to depths of 20 to 30 ft. (Samples 5-1 to 5-4 were collected from a 5-ft test trench; samples 5-5 and 5-6 were collected from a scarp of the mesita.)

Profile S54-6. *Atate clay, on Bolanos Pyroclastic Member of the Umatac Formation*

Location.—About 2.85 miles south of center of Talofofo village (lat 13°18′38″ N., long 144°44′45″ E.), and about 1 mile west of paved highway (Yona to Inarajan), along north side of road through Martinez pasture, 100 yd east of concrete house on high gently sloping ridge.

Topography.—Narrow upland flat or mesita (alt about 330 ft) with about 4 percent eastward slope; nearly vertical scarps rise 10 to 25 ft above erosion-scarred terrain immediately adjacent to the mesita.

Vegetation.—Chiefly *Dimeria* in soft-tufted small clumps, and clumps of *Lemonchina* and *Pandanus*.

Profile S54-6—Continued

Sample	*Depth*	*Description*
S54-6-1	0–2 in.	Dark-reddish-brown (5YR 3/3, dry) clay; strong fine granular to coarse subangular blocky; hard; porous; some limonite pellets and subangular concretions (1 to 8 mm diameter); numerous small roots and few larger ones; pH 6.0.
6-2	2–10 in.	Dark-reddish-brown (5YR 3/4, dry) clay; coarse subangular blocky; hard; slightly to moderately plastic; numerous fine (<0.5 mm diameter) grains of magnetite and some pellets of limonite (2 to 3 mm diameter); a few small (0.5 to 5.0 mm diameter) pitted concretions of a whitish mineral; porous; numerous pinholes and small joints; small roots; pH 5.5.
6-3	10–16 in.	Mixed dark-reddish-brown and dark-red clay, gradational to horizon below.
6-4	16–32 in.	Dark-red (2.5YR 3/6, dry) clay; very firm; plastic; hard when dry; numerous small joints or fracture faces; several small soft rounded grains of white light-gray and pale-yellow clayey material; some hard pitted whitish concretions; numerous small black hard grains or crystals of magnetite, and some soft grains, probably manganese; pH 5.0.
6-5	32–46 in.	Dark-red (2.5YR 3/6, moist) to red (2.5YR 4/6, moist) clay; firm; slightly plastic; porous; similar to overlying horizon, black grains less numerous; whitish concretions as much as 10 mm diameter; pH 5.0.
6-6	46–60 in.	Faintly banded (1 to 2 in. width) red and dark-red clay; moderately firm to slightly friable; few small black grains in dark-red parts; few small soft white, pale-yellow, and light-yellowish-brown grains throughout; soft ped faces have glistening soapy appearance; porous; few small root hairs; pH 5.0.

Profile S54-6—Continued

Sample	*Depth*	*Description*
S54-6-7	13.5-14.5 ft	Red (7.5R 4/6, dry) clay; some original tuff structure preserved; distinct layers of light-red (7.5R 6/6, dry) clay common; white grains numerous throughout, concentrated in some layers giving banded appearance; pH 4.5.

The underlying material is fine- to coarse-grained "sandy" tuff and agglomerate, mostly weathered to clay to a depth of 65 ft.

(Samples 6-1 to 6-6 were collected from a 5-ft test trench; sample 6-7 was collected from the scarp below the trench.)

Profile S54-10. *Atate clay, on Bolanos Pyroclastic Member of the Umatac Formation*

Location.—About 4 miles northwest of Talofofo Bay (lat 13°17′10″ N., long 144°44′19″ E.) and about 0.8 mile northwest of the village of Inarajan, on a mesita about one-third mile southeast of the Inarajan water-point, 700 ft south of the road leading to the water-point from Inarajan village.

Topography.—Upland flat or mesita (alt 270 ft) about 5 ft higher than the eroded terrain immediately adjacent; mesita surface slopes at about 4 percent in a north-northwest direction.

Vegetation.—Thick stand of *Miscanthus floridulus* and some *Stachytorpheta indica*.

Sample	*Depth*	*Description*
S54-10-1	0-3 in.	Dark-reddish-brown (5YR 3/3, dry) clay; granular to subangular blocky; slightly friable; hard; dark coloring largely due to organic matter; contains many roots; pH 5.5 to 6.0.
10-2	3-15 in.	Dark-red (2.5YR 3/6, dry) clay; medium-subangular blocky; very hard; contains many roots and some animal burrows as large as 5 mm diameter; pH 5.0.
10-3	15-28 in.	Red (10R 4/8, dry; 2.5YR 4/8, moist) clay of soft lapilli basalt or pyroclastic weathered material; slightly hard; slightly friable; contains many faint to prominent mottles that vary in color from dark red (2.5YR 3/6, dry) to yellow (10YR 8/6 dry, to 7/8 dry) with some light gray; slightly plastic; pH 5.0.
S54-10-4	28-60+ in.	Dark-red (10YR 3/6, moist) clay, with some of the original rock structure preserved or visible in outline; weak medium-subangular blocky to massive; friable; slightly plastic; contains some soft zeolitic(?) material and iron oxide staining; pH 5.0 to 5.5.
10-5	11.3-12.3 ft	Red (2.5YR 4/6, dry) tuffaceous agglomerate, now weathered to clay; soft; slightly plastic; sticky; contains many medium-sized white, purple, and blue mottles; material expands appreciably when wetted; pH 5.0. (Samples 10-1 to 10-4 were collected from a 5-ft test trench; sample 10-5 was collected from eroded scarp below trench).

Profile S54-12. *Atate clay, on Facpi Volcanic Member of Umatac Formation.*

Location.—About 2.5 miles south of center of Agat village (lat 13°21′4″ N., long 144°39′0″ E.), on first high mesita about 100 yards south of the area known as "Agat dump."

Topography.—A narrow mesita (alt about 480 ft) with nearly vertical erosional escarpment on three sides rising to 15 to 65 ft above severely erroded terrain immediately adjacent; the surface at the sampling site slopes westward at about 3 percent gradient.

Vegetation.—Scattered clumps of *Miscanthus floridulus* and *Dimeria*, with *Casuarina equisetifolia*, *Glochidion* sp., *Phyllanthus simplex*, *Myrtella benningsenniana*, *Gleichenia linearis*, and a grass (*Cladium* sp.?).

Sample	*Depth*	*Description*
S54-12-1	0-6 in.	Dark-reddish-brown (5YR 3/4, dry) clay; granular; hard; porous; numerous roots; contains some small white grains or crystals, and some small soft black concretions, mostly all less than 1 mm diameter; pH 5.5 to 6.0.
12-2	6-13 in.	Reddish-brown (2.5YR 4/4, moist) clay; strong granular to subangular blocky; firm to friable; several cracks, fractures, and pinholes (1 to 2 mm diameter) contributing to porous condition; some soft black concretions (<1 mm diameter); pH 5.5 to 6.0.

Profile S54–12—Continued

Sample	*Depth*	*Description*
S54–12–3	13–40 in.	Dark-reddish-brown (2.5YR 5/4, moist) clay; firm to friable; slightly plastic; porous; numerous fractures, pores and larger holes made by worms or roots; soft, powdery black film or coatings on 20 to 30 percent of the peds, fracture faces, and inside holes (this condition is more pronounced in the lower part); pH 6.5.
12–4	40–48+ in.	Dark-red (2.5YR 3/5, moist) clay; moderately strong granular; friable; contains numerous small (<1 mm diameter) pinholes or pores; some grains or aggregates of grains are light gray, pale yellow, and yellowish red; small black flecks (<0.5 mm diameter) and black coatings on some grains and in some pores; a few root holes or channels (2 to 3 mm diameter); pH 6.5.
12–5	9. 0–10. 0 ft	Weak-red (10R 5/4, dry) clay with pillow basalt structure preserved; contains many faint fine mottles of various shades of purple, red, yellow, and brown; soft to slightly hard when dry; sticky and slightly plastic when wet; porous; pH 5.0.
12–8	22.5–23.0 ft	Pillow basalt weathered to clay; the overall color of the clayey matrix is pale red, with spots, splotches, coatings, and veins of dusky red, purple, brown, yellow, and black; blocky; soft when dry; sticky and plastic when wet; porous; pH 4.5 to 5.0. Underlying material is saprolitic pillow basalt weathered to a depth of 75 ft or more. Outlines of pillows are visible in the saprolite of the mesita escarpment downward from about 8 to 10 ft below the top of the mesita. (Samples 12–1 to 12–4 were collected from a 5-ft test trench; samples 12–5 and 12–8 were collected from the side of the mesita scarp.)

Profile S54–20. *Atate clay, on Alutom Formation*

Location—About 0.7 mile northwest of Yigo Baptist Church (lat 13°32′39″ N., long 144°52′47″ E.). The site is found by traveling a quarter of a mile north along the Yigo-Anderson Air Force Base paved highway, turning left onto jeep trail for about 0.65 mile to a point 100 ft west of east end of crest of Mount Mataguac.

Topography—Gently rounded ridge crest (alt about 750 ft) with a gradient of 2 to 8 percent, about 50 to 60 ft above lowest adjacent terrain.

Vegetation—Scattered coconut, Chinese inkberry, *Hibiscus tileaceous, Leucaena glauca, Hyptis pectinata, Penesetum polystachium,* fern, and numerous weeds, grasses, vines, and shrubs.

Profile S54–20—Continued

Sample	*Depth*	*Description*
S54–20–1	0–4 in.	Dark-reddish-brown (5YR 3/2, dry) clay; some granular structure, but mostly fine to coarse subangular blocky; hard when dry; friable when moist; slightly to moderately plastic when wet; contains numerous roots and is somewhat porous because of root penetration; soil cracks when dry, cracks being 2 to 8 mm wide and penetrating to depths of 30 to 36 in. (Pieces of limestone ranging from 1 to 10 in. in diameter have probably been carried there by man); pH about 7.0.
20–2	4–16 in.	Red (2.5YR 4/6) clay; fine to coarse subangular blocky; moderately firm and very plastic; dark-reddish-brown staining on soil peds and fracture faces; vertical cracks, worm holes, and root channels show fillings of soil from surface horizon (earth worms are more numerous than in most soils sampled on Guam). The soil is fairly fine and compact between the holes, cracks, and crevices, but has small pinholes; pH 6.0.
20–3	16–36 in.	Red (10R 4/6, moist) clay, with increasing amounts of weak-red (7.5R 5/4, moist) and pale-red (10R 6/2, moist), and light-gray saprolitic tuff; subangular blocks ranging from 0.5 to 3 in. in diameter; moderately firm; very plastic; numerous pinholes and fractures, some with yellowish-brown and light-gray staining; many fine joints in the tuff filled with paper-thin red staining; some pink (5YR 7/3, moist) tuff near base of horizon; finely porous; pH 5.0. The underlying material consists of water-laid volcanic ash and basaltic pyroclastics, now almost completely weathered to a depth of more than 50 ft.

Profile S54–21. *Atate clay, on Alutom Formation*

Location.—About 1.5 miles east-northeast of Yigo village (lat 13°32′22″ N., long 144°52′49″ E.), 0.82 mile north of intersection of Yigo road with new blacktop (BPM) highway, and about 550 ft east-southeast of the highway, on a mesita on the western slope of Mount Santa Rosa.

Topography.—Gently concave narrow upland ridge crest (alt about 630 ft) with steep erosional scarps on 3 sides; slope of surface N. 55° W. at prevailing gradient of 6 to 7 percent; local relief about 25 to 50 ft.

Vegetation.—*Miscanthus floridulus, Scaevola frutescens, Hyptis pectinata,* a small sedge, a low creeping grass.

Profile S54–21—Continued

Sample	*Depth*	*Description*
S54–21–1	0–16 in.	Dark-reddish-brown (5YR 3/4, dry) clay; very fine to fine granular structure; hard; friable; slightly plastic; porous, with cracks, worm and root holes; roots and root hairs numerous; some pieces (floaters) of hard to soft light-yellowish brown (2.5YR 6/4, dry) weathered clayey tuff (0.25 to 1 in. diameter), with greenish and reddish-brown phenocrysts; a few small (<1 mm diameter) soft black concretions; pH 6.0.
21–2	16–36 in.	Red (2.5YR 4/6, moist) clay; medium-subangular blocky; firm; plastic; numerous pinholes or small root channels; some red (7.5R) and weak-red to pale-red soft tuff in the lowest 2 in.; pH 5.5.
21–3	36–66 in.	Consists of about equal parts red clay as above and soft weak-red, pale-red, pink to pale-yellow grains of tuff weathered to clay; massive to columnar jointed; hard to firm when dry, friable when moist; feels somewhat "greasy" and "sandy," but grittiness is probably due to powdery manganese concretionary or joint-filling material; pH 5.0.
21–4	8. 0–9. 0 ft	Saprolitic tuff; fine to coarse granular to massive; firm to friable; slightly plastic; chiefly bright red, yellowish brown, yellow and black; pH 5.0.

Underlying material is massive fine- to coarse-grained tuff weathered to clay to a depth of 50 ft or more, but with original texture and structure preserved up to the soil solum. (Samples were collected from a trench, 1 by 1½ by 10 ft, cut vertically down the scarp face from the surface of the mesita.)

Profile S54–23. *Asan clay, on Alutom Formation*

Location.—About 1 mile southwest of ComNavMar Headquarters Command building (lat 13°26′54″ N., long 144°42′57″ E.), along north side of pipeline road, about 1,500 ft east of its intersection with the Mount Tenjo road, 0.8 mile south of Spruance Drive.

Topography.—Convex ridge top (alt about 540 ft) of low to intermediate height in gently sloping to rolling terrain; surface gradient about 3 percent at point of sampling.

Vegetation.—*Miscanthus floridulus.*

Sample	*Depth*	*Description*
S54–23–1	0– 8 in.	Dark-grayish-brown (10YR 4/2.2, dry) clay; coarse granular to coarse subangular blocky; hard when dry; contains pale-yellow spots (<1 mm diameter), and has numerous soft reddish-yellow to yellowish-brown (7.5YR 6/8, dry) stained lapilli or concretions (4 to 15 mm diameter); pH 5.5 to 6.0. Changes abruptly to horizon below.
23–2	8–36 in.	Pale-yellow (5Y 7/4, dry) to pale-olive (5Y 6/4) and greenish clay, with dark-red (2.5YR 3/6, dry) and dark-reddish-brown thin coatings or staining on some fracture faces. The different shades of yellow clay seem to be alteration patches in the greenish or olive matrix; coarse subangular blocky to massive; some small lapilli or pellets of pink or weak-red clay in the olive matrix, and some very dark-gray lapilli (¼ in. diameter) with small pale-yellow inclusions; coatings or film of dark-red on some fracture faces and some red has penetrated into the soft interior of angular pieces broken during excavation; hard when dry; pH 5.5 to 6.0. The underlying material is a massive lapilli pyroclastic rock, now a saprolite to a depth of 30 ft or more. (Samples were collected from a 2- by 3-ft channel cut back in roadcut.)

SOILS ON LIMESTONE

Profile S54–16. *Guam clay, red latosol, on Barrigada Limestone*

Location.—About 1.75 miles southwest of Northwest Airfield (lat 13°35′05″ N., long 144°51′15″ E.), about half a mile southwest of Potts Junction, and 0.1 mile northwest of paved road which runs southwest to the Naval Communications Station area.

Topography.—Long narrow shallow depressed area (alt about 500 ft) in undulating limestone plateau; prevailing surface gradient less than 3 percent at sampling site.

Vegetation.—Coconut, papaya, *Pasiflora foetida*, *Artocarpus* sp., Chinese inkberry (*Cestrum diurnum*), and a fern.

Sample	*Depth*	*Description*
S54–16–1	0–60 in.	Dusky-red (10R 3/3, moist) clay; surface soil is loose, medium to coarse granular; weak to moderate subangular structure; somewhat plastic and sticky when wet; porous, dries out rapidly after heavy rain. Contains a few limestone floaters; pH 6.5 to 7.0. The soil is 31 ft deep where sampled, and represents a soil-filled limestone-fissure condition that is somewhat common in areas of Guam clay. The underlying bedrock is exposed within 50 ft of the sampling site. Sample S54–16–2 is white hard porous limestone that is the presumed parent material of the soil.)

Profile S54–17. *Guam clay, on Mariana Limestone, detrital facies*

Location.—About 5 miles east-southeast of Agana (lat 13°27′46″ N., long 144°49′44″ E.), and 1.55 miles N. 15° E. of Fadian Point, on the central east coast of Guam.

Topography.—Flat to microundulating relief (alt about 320 ft), near edge of small shallow limestone sink; slope is less than 3 percent at sampling site.

Vegetation.—*Hibiscus tiliaceous*, *Artocarpus* sp., *Cestrum diurnum*, *Penisetum polystachium*, *Leucaena glauca*, pandanus

Sample	*Depth*	*Description*
S54–17–1	0–3 in.	Dark-reddish-brown (2.5YR 3/4, dry) clay; moderate medium to coarse granular; soft to slightly hard when dry; friable when moist; sticky and plastic when wet; contains numerous roots; pH 7.0 to 8.0.
17–2	3–24 in.	Dusky-red (10R 3/3, dry) clay; weak medium-subangular blocky structure; friable when moist; porous; numerous earthworm burrows; 1 coral fragment (4 in. diameter) at 10 in. depth; pH 8.0. (Sample S54–17–3 is quarry-run Mariana Limestone, Dean Bros. quarry, Tamuning; white, very porous hard lagoonal limestone is presumed parent material of soil.)

Profile S54–18. *Guam clay, on Mariana Limestone, molluscan facies*

Location.—Two miles west of the southern end of Anderson Air Force base (lat 13°31′39″ N., long 144°52′47″ E.), half a mile south of the center of Agafa Gumas camp area, near edge of shallow limestone sink-basin, 25 ft north of jeep road, at south edge of small farm clearing.

Topography.—Undulating upland plateau (alt about 500 ft); range of surface gradient 1 to 8 percent, but about 3 percent at sampling site.

Vegetation.—Pandanus, scattered ifilwood, banyan, and other trees, a few cycads, morning glory, and weeds.

Sample	*Depth*	*Description*
S54–18–1	0–1 in.	Dark-red (2.5YR 3/6, dry) clay; very fine to coarse granular; hard when dry; friable when moist; some very dark-gray to black coatings on many of the peds or granules; porous; contains some root fibers; pH 7.5.
18–2	1–15 in.	Dark-red (2.5YR 3/6, dry) clay; very fine granular friable; porous; contains a few roots; and some small powdery, white limestone particles; pH 7.0. Rest on limestone surface. (Sample S54–18–3, extending from 15 in. to unknown depth, is white (10YR 8/2, dry) limestone containing many large molluscan fossils; porous, especially in cavities or cracks between the fossils; some weak-red to light-reddish-brown soil adhering to the rock surface. This rock is the molluscan facies of the Mariana Limestone.)

Profile S54–19. Guam clay, on Mariana Limestone, reef facies

Location.—At a point 1,600 ft northeast of the northwest corner of Northwest Airfield (lat 13°38′06″ N., long 144°52′05″ E.).

Topography.—Gently sloping limestone plateau (alt about 510 ft); surface gradient about 2 to 3 percent at sampling site.

Vegetation.—Scattered ifilwood, pandanus, and casuarina trees, a few shrubs and some grass and vines.

Sample	*Depth*	*Description*
S54–19–1	0–4 in.	Yellowish-red (5YR 4/6, dry) clay; strong very fine granular; some dark-reddish-brown coatings; soft; friable; porous; contains some pieces of white limestone as much as 8 mm diameter, and some small pieces of charcoal, wood, and plant fibers; pH 7.0.

Profile S54–19—Continued

Sample	*Depth*	*Description*
S54–19–2	4–12 in.	Red (4YR 4/6, dry) clay; very fine granules; soft to moderately hard; friable; contains several pieces of pitted white limestone (<0.5 to 50 mm diameter); some roots; pH 8.0. (Sample S54–19–3, from 12 to more than 20 in., is hard white dense to porous limestone with some white powdery material on newly broken faces; some small irregularly shaped cavities as much as 0.5-in. diameter.)

Profile S54–24. *Fossil latosol, on Alifan Limestone, overlain by 5 ft of the Agana Argillaceous Member of the Mariana Limestone.*

Location.—About 0.6 mile south of Sinajana village (lat 13°26′57″ N., long 144°45′25″ E.), on east roadcut along main paved highway (site is just before first east farm road intersection near top of hill south of the river bridge.)

Topography.—Narrow convex ridge (alt about 150 ft) through which there is a steep highway cut.

Vegetation.—*Leucanea glauca* and lemonchina.

Sample[1]	*Depth*	*Description*
S54–24–1		Red (2.5YR 4/8, dry) clay; columnar blocky; very hard when dry; friable when moist; slightly porous with numerous vertical small fractures and pinholes; one roundish whitish concretion (2 to 3 mm diameter) possibly is chalcedony; numerous small pieces of magnetite or manganese; small slickensides on vertical columnar fracture faces; pH 8.0. A 1-in. band of distinct yellowish-brown clay at base of the red clay, at contact with the underlying Alifan Limestone, a hard dense pinkish-white limestone with fossil cavities (cavities partly filled with fossils or casts), some containing red to reddish-brown soft silt or rust; some limestone appears bedded, and some appears to be in the shape of large "heads" or boulders. The limestone overlying the fossil latosol has a foot or two of soil on it, consisting of 6 to 8 in. of dark-grayish-brown clay over brown to strong brown, firm plastic clay.

Profile S54–1. *Chacha clay, on Agana Argillaceous Member of the Mariana Limestone*

Location.—About 2.5 miles east-southeast of Agana (lat 13°27′51″ N., long 144°48′25″ E.), at a point a quarter of a mile south of the highway, half a mile east of Barrigada village main intersection.

Profile S54–1—Continued

Topography.—Undulating to rolling upland limestone karst topography (alt about 200 ft). Surface gradient is about 3 percent at the sampling site.

Vegetation.—Pasture at edge of fairly large cultivated area; contains weeds, shrubs, vines and scattered scrubby *Leuceana glauca*, and some lemonchina 15 to 18 ft high.

Sample	*Depth*	*Description*
S54–1–1	0–6 in.	Very dark grayish brown (10YR 3/2, dry) clay; subangular blocky, but coarsely granular at surface of soil; plastic when wet; firm when moist; very hard when dry; contains a few small black egg-shaped pellets or concretions of manganese (2 to 3 mm diameter); pH 6.5.
1–2	6–18 in.	Mixed brown (7.5YR 4/4, moist) and strong brown (7.5YR 5/6, moist) clay; angular blocky; moderately plastic when wet; very firm when moist; very hard when dry; contains numerous root hairs and pinholes; coarse roots in upper part. The peds, fracture faces, and root channels are coated with dark-brown (7.5YR 3/2, moist) and reddish-brown (5YR 4/4, moist) clay. Contains many small (<1.0 mm diameter) hard to somewhat soft black to reddish-brown concretions; fairly porous when dry, with many small cracks, fractures, and worm or root holes; pH 5.5.
1–3	18–32 in.	Strong brown (7.5YR 5/6 moist) clay; subangular blocky; firm; plastic; a few root hairs and some old root channels (<1-in. diameter) filled with hard reddish-brown (5YR 4/4) clay; small soft black concretions occur sporadically in upper part of horizon; some roots about 0.25-in. diameter and cracks 0.25-in. wide at the soil surface extend down through this horizon; pH 6.5.
1–4	32–46 in.	Similar to overlying horizon, but with less discoloration on fracture faces; fewer roots; fewer concretions (except in upper part). Rests on rubbly white argillaceous limestone at 40 to 46 in.; pH 8.0, measured 2 in. above limestone. (Sample S54–1–5, from 46 to 52 in., is a rubbly white argillaceous limestone, pitted and angular, soft, powdery, containing numerous cavities partly filled with brown and strong brown clay; some cavities partly filled with limonite coatings.) (Samples collected from a 5-ft test trench.)

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[1] Sample obtained from 3-ft vertical channel in middle of 6-ft soil exposure on roadside cutbank.

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