Geology of Saipan Mariana Islands

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Part 2. Petrology and Soils:

GEOLOGICAL SURVEY PROFESSIONAL PAPER 280-B-D

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Part 2. Petrology and Soils

GEOLOGICAL SURVEY PROFESSIONAL PAPER 280-B-D

Chapter B. Petrology of the Volcanic Rocks
By ROBERT GEORGE SCHMIDT

Chapter C. Petrography of the Limestones
By J. HARLAN JOHNSON

Chapter D. Soils
By RALPH J. McCRACKEN

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GEOLOGY OF SAIPAN, MARIANA ISLANDS

PETROLOGY OF THE VOLCANIC ROCKS

By ROBERT GEORGE SCHMIDT

ABSTRACT

The rocks that comprise the volcanic formations of Saipan are of two principal types: dacites, which are characteristically glassy, and andesites, which are comparatively crystalline. The dacites consist primarily of silicic glass, oligoclase, and silica minerals (quartz, tridymite, cristobalite, chalcedony, and opal). Minor constituents in these rocks are green hornblende, biotite, magnetite, and hematite. The andesites are composed principally of labradorite, hypersthene, augite, and subcalcic augite. Minor but also characteristic constituents of the andesites are quartz, tridymite, cristobalite, anorthoclase, and accessory magnetite, ilmenite, rutile, and apatite. Nine varieties of dacite and andesite are recognized on the basis of chemical composition, mineralogy, and texture. These are dacite, dacite vitrophyre, dacite perlite, hornblende-bearing dacite porphyry, augite-hypersthene andesite, quartz-bearing augite-hypersthene andesite, quartz-bearing augite-hypersthene andesite porphyry, augite andesite, and hypersthene andesite.

Chemically, the volcanic rocks of Saipan are characterized by a high silica and alumina content and a low potash, titanium dioxide, and phosphorus pentoxide content. Quartz is universally present in the norm, attaining as much as 49 percent in the dacites. The andesites are extremely calcic and contain a large excess of lime over alkalies.

The andesites and dacites of Saipan generally are close in composition to volcanic rocks of other islands in the system of arcs extending from Japan to the Palau Islands. Apparently the great bulk of the volcanic rocks in this region belong to a characteristic calc-alkaline suite and form a well-defined petrographic province. The general uniformity of composition of the rocks throughout the province is a reflection of origin under similar geological conditions.

Many features of the andesites and dacites of Saipan, especially the high silica content and peraluminous nature of the dacites, are difficult to reconcile with simple differentiation of a primary basaltic magma. Providing these rocks are related to ancestral basalts, it seems necessary to assume assimilation of important amounts of siliceous and aluminous crustal material to account for their composition. The absence of basalts on Saipan, and the wide compositional gap between the andesites and dacites, may indicate that the andesitic and dacitic magmas originated independently.

Volcanism is a normal accompaniment to the structural development of the island arcs which border the western and northern Pacific Basin, and this suggests that igneous activity and structural evolution of the arcs are interrelated phenomena.

The andesites and dacites of Saipan lie within the western part of the circum-Pacific province in which the characteristic volcanic association is basalt, andesite, dacite, and rhyolite or some combination of these types. This rock kindred is in marked contrast to that of the adjacent intra-Pacific or Pacific Basin province in which the typical rock association is decidedly more alkalic and consists of olivine and picrite basalt and smaller amounts of their differentiation products such as oligoclase andesite and trachyte. Around much of the Pacific margin the transition between the circum-Pacific and intra-Pacific rock provinces seems to be across a relatively narrow zone, and it is this narrow transition zone that has been called the andesite line. The significance of the andesite line, from the standpoint of petrogenesis, is that it marks a combined petrologic, structural, and physiographic boundary separating a continental-type region (the circum-Pacific province) in which rock evolution and rock composition are related to orogeny and the presence of a sialic layer, from an oceanic-type region (the intra-Pacific province) in which rock evolution and rock composition are related to crustal stability and the absence of a sialic layer.

INTRODUCTION

This report presents the results of laboratory studies carried on from 1950 to 1952 as part of a general investigation of the geology of Saipan. Its purpose is to describe the physical and chemical characteristics of the volcanic rocks, to discuss their relationship to rocks of adjoining regions, and to make deductions and suggestions as to their origin.

Laboratory investigation of the volcanic rocks has involved microscopic examination of 350 rock sections, X-ray studies of the groundmass of dacitic flow rocks, and microscopic study of rock-forming minerals. Point-counter analyses (see Chayes, 1949, p. 1–11) were made on sections of chemically analyzed rocks to obtain the volumetric mineral composition of principal rock types and the composition of their groundmass. The average chemical composition of plagioclase feldspar phenocrysts in several varieties of andesite was determined by specific-gravity measurements. Chemical analyses were obtained for 10 samples of volcanic rocks from Saipan, 1 of andesite from Guam, and 5 of basalt from the islands of Alamagan, Pagan, and Agrihan (Agrigan).

Saipan lies about midway between Japan and New Guinea in the western Pacific Ocean (fig. 11). It is one of the larger of the Mariana Islands and is situated near the center of that island chain, about 120 miles

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north of Guam. On the west the Marianas are bounded by the Philippine Sea; the Pacific Ocean proper lies on the east.

The Marianas form a principal link in the system of island arcs that extends southward from the Izu Peninsula of Japan to the southern limit of the Palau Islands, along the east border of the Philippine Sea. The salient features of the Mariana arc are shown in figure 12. The

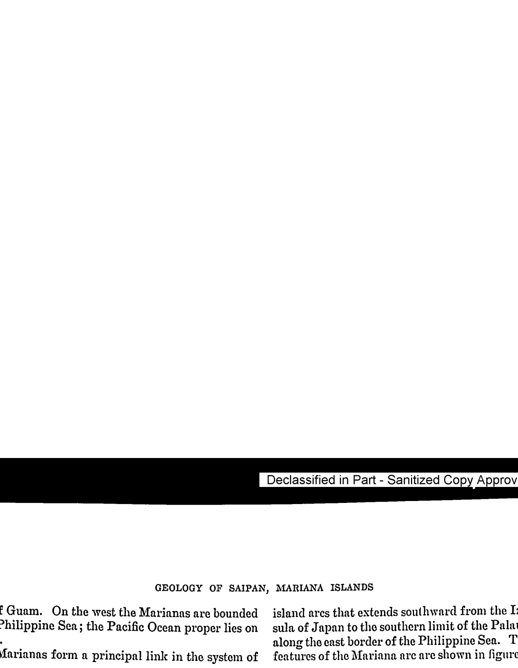

FIGURE 11.—Index map of the western north Pacific Ocean.

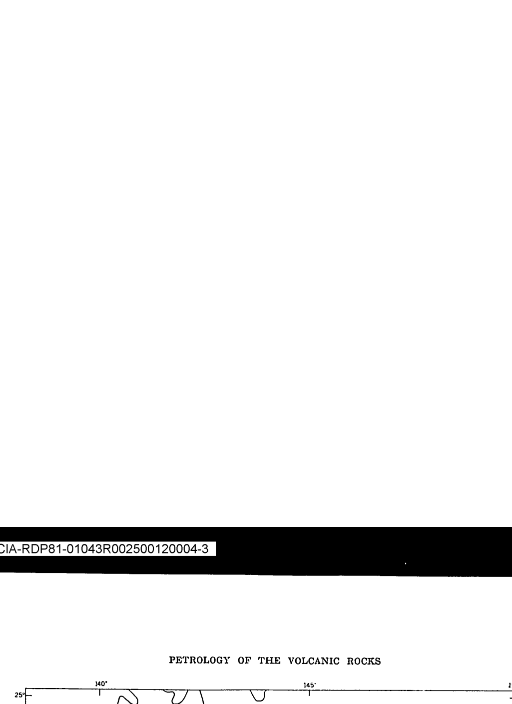

FIGURE 12.—Simplified bathymetric chart of the Mariana arc. After Hess, 1948, p. 427.

islands form a smoothly curving chain 400 miles long on the crest of a generally submerged ridge. Actually the islands are divisible into two separate chains—the southern Marianas, which include Saipan, alined along an eastern arc and consisting primarily of Tertiary volcanic rocks and limestones; and the northern Marianas, forming a western arc of Quaternary volcanoes. On the east the Mariana ridge is bordered by a narrow, arcuate deep, the Mariana trench, which attains a depth of more than 3,500 fathoms throughout most of its length. Volcanic activity has been confined to the west side of the trench along or near the crest of the Mariana ridge. Recent volcanic activity, centered in the northern islands, is concentrated along an inner belt on the back slope of the ridge, about 25 miles inside the line of older, southern islands. There is no indication of volcanic activity in the vicinity of the trench or along its east side. The regional setting and origin of the Mariana arc are discussed in Chapter A, General Geology (Cloud, Schmidt, and Burke, 1956).

The volcanic rocks of Saipan (pl. 2) are grouped in four named formations: the Sankakuyama, Hagman, and Densinyama formations, of late Eocene age, and the Fina-sisu formation, of probable late Oligocene age. These units consist mainly of flows and pyroclastic rocks, the latter including volcanic sediments (conglomerates, sandstones) as well as rocks of a wholly eruptive origin (breccias, tuff breccias, tuffs). The general lithologic nature of the volcanic formations of Saipan is summarized in table 1 and the chart. Detailed descriptions of the formations are given in Chapter A (Cloud, Schmidt, and Burke, 1956).

Throughout the report, individual rock specimens are referred to by their field locality number, consisting of the letter S (for Schmidt) followed by a numeral or numerals (for example, S135). The collection of volcanic rocks from the island of Saipan, upon which the present study is based, is on deposit with the United States National Museum, in Washington, D. C., and bears U. S. National Museum collection number 108982.

PREVIOUS PETROLOGIC INVESTIGATIONS

A summary of previous investigations that relate to the exploration, history, geography, geology, and natural history of the Mariana Islands is contained in Chapter A (Cloud, Schmidt, and Burke, 1956). A more extended account of those investigations that deal with the petrography of the volcanic rocks of the Mariana Islands is given here.

The earliest petrographic investigations of volcanic rocks from the Mariana Islands were made by Kaiser (1903, p. 114–120), who described and published chemical analyses of single hand specimens of augite-hypersthene andesite from Pajaros and augite andesite from Saipan and who also described a specimen of andesitic tuff from Saipan. However, according to Kaiser the augite andesite of Saipan was collected from an ancient and presumably prehistoric ruin at Magpi, in the northern part of the island, and may not have come originally from Saipan. The chemical analysis of this rock is given in table 5 (analysis 4) of this report and does not conform well with recent analyses of volcanic rocks from Saipan.

TABLE 1.—*Volcanic formations of Saipan*

Age	Formation	Character	Maximum outcrop thickness (feet)
Late Oligocene.	Fina-sisu ..	Andesite flow rock and marine andesite tuff	400
Late Eocene .	Densinyama	Impure limestone and calcareous conglomerate, andesitic conglomerate and sandstone, andesitic breccia.	730
Late Eocene .	Hagman .	Andesitic conglomerate and sandstone, andesitic breccia and tuff, andesite flow rock	600
Late Eocene .	Sankakuyama.	Mixed dacitic pyroclastic rocks, dacitic tuff, vitrophyric and perlitic dacite breccia, dacite flow rock.	1,800

Marshall (1912, p. 8–9), Iddings (1913, p. 650–651), and Daly (1916, p. 337) recorded the presence of augite andesite at Pajaros and augite andesite and andesitic tuff at Saipan on the basis of Kaiser's earlier descriptions. However, Iddings' account was worded in a manner such as to give the impression that olivine-bearing hypersthene-augite andesite had been reported from the island of Alamagan, whereas this rock is actually the one described by Kaiser from Pajaros. Daly's highly provocative and informative report still stands as one of the best regional discussions of rock types in the Pacific. However, his tabulation of rock types from the Marianas was also incorrect in that it listed augite andesite from Alamagan on the authority of Iddings and recorded Kaiser's augite andesite from Saipan as an amphibole-bearing augite andesite, although Kaiser (1903, p. 119–120) does not mention the presence of amphibole in the rock.

A suite of rocks from the Marianas was studied and described by Koert and Finckh (1920, p. 10–12), but because the localities given for several of the specimens in this suite appear to be incorrect, this paper loses much of its value. Among these rocks Koert and Finckh described serpentinized peridotite from the islands of Tinian and Agrihan. More recent and more detailed papers by Tayama (1936 b, 1938, 1940) make no mention of serpentinized peridotite on Saipan, Tinian, Aguijan, and Agrihan, and the present writer and his colleagues have been unable to find serpentinized peridotite or rocks of a related nature on Saipan, Tinian, and Guam, or on the islands of Alamagan, Pagan, and Agrihan in the northern Marianas. The reported presence of serpentinized peridotite on Tinian and Agrihan should therefore be regarded as highly questionable.

Von Wolff (1923, p. 161–162) gave a short description of the petrography of the Mariana Islands, based largely on the earlier account by Kaiser, and listed Kaiser's analyses of andesites from Saipan and Pajaros. Tsuboya (1932, p. 208–211) described and published a chemical analysis of a single hand specimen of hypersthene andesite from Saipan.

The Japanese petrographer Yoshii (1936, p. 1–22) described single specimens of quartz dacite, andesite, and andesitic tuff from Saipan and andesitic rocks from Tinian, Rota, Pagan, and Maug. Yoshii (1937) also gave a valuable account of the distribution of volcanic and metamorphic rock types in the western north Pacific. Tanakadate (1940) described the physiography and recent activity of the volcanoes of the northern Mariana Islands and published four analyses of basalts and andesites from the islands of Pagan and Pajaros.

From the foregoing, it is evident that surprisingly little has previously been published regarding the petrography and chemistry of the volcanic rocks of the Mariana Islands. Apart from the present study, detailed petrographic descriptions of volcanic rocks from the Marianas are to be found only in the reports of Kaiser (1903, p. 114–120), Tsuboya (1932, p. 208–211), and Yoshii (1936, p. 6–19).

ACKNOWLEDGMENTS

The author is grateful to Marland P. Billings and James B. Thompson, of Harvard University, and to George C. Kennedy, for helpful discussion of problems and critical reading of an early draft of the manuscript. The petrographic and mineralogic research on the volcanic rocks described in this report was performed in the laboratories of the Division of Geological Sciences, Harvard University.

Fourteen new chemical analyses of volcanic rocks from the Mariana Islands, listed in tables 5 and 6 and elsewhere in the report, were made by A. C. Vlisidis, Leonard Shapiro, and S. M. Berthold of the United States Geological Survey. Two new chemical analyses of volcanic rocks from the island of Saipan (table 5) were made by Forrest A. Gonyer, with funds supplied by the Department of Mineralogy and Petrography, Harvard University.

Chemical analyses of volcanic rocks from the Palau Islands and the island of Guam, plotted on the diagrams of figure 18, were kindly made available for this purpose by Gilbert Corwin and John T. Stark.

Helpful advice was received from Hisashi Kuno, of Tokyo University, concerning the identity and relationships of silica minerals and feldspar in the groundmass of the andesitic rocks from Saipan.

The McGraw-Hill Book Company kindly granted permission to use the quotation on page 171.

CLASSIFICATION OF ROCKS

The igneous rocks of Saipan belong to two principal classes or types of effusive rock: dacites, which are characteristically glassy, and andesites, which are comparatively crystalline. These rocks are classified primarily on the basis of the sum of their modal and normative femic minerals (pyroxene, hornblende, magnetite, ilmenite, and hematite). The secondary basis of classification is the average composition of the modal feldspar. Modal analyses were made by the point-counter method to determine the color index (volume percent of femic minerals) of rocks of a holocrystalline and coarsely porphyritic nature. When it was not possible to determine the modal composition of a rock, but the chemical composition was known, the color index was taken as the sum of the normative femic constituents (wo+en+fs+mt+il+hm). Rocks for which no chemical or modal analysis was available are classified on the basis of comparison to the analyzed rocks.

A small amount of potash-rich feldspar, believed to be anorthoclase, is present in the groundmass of the andesites from Saipan, but it is not considered in the classification. All of the igneous rocks are oversaturated with silica, and the andesites contain a large amount of normative quartz but little or no modal quartz. The presence or absence of quartz is not considered in the primary classification.

The dacites of Saipan are leucocratic rocks that contain less than 10 percent by volume of femic minerals and modal plagioclase feldspar with an average composition ranging from approximately An_{12} to An_{25}. All the dacites contain modal quartz and are relatively high in silica and low in alumina, iron, magnesia, lime, and potash compared to the average composition of dacite given by Daly (1933, p. 15). The andesites of Saipan are leucocratic rocks that contain between 10 and 30 percent femic minerals and modal plagioclase feldspar with an average composition ranging from approximately An_{55} to An_{70}. All the andesites contain an abundance of calcic plagioclase and a relatively large amount of normative quartz. They are relatively high in alumina and lime and low in potash compared to the average composition of andesite given by Daly (1933, p. 16).

Subdivisions of the major igneous rock types are made by use of appropriate modifying textural and mineral names. Dacite refers to a felsic rock containing small and relatively few phenocrysts of quartz and oligoclase, whereas dacite porphyry refers to a felsic rock in which these phenocrysts are large and abundant. Dacite vitrophyre refers to a porphyritic rock of pitchstonelike appearance in which small scattered phenocrysts of quartz and oligoclase lie in a groundmass of silicic dacitic glass. Perlite is a type of vitrophyre with a groundmass of small spheroids of glass bounded by arcuate cracks. The andesites of Saipan are grouped into various subtypes principally on the basis of their dominant mafic mineral phenocrysts; for example, augite andesite (where augite is the only mafic mineral phenocryst), augite-hypersthene andesite (where there are phenocrysts of augite and hypersthene), and quartz-bearing augite-hypersthene andesite (where phenocrysts of augite and hypersthene are abundant and quartz phenocrysts few).

The volcanic rock types of Saipan are textural varieties of dacite, hornblende-bearing dacite porphyry, dacite vitrophyre, dacite perlite, augite-hypersthene andesite, quartz-bearing augite-hypersthene andesite, quartz-bearing augite-hypersthene andesite porphyry, augite andesite, and hypersthene andesite.

The andesites and dacites of Saipan bear a close compositional resemblance to counterparts amongst the volcanic rocks of the Izu Peninsula region of Japan and other islands in the oceanic area between Honshu and the Palau Islands, and it appears that the great bulk of volcanic rocks throughout this region constitute a well-defined petrographic province. Within this province the rocks comprise a gradational series that ranges from mafic olivine-bearing pyroxene basalt through intermediate rock types to extremely silicic dacites and rhyolites. The andesites of Saipan correspond to intermediate members of the series, and the dacites of Saipan correspond to rocks at the silicic end of the series. The classification followed in this report furnishes a satisfactory medium for regional petrological discussion and comparison in that it defines the position of the rocks in the regional series and conforms to classifications and terminology already in use for the volcanic rocks of the western Pacific region. The classification is generally consistent with those established by Kuno (1950b, p. 958–959) and other Japanese petrographers for the volcanic rocks of the Izu Peninsula region of Japan.

Under more complex schemes of classification, such as those outlined in many American textbooks, the rocks which are called dacite in this report would be classed as rhyolites, soda rhyolites, or rhyodacites, and the rocks which are called andesite would be classed as basalt, quartz basalt, or basaltic andesite. In the system of classification proposed by Shand (1946, p. 225–245) the dacites of Saipan are soda rhyolites (*DO₀βL*), while the andesites are equivalent to his lime andesites (*DO* $_{m-\delta}$ *L*). In Johannsen's classification (1939, p. 155–156), the dacites become leucodacite (128E) and the andesites are equivalent to his quartz basalt (238E).

MINERALOGY

PRIMARY MINERALS

PLAGIOCLASE FELDSPAR

Plagioclase feldspar is the most abundant mineral component of the volcanic rocks, occurring both as phenocrysts and as a groundmass constituent. The absolute range in composition of the plagioclase is from medium bytownite in andesites to sodic oligoclase in dacites. Phenocrysts commonly display compositional zoning, and the zonal structure is more pronounced and more complicated in the intermediate to calcic plagioclase of the andesites than in sodic plagioclase crystals of the dacites. Plagioclase of the andesites also tends to be more highly twinned and more prone to contain inclusions.

The plagioclase of andesites ranges in composition from about An_{80} in the cores of zoned phenocrysts to An_{50} and more rarely to An_{10} in outer rims of zoned crystals and in groundmass feldspar. The compositional range of the plagioclase within a single rock normally exceeds 20 percent of anorthite. Table 2 gives the specific gravity and corresponding average molecular composition of zoned phenocryst feldspar in various andesites from Saipan as determined from the density curve published by Goranson (1926, p. 153). A small amount of groundmass feldspar was probably included in the samples of plagioclase separated from the rocks, but the samples are thought to be nearly representative of the average phenocryst plagioclase in the several rock specimens from which they were obtained. The average composition of phenocrysts in the rocks listed in table 2 ranges from An_{55-58} to An_{65-68}.

TABLE 2.—*Specific gravity and composition of plagioclase feldspar phenocrysts from various andesites of the Hagman formation, Saipan*

Specimen no.	Rock type	Specific gravity [1]			Average composition
		1st run	2d run	Average [2]	
S15 [3]	Augite-hypersthene andesite	2.700	2.706	2.703	An_{55}–An_{58}
S2G	do	2.707	2.705	2.706	An_{57}–An_{60}
S135 [3]	do	2.710	2.709	2.7095	An_{59}–An_{60}
S107 [3]	do	2.716	2.711	2.7135	An_{61}–An_{64}
S3G	do	2.713	2.718	2.715	An_{62}–An_{65}
S67A [3]	do	2.717	2.713	2.715	An_{62}–An_{63}
S3F	do	2.716	2.717	2.7165	An_{63}–An_{64}
S3C	do	2.721	2.716	2.7185	An_{65}–An_{68}
S141	Quartz-bearing augite-hypersthene andesite.	2.719	2.718	2.7185	An_{65}–An_{68}

[1] Obtained by means of a quartz pycnometer (volume 4.72 ml), using distilled water

[2] Average deviation is ±0.002, as calculated from 5 specific-gravity determinations on feldspar of specimen S107. Two determinations were made on the other specimens.

[3] Chemical analysis of rock is given in table 5.

The commonest type of zoning of plagioclase in the andesites is of normal type, where a relatively large homogeneous core of sodic bytownite or calcic labradorite is surrounded by narrow zones that become successively more sodic toward the margins. However, oscillatory or repetitive zoning is a common feature of strongly zoned crystals of intermediate to calcic labradorite (pl. 30*A*, *B*). In these crystals one or more outer zones, or the innermost zone alone, has a more calcic composition than one or more inner adjacent zones, but the cores of the crystals are always more calcic than any of the outer zones.

Labradorite phenocrysts and groundmass grains commonly exhibit albite and carlsbad twinning, and many crystals are twinned according to both laws. The albite twinning is polysynthetic, and individual crystals are commonly coarsely striated by several albite twin lamella. Some crystals show polysynthetic pericline twinning which can be observed in sections known to be cut parallel to {010}. The pericline composition plane is inclined approximately 8° to 12° from the basal plane in crystals of calcic labradorite, but ordinarily this cannot be determined due to the imperfect nature of the crystals.

Phenocrysts of plagioclase in the andesites commonly exhibit peculiar textures due to inclusions. The commonest inclusions are blebs of clear light-brown volcanic glass oriented in such a way that they conform to zonal boundaries. Ordinarily they are concentrated in the outer borders of zoned crystals in which the calcic cores are free of inclusions, this being a common feature of zoned plagioclase phenocrysts in most volcanic rocks. Probably the outermost zones containing the inclusions were grown after extrusion, whereupon growth was extremely rapid, favoring incorporation of groundmass material in the outer parts of the crystals. Where the particles of glass are coarse they commonly form irregular or vermicular shapes, which interconnect, and give the crystal a honeycomb or spongelike appearance. A few crystals were noted with randomly oriented glass inclusions distributed throughout the entire body of the crystal, and these crystals are weakly zoned or appear to be homogeneous and are not visibly zoned. These features, however, may be illusory and due to the fact that the observed crystals are cut (sectioned) parallel to zone boundaries.

A second type of texture, less common than that formed by glass inclusions, consists of plagioclase containing microscopic opaque particles. These inclusions, as nearly as can be determined, are a mixture of monoclinic pyroxene and iron oxide, with or without small particles of glass, and are present in concentrations oriented parallel to zonal (crystal) boundaries. The inclusions are mostly concentrated in the outer parts of zoned crystals, as are the glass inclusions, and in some crystals form a separate outer zone, the outer margin of which is parallel to the outline of the plagioclase crystal. In many crystals the inner margin of the inclusion zone is regular, but in some crystals it is irregular, and narrow apophyses of the inclusions extend across zonal boundaries toward the center of the crystals. However, none of these stringers were observed to reach the central portion of the crystals as is reported by Kuno (1950b, p. 968) for some plagioclase phenocrysts in rocks from the Hakone region of Japan.

Plagioclase feldspar of dacites ranges in composition from about An_{35} in the cores of zoned phenocrysts to about An_{10-15} in the outer rims of zoned crystals and in groundmass feldspar. The compositional range of the plagioclase within a single rock rarely exceeds 10 to 15 percent of anorthite. The zoning of the feldspars is ordinarily weak, and commonly larger phenocrysts in dacite and vitrophyre appear to be homogeneous and are not recognizably zoned in section. Unlike many of the calcic plagioclase crystals of the andesites, the plagioclase crystals in the dacites are free of inclusions.

The normative feldspar composition of analyzed andesites and dacites from Saipan and of Daly's average calc-alkaline rock types of the world is plotted on the triangular diagram of figure 13. Compared to the average basalts and andesites of the world the normative feldspar of the andesites of Saipan is significantly higher in lime and lower in potash. The normative feldspar of the dacites of Saipan is more sodic and generally contains less potash than that of the average world dacite and is much less potash-rich than that of the average world rhyolite. The normative feldspars of the volcanic rocks of Saipan thus form a potash-poor series that is correlated with the comparatively low content of potash in the bulk composition of these rocks.

ALKALI FELDSPAR

Alkali feldspar is found in many of the andesites of Saipan and appears to be most abundant (or at least most noticeable) in varieties of augite-hypersthene andesite. The alkali feldspar is confined to the groundmass of the andesites and is mostly present as an irregular interstitial filling between groundmass tridymite, plagioclase, and pyroxene grains (pl. 28*A*, *B*). In this type of occurrence, the potash feldspar commonly fills interstices between elongate tridymite crystals and, in addition, encloses small slender prisms of tridymite and cristobalite(?). More rarely, individual microscopic prisms and irregular forms of alkali feldspar, mostly less than 0.05 millimeter in diameter, are associated with a mixture of finely granular quartz and sodic plagioclase (andesine?) which forms irregular reaction zones at the borders of large plagioclase (labradorite) phenocrysts in some of the andesites.

FIGURE. 13.—Composition diagram of normative feldspar of analyzed andesites from Saipan, analyzed dacites from Saipan, and Daly's average rock types.

Individual grains and irregular fillings of alkali feldspar have an index of refraction less than 1.54 (considerably below that of balsam), a low birefringence, and many are nearly isotropic. Separation of the alkali feldspar was not possible, and the composition was not determined. However, the low index of refraction, the low birefringence, and the intimate association of the material with plagioclase suggest that it is either anorthoclase or perhaps a potash-rich plagioclase. Both anorthoclase and potash oligoclase are found in the groundmass of andesites of the Hakone Volcano of Japan (Kuno, 1950b, p. 966–967), and the optical properties, habit, and mineral association of the alkali feldspar of these rocks are similar to that of the andesites of Saipan. Kuno (1950b, p. 967) believes that the andesine, potash oligoclase, and anorthoclase in the rocks of Hakone constitute a simple solid-solution series which forms either a continuous zoning with calcic plagioclase or a discontinuous zoning without the formation of potash oligoclase.

The alkali feldspar forms isolated prisms and interstitial fillings between and around groundmass plagioclase and pyroxene and is associated with prisms of tridymite, which are also interstitial to primary groundmass mineral grains. These relationships suggest that the alkali feldspar represents the very end product of crystallization in the andesites.

Alkali feldspar was not recognized in the dacites of Saipan, but it is probable that outer rims of zoned oligoclase phenocrysts and groundmass plagioclase of the dacites have a high potash content and are, literally speaking, potash oligoclase.

Pure potash feldspar (orthoclase, sanidine) was not recognized and is probably not present in the volcanic rocks of Saipan.

SILICA MINERALS

Nearly all the volcanic rock types of Saipan contain one or more silica minerals in the form of quartz, tridymite, cristobalite, opal, or chalcedony. With the exception of quartz, all are confined to the groundmass of the rocks.

Quartz is abundant in the form of small phenocrysts in dacite, dacite vitrophyre, and dacite perlite; as large phenocrysts in hornblende-bearing dacite porphyry and vitric dacitic tuffs; and as small grains and finely granular patches in the groundmass of the dacitic rocks. Quartz phenocrysts in the dacitic rocks are generally subhedral to anhedral, though some are idiomorphic and bounded by crystal faces. Certain dacite porphyries and vitric tuffs, for example, contain perfectly formed stubby crystals of quartz with a poorly developed prism zone doubly terminated by {10$\bar{1}$1} and {01$\bar{1}$1}, which are commonly so equally developed as to resemble a hexagonal dipyramid. Many of these crystals are shattered, which, together with their dominantly pyramidal habit, indicates they crystallized as β quartz.

Small quartz phenocrysts, generally less than 2 millimeters in length, are present in quartz-bearing pyroxene andesites and in quartz-bearing andesite porphyry (pl. 29*D*). These and other andesites contain scattered grains of quartz in the groundmass as well as finely granular patches of quartz that are intimately associated with fibrous chalcedony, tridymite, cristobalite(?), and anorthoclase. The quartz phenocrysts and smaller individual grains in the groundmass of the andesites are invariably rounded and embayed and have irregular, serrate borders against the groundmass, indicating that they are strongly resorbed.

Opal and chalcedony are abundant constituents of the groundmass of dacites, in which they partly or completely fill vesicles and form irregular intergrown patches. Chalcedony commonly forms narrow seams veining the dacites. Opal and chalcedony are also present in the groundmass of many of the andesites but are not so abundant here as in the dacites.

Aggregates of wedge-shaped tridymite crystals, associated with fine-grained quartz, commonly form irregular patches and seams in the groundmass of dacites, and tridymite crystals are also present in small irregularly filled vesicles in these rocks (pl. 26*C*, *D*). Tridymite is almost universally present in small amount in the groundmass of andesites, where it most commonly forms isolated and tabular crystals, generally less than 0.1 millimeter in length, and aggregates of small crystals associated with interstitial anorthoclase, granular quartz, and chalcedony. In many of the andesites, individual crystals of tridymite project into or are completely enclosed in prisms and interstitial fillings of anorthclase (pl. 28*A*, *B*), and the crystals also appear to project into or fill small interstices in the groundmass (pl. 29*C*).

Cristobalite is sparse in the groundmass of dacites and in these rocks is most commonly associated with finely crystalline aggregates of quartz, tridymite, chalcedony, and opal. Generally the cristobalite forms small irregular patches with a characteristic mosaic pattern due to complex twinning. More rarely, cristobalite is present in the dacites as small ball-like aggregates attached to the walls of vesicles. Cristobalite is rare in the groundmass of andesites, but in several specimens of augite-hypersthene andesite the mineral forms small irregularly rounded patches with the characteristic mosaic pattern. In the andesites, most of the cristobalite is associated with finely granular quartz, chalcedony, and opal. In a few rocks it is found with tridymite in small cavities.

The relationships of quartz, tridymite, and cristobalite in the volcanic rocks of Saipan correspond closely with those described by Larsen, Jr., Irving, Gonyer, and Larsen, 3d (1936, p. 681–694) in the rocks of the San Juan Mountains of Colorado and with those described by Kuno (1950b, p. 968–969) in the rocks of the Hakone Volcano of Japan. Like that of the lavas of the San Juan and Hakone areas, the tridymite and cristobalite in the volcanic rocks of Saipan appear to have been mostly a product of primary crystallization of the groundmass and only to a small extent of secondary (hydrothermal) origin, deposited in gas cavities after solidification.

PYROXENES

Pyroxenes are the chief femic mineral constituent of the andesites of Saipan and form about 10 to 25 percent of the rocks by volume. As herein given, the nomenclature of the pyroxenes generally follows the system of classification proposed by Poldervaart and Hess (1951, p. 474). The principal types of pyroxene in the andesites of Saipan are hypersthene, augite, and subcalcic (pigeonitic) augite.

In general, the pyroxene assemblage in the various types of andesite is a simple one, being some combination of the three principal types given above. However, the composition of the pyroxenes in the different types of andesite, in individual hand specimens, and even in single crystals, is somewhat variable, indicating, as do the complexly zoned feldspars, that the conditions under which these minerals crystallized were erratic.

Augite forms phenocrysts and small scattered groundmass grains. Phenocrysts are commonly idiomorphic, stout prismatic to elongate prismatic, with a prominent prism zone terminated by the pyramid {111}. Simple twinning on the orthopinacoid {100} is common. In a few rocks, elongation parallel to the *c* crystallographic axis is pronounced, the crystals attaining a length of 1 centimeter. In section, augite is ordinarily colorless and without pleochroism. The refractive index, β, ranges from about 1.694 to 1.714 and seems to be most commonly between 1.700 and 1.706. The angle $Z \wedge c$ ranges from about 42° to 48°. The optic angle $2V$ ranges from about 48° to 58° and is most commonly between 52° and 56°. Optical properties and the average molecular composition of augite from various specimens of andesite are given in table 3.

The estimated average composition of phenocryst pyroxenes from various andesites, as determined from diagrams published by Kennedy (1947, p. 564, 568), is plotted in figure 14. The augite contains a relatively high proportion of diopside-hedenbergite, a low proportion of enstatite, and generally a somewhat higher proportion of ferrosilite than corresponding phenocryst augite of the volcanic rocks of the Izu Peninsula region of Japan (see fig. 15). The most ferriferous augites are found in inclusions of augite andesite and quartz-bearing augite-hypersthene andesite (specimens S235 and S583) derived from dacitic breccias of the Sankakuyama formation. According to the classification of Poldervaart and Hess (1951, p. 474) the augite phenocrysts mostly fall into the augite field, and the most ferriferous augite (Fs_{31}) lies in the ferroaugite field near the augite boundary.

Augite phenocrysts are commonly marginally zoned, the outer zone being usually slightly more ferriferous and less calcic than the inner core, as inferred from the difference in refractive index and optic angle between core and margin. The outer zone of several crystals, in which it was possible to determine optical properties, has an optic angle $2V$ that ranges between 50° and 40°, and the material thus corresponds to augite and subcalcic augite.

Hypersthene forms large phenocrysts in andesites and, more rarely, scattered lath-shaped and needlelike crystals in the groundmass of certain andesites. The phenocrysts are commonly prismatic and elongate, with broad and narrow pinacoidal and prismatic faces terminated with bipyramidal faces. In some rocks, crystals elongated parallel to the *c* crystallographic axis

TABLE 3.—*Optical properties and composition of pyroxenes in andesites from Saipan*

Specimen no.[1]	Augite									Hypersthene					
	α	β (range)	γ	Z∧c	2V	Avg 2V	Wo (mol. %)	En (mol. %)	Fs (mol. %)	α	β	γ (range)	2V	En (mol. %)	Fs (mol. %)
Phenocrysts															
S2G	1.694	1.702–1.704	1.721	42°	57°	------	43	34	23	1.698	1.709	1.712–1.714	60°	64	36
S3C	1.695	1.703–1.705	1.723	------	52°	------	33	39	28	1.698	1.710	1.713	60°	64	36
S3D	------	1.705–1.708	1.726	42°–43°	52°	------	33	37	30	1.700	1.711	1.713–1.714	60°	63	37
S3F	------	1.702–1.703	1.722	41°	55°	------	39	37	24	1.697	1.708	1.710–1.711	------	65	35
S3G	------	1.704	1.724	------	54°	------	37	36	27			1.709–1.714	60°	65	35
S15[2]	------	1.700–1.704	1.720	------	53°–55°	54°	38	38	24	1.699	1.710	1.713	------	64	36
S37[2]	------	------	------	------	52°–54°	53°	------	------	------	------	------	------	------	------	------
S67A[2]	------	1.698–1.700	1.719	------	52°–54°	53°	36	41	23	------	------	1.710–1.712	------	65	35
S107[2]	------	1.697–1.698	1.719	------	53°	------	37	41	22	------	------	1.709	65°	67	33
S135[2]	------	1.696–1.698	1.718	40°	48°–55°	52°	34	43	23	------	------	1.709	65°	67	33
S583	1.703	1.710–1.712	1.730	------	52°–56°	54°	36	34	30	------	------	------	------	------	------
S235	1.705	1.711–1.714	1.728	48°	55°–58°	56°	40	20	31	------	------	------	------	------	------
S636A[2]	------	1.705–1.706	1.726	------	55°	------	37	36	27	------	------	------	------	------	------
Groundmass															
S2F	1.697	1.705	1.722	------	52°	------	33	38	29	------	------	------	------	------	------
S43	------	1.698–1.700	------	------	40°–48°	44°	24	46	30	------	------	------	------	------	------
S135[2]	------	1.700	------	------	42°–46°	44°	21	45	31	------	------	------	------	------	------

[1] All specimens are augite-hypersthene andesite, with the exception of S583 (quartz-bearing augite-hypersthene andesite), S235 (augite andesite), and S636A (augite andesite).
[2] Chemical analysis of rock is given in table 5.

are about 4 times as long as they are broad and attain lengths of as much as 1 centimeter or slightly more.

In sections of various andesites the hypersthene shows a distinct weak pleochroism, and in thicker grains in oil immersion the pleochroism is strong: X=light to dark reddish brown, Y = light brown to pale greenish brown, and Z = light to dark green, with absorption $X>Z>Y$. The refractive index, γ, ranges from about 1.709 to 1.714 and seems to be most commonly between about 1.710 and 1.713. The hypersthene is optically negative with an optic angle $2V$ ranging from about 60° to 65°, and the dispersion is distinct with $r>v$. The most iron-rich hypersthene is found in a specimen of augite-hypersthene andesite (specimen S3D) from the breccia facies of the Hagman formation. The optical properties and molecular composition of phenocryst hypersthene from various specimens of andesite are given in table 3, and the average molecular composition is plotted on the diagram of figure 14, together with phenocryst and groundmass augite and the normative pyroxene composition of analyzed rocks.

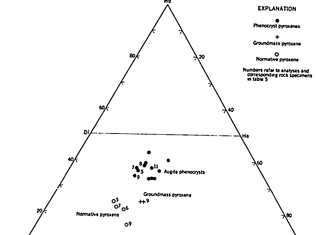

FIGURE 14.—Composition diagram of phenocryst pyroxenes of andesites from Saipan, groundmass pyroxene of andesites from Saipan, and normative pyroxene of analyzed andesites from Saipan.

Like the augite phenocrysts, the composition of hypersthene varies somewhat in different grains within individual hand specimens as well as in single crystals. This latter variation is not evident in section but is apparent in crystals powdered and examined in oil immersion, and probably it indicates a weak compositional zoning of the hypersthene phenocrysts. The widest range of composition found in a single rock is from $En_{67}Fs_{33}$ to $En_{63}Fs_{37}$ and in a single crystal from about $En_{66}Fs_{34}$ to $En_{64}Fs_{36}$.

The groundmass pyroxene of the andesites of Saipan appears to be predominantly augite and subcalcic augite, though in most rocks these elements are in such a fine-grained form that they cannot be separated from the rocks for optical analysis. In addition, it proved to be impossible to prevent contamination of the groundmass pyroxene with phenocryst pyroxene in the separations that were attempted on porphyritic rocks. However, several specimens contained groundmass pyroxene coarse enough to permit a rough determination of the optic angle of larger grains, and groundmass pyroxene, perhaps only slightly contaminated with phenocryst augite, was separated from 2 specimens (S43 and S135, table 3) of augite-hypersthene andesite. The optic angle $2V$ of the groundmass pyroxene in these rocks, as measured on the universal stage, ranges from about 40° to 48°, and the average is probably about 44° or slightly more. The β index is between about 1.698 and 1.700, and the compositional range is between approximately $Wo_{21}En_{47}Fs_{32}$ and $Wo_{27}En_{44}Fs_{29}$.

Pigeonite was not recognized and is probably not present in the andesites of Saipan. In figure 14 the normative pyroxene composition of various andesites lies generally on a line between the grouping of points representing phenocryst augite and hypersthene and is displaced slightly toward the $MgSiO_3$ side of this line. However, the normative composition should fall on the $FeSiO_3$ side of the line and is probably displaced to the left because of the inherent error in the norm calculation. Specifically, the assumption that all ferric iron and titanium are in magnetite and ilmenite is not correct and means that normative ferrosilite is too small by a significant amount. Normative wollastonite is also a bit low because of the assumption that all the alumina is in feldspar.

Although the real normative pyroxene composition of the andesites of Saipan is therefore believed to be slightly higher in ferrosilite than the phenocryst pyroxenes, there is a sharp contrast between the normative pyroxene of the andesites of Saipan and that of the majority of basalts and andesites of the Izu Peninsula region of Japan, a plot of which is shown in figure 15. In the rocks of the Izu Peninsula, iron-rich pigeonite is the common pyroxene of the groundmass, and the augite phenocrysts tend to be less calcic and slightly more magnesian rich than those in the andesites of Saipan. The normative pyroxene composition of the rocks of the Izu Peninsula region therefore falls considerably to the right and on the $FeSiO_3$ side of the line between the grouping of points representing phenocryst augite and phenocryst hypersthene, about midway between the line and the grouping of points representing groundmass pigeonite.

The absence of pigeonite in the groundmass of the andesites of Saipan, and the apparent slight increase in iron content of the subcalcic groundmass pyroxene of these rocks, is not in general accord with pyroxene relationships within the andesites of Japan, nor does it entirely agree with what would be expected from the physical chemistry of pyroxene crystallization in lavas. However, the andesites of Saipan bear a strong resemblance to rocks of the Hakone region of Japan that belong to the hypersthenic rock series as defined by Kuno (1950b, p. 992–993). In these rocks the groundmass pyroxenes are characteristically hypersthene and augite; more rarely hypersthene, augite, and pigeonite; and the ratios of $FeSiO_3$ to $MgSiO_3$ in the groundmass pyroxenes are rarely higher than unity. These relationships generally agree with those in the andesites of Saipan, many of which contain hypersthene and augite or augite and subcalcic augite in the groundmass. The absence of pigeonite in the lavas (andesites) of Saipan is probably the result of the low ratio of Fe to Mg in these rocks, with crystallization therefore prevailing in a relatively magnesian-rich system at temperatures below the clinopyroxene-orthopyroxene inversion curve. Under these conditions hypersthene, rather than pigeonite, crystallized along with augite.

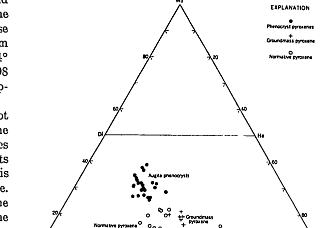

FIGURE 15.—Composition diagram of phenocryst pyroxenes, groundmass pyroxene, and normative pyroxene of analyzed basalts and andesites from the Izu Peninsula region of Japan and the Izu Islands. Computed from data in Tsuya, 1937, p. 234–315.

In many instances hypersthene and augite phenocrysts, as well as small lath-shaped hypersthene crystals in the groundmass of the andesites of Saipan, have been resorbed by reaction with the groundmass and are bordered by reaction rims. Hypersthene and augite crystals are commonly surrounded by narrow to broad opaque rims of finely divided hematite, monoclinic pyroxene, and plagioclase feldspar (?), and small hypersthene crystals in the groundmass are completely resorbed, their former position now occupied by a pseudomorphic replacement of finely divided hematite. In several rocks, hypersthene crystals are surrounded by narrow irregular rims of subcalcic augite (pl. 29*A*, *B*), and in these same rocks augite is marginally zoned with a broad outer zone of augite of less calcic composition than the core and with a probable composition tending toward subcalcic augite.

Hypersthene is always resorbed to a greater degree than augite in the same rock, and in the majority of rocks in which hypersthene is strongly resorbed, augite commonly shows no effects of reaction. This contrast in stability of augite and hypersthene is also reflected in the secondary alteration of the pyroxenes, hypersthene commonly altering to serpentine (bastite) whereas augite in the same rock is unaltered.

HORNBLENDE

Green hornblende is a rare mineral in the volcanic rocks of Saipan and is found sparingly in dacite perlite and in hornblende-bearing quartz dacite porphyry. It is present in these rocks as narrow, acicular crystals (microphenocrysts) as much as 1 millimeter in length, but most less than 0.1 millimeter in length, scattered throughout the groundmass. The crystals are euhedral and prismatic and show no indication of resorption.

ACCESSORY MINERALS

BIOTITE

Biotite is confined to silicic dacites, where it is present as tiny plates (0.001 to 0.020 mm in width) embedded in the glassy portions of the groundmass and associated with silica minerals and microlites of oligoclase feldspar. The biotite crystals have a high birefrigence, are strongly pleochroic, and are perhaps of a phlogopitic variety and similar to biotite described by Kuno (1950b, p. 982) in the groundmass of silicic dacites from the Hakone Volcano of Japan.

MAGNETITE

Magnetite is present in the groundmass of all the various types of andesite and dacite, and in the dacites it forms small microphenocrysts that are commonly either perfectly formed or slightly distorted octahedra which average slightly less than 0.5 millimeter in diameter. Magnetite forms less than 0.5 percent of the dacites by volume. In andesites, magnetite is essentially confined to the groundmass and forms small subhedral to anhedral grains interstitial to groundmass feldspar. Finely granular magnetite is present as inclusions in feldspar and is also produced at the borders of resorbed pyroxene phenocrysts. Skeletal crystals and dendritic growths of magnetite are present in the interstitial glass of certain andesites. In reflected light the magnetite grains are grayish white.

ILMENITE

Ilmenite was noted in the form of small flakes and equant crystals in the groundmass of a few andesites and has a dark brown to nearly black color in reflected light. Ilmenite is apparently not an abundant constituent in the andesites, however, and this is correlated with the generally low content of titanium in the rocks.

HEMATITE

Hematite forms small microscopic flecks scattered throughout the groundmass of dacite flows, but it is a very minor constituent of these rocks. In part, at least, the dacite flows may owe their reddish color to the included hematite. In andesites, finely granular hematite is found with magnetite as reaction rims around large hypersthene phenocrysts. In some of these rocks, smaller hypersthene grains are completely resorbed and replaced by finely granular hematite.

RUTILE

Rutile is a rare accessory mineral of the andesites but is generally present in small amount as small, short, needlelike crystals embedded in interstitial groundmass glass or interspersed in finely crystalline interstitial material.

A single specimen of augite-hypersthene andesite (specimen S3B) contains relatively large crystals of what is believed to be rutile of a decidedly different habit. In section, the crystals have a dark amber color and are embedded in a cryptocrystalline and nearly opaque groundmass clouded with dust-sized magnetite and ilmenite(?) grains. They are equant, euhedral, as much as 0.4 millimeter in diameter, and appear to be uniaxial, with a high refractive index and high birefringence. Most of the crystals have a well-developed prismatic cleavage, and basal(?) sections exhibit a triangular twin pattern, with dark bands and irregular inclusions of opaque ilmenite(?) traversing the mineral parallel to and along the twin lamellae.

APATITE

Apatite is confined to the groundmass of andesites and generally forms needlelike crystals less than 0.05 millimeter in length set in finely crystalline or glassy material interspersed between feldspar laths. Apatite is most abundant in flows of augite andesite which contain a relatively large amount of P_2O_5.

ZEOLITES

Zeolites, largely of deuteric origin but in part the result of weathering, form rounded and irregular aggregates in the groundmass of the andesites and are particularly abundant as coatings on the walls of vesicles in flows of augite andesite. The common zeolites are chabazite (gmelinite?), heulandite, analcite, and stilbite.

ALTERATION MINERALS

Secondary alteration minerals include zeolites (principally analcite), calcite, serpentine (bastite), chlorite, sepiolite(?), kaolinite, opal, chalcedony, and quartz. Highly weathered rocks are altered to various clay minerals and hydrous iron oxides, chief among which are kaolinite, montmorillonite, nontronite(?), goethite, limonite, and hematite.

PETROGRAPHY

The dacites of Saipan are primarily restricted to flows and fragmental pyroclastic materials of the Sankakuyama formation and to 1 of 2 small volcanic plugs presumably related to the dacitic succession. Andesites are the chief rock component of the various facies of the Hagman, Densinyama, and Fina-sisu formations. Locally, however, accessory fragments of dacite are fairly common in parts of the Densinyama formation, a few fragments of dacite are present in andesitic sandstone and conglomerate beds of the Hagman formation, and accessory inclusions of andesite are found in dacitic breccias of the Sankakuyama formation. The classification, texture, and mineral composition of the principal volcanic rock types of Saipan are given in table 4.

DACITES

The chief textural varieties of dacite in the volcanic formations of Saipan are dacite, dacite vitrophyre, dacite perlite, and hornblende-bearing dacite porphyry.

DACITE

Dacite forms the tabular flows and irregular masses of rock that comprise the flow-rock facies of the Sankakuyama formation, and small fragments of dacite also are found in dacitic breccias and tuffs of the Sankakuyama formation and in andesitic breccia and conglomerate beds of the Densinyama formation. The dacite fragments in the Densinyama formation are believed to be accessory inclusions derived from the older flow rocks of the Sankakuyama formation.

The typical rock is grayish red, pale red, pale brown, brownish gray, and light gray and is composed of a glassy groundmass enclosing small scattered phenocrysts of oligoclase and quartz and rare euhedral crystals of magnetite. It is massive to highly vesicular, glassy, rarely cryptocrystalline, foliated (flowbanded), and finely porphyritic. The measured specific gravity of the more massive varieties of dacite ranges from 2.26 to 2.45 and averages about 2.30. However, these values do not take into account the pore spaces (vesicles) in the rocks and are therefore somewhat low. The true specific gravity of the typical rock is probably close to the maximum value of 2.45.

The groundmass is generally glassy and is only rarely cryptocrystalline where the dacitic glass of the groundmass is nearly or completely devitrified. Ordinarily the groundmass is highly vesicular (pl. 26*C*), but the vesicles of some of the rocks are filled with silica minerals (mainly tridymite, opal, and chalcedony), and such rocks have a massive, flintlike texture. The groundmass is generally composed of small microlites and crystallites of oligoclase feldspar (An_{10-15}) less than 0.5 mm long, equant grains of oligoclase and quartz between 0.05 and 0.1 mm across, small irregular patches and elongate crystals of tridymite, small needlelike crystals of cristobalite less than 0.05 mm long, tiny plates of biotite (perhaps phlogopite) between about 0.001 and 0.02 mm in width, small euhedral grains of magnetite less than 0.1 mm in diameter, and small scattered flecks of hematite set in a mesostasis of clear or partly devitrified glass. In some rocks, small rounded spherulites less than 0.1 mm in diameter are abundant and form about 5 percent of the rock, but generally they are rare or altogether absent. They are formed of a radiating intergrowth of silica minerals and feldspar(?).

The dacite flows of the Sankakuyama formation are mostly highly vesicular, and some are pumiceous. The vesicles are narrow and elongate, average about 1 mm in length, and are generally about one-fifth as broad. They are commonly lined or filled with silica minerals, the most common of which are tridymite, opal, and chalcedony. Many individual vesicles have a lining of opal and a center filled with chalcedony, the opal always forming the innermost lining against the walls of the vesicles. Other vesicles are entirely filled with opal. In some rocks, small irregular aggregates of tridymite form the lining of vesicles (pl. 26*C*, *D*). The tridymite is weakly birefringent and has an index of refraction of about 1.48.

The principal constituent of the groundmass of the porphyritic dacites is a pale-red or light-grayish-red dacitic glass. In some of the flow rocks the glass is partly devitrified, and small recrystallized patches of glass alternate with areas of clear glass on a microscopic scale. The groundmass glass has an index of refraction between 1.49 and 1.50; the average specific gravity of the glass is about 2.30.

All the flow rocks contain small subhedral to rounded phenocrysts of oligoclase feldspar and quartz, and scarce euhedral crystals of magnetite, most of which properly fall into the category of microphenocrysts. The phenocrysts of oligoclase and quartz form about 5 to 8 percent of the rock and are less than 2 mm in diameter, with an average of about 1 mm. Oligoclase phenocrysts are weakly zoned, generally subhedral and

TABLE 4.—*Estimated mineral composition of the principal volcanic-rock types of Saipan*

Rock	Symbol in Shand's classification	Symbol in Johannsen's classification	Megascopic texture	Microscopic texture	Phenocrysts (volume percent): Plagioclase	Quartz	Augite	Hypersthene	Hornblende	Magnetite
Dacite	$DO_p\beta L$	128E	Finely porphyritic, aphanitic to glassy	Holocrystalline to hyalopilitic	An_{15-30} 3-5	1-3				<1
Dacite vitrophyre and perlite	$DO_p\beta L$	128E	Finely porphyritic, glassy	Hyalopilitic	An_{15-30} 3-5	1-3			<1	<1
Hornblende-bearing dacite porphyry	$DO_p\beta L$	128E	Coarsely porphyritic, aphanitic to glassy	Holocrystalline to hyalopilitic	An_{20-35} 8-12	4-6			<1	<1
Augite-hypersthene andesite	$DO_m\delta L$	238E	Porphyritic, phenocrysts generally large	Pilotaxitic to hyalopilitic, rarely intersertal.	An_{50-80} 20-45		1-10	1-12		2
Quartz-bearing augite-hypersthene andesite.	$DO_m\delta L$	238E	do	do.	An_{50-75} 5-40	0-3	1-10	1-10		2
Quartz-bearing augite-hypersthene andesite porphyry.	$DO_m\delta L$	238E	Coarsely porphyritic, phenocrysts very large.	Pilotaxitic	An_{50-80} 15-20	2-4	[illegible]	1-2		2
Augite andesite	$DO_{mp}\delta L$	238E	Finely porphyritic, phenocrysts small	Intersertal	An_{55-75} 0-5		0-1			
Hypersthene andesite [1]	$DO_m\delta L$	238E	Porphyritic, phenocrysts large	Pilotaxitic	An_{55-80} 20-25			5		2

Rock	Groundmass (volume percent): Plagioclase	Anorthoclase	Quartz, chalcedony	Opal	Tridymite, cristobalite	Monoclinic pyroxene	Hypersthene	Hornblende	Biotite	Magnetite	Ilmenite	Hematite	Rutile	Apatite	Volcanic glass	Typical stratigraphic distribution
Dacite	An_{10-20} 5-15	Present(?)	0-5	0-15	5-20				<1	<1		1			40-70	Sankakuyama formation.
Dacite vitrophyre and perlite.	An_{10-20} 5-10	do			0-5			<1		<1					80-85	Do.
Hornblende-bearing dacite porphyry.	An_{15-25} 20-30	do	1-5	0-5	5-10			<1		<1					40-50	Dacitic volcanic plug.
Augite-hypersthene andesite.	An_{40-60} 5-35	0-10	0-2	Rare	0-10	1-10	0-5			1-5	0-3	0-3	Tr.	Tr.	0-25	Hagman, Densinyama and Fina-sisu formation.
Quartz-bearing augite-hypersthene andesite.	An_{15-55} 10-35	0-10	2-5	do	0-10	1-10	0-5			1-5	0-3		Tr.	Tr.	0-20	
Quartz-bearing augite-hypersthene andesite porphyry.	An_{40-60} 30-40	Present(?)			2-5	5-10	2-3			3-5					5-10	Do.
Augite andesite	An_{55-80} 50-60	Rare.				10-20				3-5	0-3		Tr.	Tr.	10-20	Do.
Hypersthene andesite [1]	An_{55-60} 20-25	Present(?)			Present (?)		5-10			3-5		1-2	Tr.	Tr.	10-20	Do.

[1] Estimate based on description by Tsuboya, 1932, p. 208-211

slightly elongate, and range in composition between about An_{30} (cores) and An_{15} (rims). Quartz phenocrysts are subhedral to rounded in outline, generally unbroken, clear, and show no strain shadows. Only a few of the oligoclase and quartz phenocrysts examined in section have irregular borders against the groundmass, but occasional crystals of both quartz and oligoclase are surrounded by narrow rims of fibrous and cryptocrystalline intergrowths of quartz and feldspar (potash oligoclase? or perhaps anorthoclase?). Small euhedral to subhedral crystals of magnetite, between 0.01 mm and 0.5 mm in diameter, are the common accessory mineral of the dacites, and many of the magnetite crystals are perfectly formed octahedra.

X-ray powder photographs of the groundmass of five specimens of porphyritic dacite were made in an attempt to determine the qualitative mineral composition of the groundmass. All the samples gave the same X-ray powder pattern. The *d*-spacing (atomic spacings) of the lines on the groundmass photograph, and thus the lines themselves, correspond closely to the lines of higher intensity for α-cristobalite, α-tridymite, and oligoclase. The *d*-spacings of the high-intensity lines for quartz do not correspond well with the *d*-spacings of the lines on the groundmass photograph. This appears to indicate that crystalline quartz is probably a very minor constituent of the groundmass and that silica is mainly in the form of opal, cristobalite, and tridymite and is also occult in the groundmass glass.

The estimated mode of typical dacite is given in table 4, and the chemical composition of a type specimen of the rock is given in table 5.

DACITE VITROPHYRE AND PERLITE

Dacite vitrophyre and perlite are the chief rock components of pyroclastic breccias, flow breccias, and tuffs of the Sankakuyama formation. They are medium- to light-gray glassy pitchstonelike finely porphyritic rocks containing small scattered anhedral to subhedral phenocrysts of oligoclase and quartz and microphenocrysts of magnetite and green hornblende (rare). The phenocrysts and microphenocrysts form approximately 5 to 8 percent of the rock and are enclosed in a light- to dark-gray glassy groundmass.

The quartz and oligoclase phenocrysts are as much as 3 mm in diameter and have an average diameter of about 1 mm. Oligoclase phenocrysts are generally weakly zoned, subhedral in outline, equant to somewhat elongate and tabular, commonly broken, and are occasionally somewhat embayed by the groundmass. The range in composition is from about An_{30} (cores) to An_{15} (rims). Quartz phenocrysts are subhedral to anhedral in outline, clear, often broken, commonly show strain shadows, are only rarely embayed by the groundmass, and show no other effects of resorption. Small euhedral to subhedral crystals of magnetite, between 0.01 and 0.3 mm in diameter, are the common accessory mineral of the dacite vitrophyre and perlite. Many of these small magnetite crystals are perfectly formed octahedra. Small scattered acicular to equant crystals of green hornblende, as much as 0.3 mm in length, were noted in 1 section of perlite. The magnetite and hornblende together constitute less than 1 percent of the rock.

The groundmass of dacite vitrophyre and perlite (pl. 26*A*, *B*) is dominantly a light- to dark-gray (colorless in section) transparent dacitic glass containing numerous tiny acicular microlites and crystallites of oligoclase (An_{10-15}). The crystallites are generally less than 0.01 mm in length, their long axes are parallelly oriented, and they are concentrated in flow lines. Small rounded spherulites, less than 0.2 mm across, are common in some rocks but are not abundant. The spherulites have a radiating structure and, like the small spherulites in the dacitic flow rocks, are probably composed of an intergrowth of oligoclase and silica minerals (quartz, tridymite, and cristobalite).

The groundmass of the vitrophyre and perlite has a specific gravity that ranges between 2.28 and 2.32, with an average of about 2.30. The specific gravity of the rock itself is probably close to the value. The index of refraction of the groundmass glass is about 1.498.

Commonly the vitrophyre and perlite fragments exhibit a fine, almost microscopic banding of alternate light and dark laminae which are from a fraction of a millimeter to about 2 millimeters across. The banding is best seen in section and is produced by a concentration of microlites and magnetite grains into thin layers that are separated by alternating layers of clear glass. Banding of the vitrophyre and perlite is also produced by an alternation of vesicular and massive layers, though this textural banding is generally somewhat coarser than the mineral banding. The oriented microlitic bands and elongate vesicles wrap around larger phenocrysts and around small knotlike fragments of glass that have become detached in the groundmass.

The vitrophyre and perlite fragments are commonly extremely vesicular and pumiceous, containing closely spaced long, slender, tubelike vesicles that give the rock a fibrous texture. The tubular vesicles are from less than 1 mm to as much as 2 cm in length and are alined with their long axes parallel. They have an average width of about 0.2 mm, about ½ to ⅒ their length. Only rarely do the vesicles contain secondary minerals, but in some rocks the vesicles are lined with narrow (about 0.01 mm in width) coatings of a weakly bire-

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fringent silica mineral of low index of refraction that is believed to be tridymite or cristobalite (pl. 26*A*).

Many vitrophyre fragments are intricately fractured and traversed by curving cracks that pass through groundmass glass and phenocrysts alike. These cracks are not to be confused with the concentric cracks that characterize perlite, though they probably have the same origin. The groundmass of the perlite has a shot-like appearance, being made up of small ball-like aggregates of glass bounded by arcuate cracks that have formed by contraction of the glass upon cooling (pl. 26*B*). Commonly several sets of these spherical cracks develop around phenocrysts of quartz and oligoclase in the perlite.

The estimated mineral mode of typical dacite vitrophyre and perlite is given in table 4, and the chemical composition of a type specimen of the rock is given in table 5.

HORNBLENDE-BEARING DACITE PORPHYRY

Fragments of hornblende-bearing dacite porphyry are found in a small dacitic volcanic plug, are widely scattered throughout conglomerate beds of the Densinyama formation, and are sparsely distributed in andesite conglomerate beds of the Hagman formation. The typical rock is light gray, massive, and coarsely porphyritic and contains large phenocrysts of plagioclase feldspar and quartz and scarce acicular crystals of green hornblende enclosed in a microcrystalline groundmass. The phenocrysts form about 20 percent of the rock.

Plagioclase phenocrysts are subhedral, rarely euhedral, generally equant or slightly elongate, and weakly zoned. They are as much as 1 cm in length, average about 4 mm, and comprise about 8 to 12 percent of the rock. The cores of the plagioclase phenocrysts are oligoclase-andesine (An_{25-35}), the rims are medium oligoclase (about An_{20-25}), and the average composition of the phenocrysts is about An_{25}. A few of the plagioclase phenocrysts show carlsbad and albite twinning, but most are untwinned. The plagioclase phenocrysts are generally clear and without inclusions, but a few contain small regularly oriented inclusions of groundmass material. Some of the plagioclase phenocrysts show ragged edges against the groundmass, but there are no other noticeable effects of resorption. In the fragments from the dacitic volcanic plug, plagioclase phenocrysts are shattered and appear to have been crushed by shearing stress, and groundmass material fills the areas between broken parts of the crystals (pl. 27*A*). A few phenocrysts are broken into small fragments that have become widely separated in the groundmass, indicating that crushing somehow occurred while part of the groundmass of the rock was still liquid.

Quartz phenocrysts are anhedral to subhedral, generally equant, and decidedly rounded. They are as much as 8 mm in diameter, average about 3 mm, and form about 5 percent of the rock. The quartz phenocrysts are clear and without visible inclusions, but they show pronounced strain shadows in polarized light. Like the plagioclase phenocrysts, many of the larger quartz grains are crushed and broken (pl. 27*B*), and groundmass material fills the spaces between the crystal fragments. The quartz phenocrysts are rounded and generally somewhat resorbed and embayed by the groundmass.

Hornblende phenocrysts are acicular and prismatic, are as much as 2 mm in length but average less than 1 mm, and form less than 1 percent of the rock. They show no effects of resorption. Commonly the hornblende phenocrysts are altered to a dark green fibrous serpentine or chlorite.

The groundmass of the rock is light gray and microcrystalline and is composed of randomly oriented plagioclase microlites (oligoclase, approximately An_{20}) generally less than 0.1 mm in length, small equant grains of quartz with a diameter less than 0.05 mm, and tiny acicular crystals of green hornblende scattered throughout a devitrified glass base. Small rounded spherulites, as much as 0.1 mm across, are present in the devitrified portions of the groundmass and are probably radial intergrowths of quartz, tridymite, and feldspar. The devitrified glass of the groundmass is generally clear and weakly birefringent and contains a scattering of dark submicroscopic grains. Small patches of fibrous chalcedony are present in the groundmass and may be largely of secondary origin. Tridymite and cristobalite were not recognized in the groundmass but are probably present as submicroscopic grains and in spherulites.

The groundmass of some of the rocks, particularly those from the dacitic volcanic plug, is traversed by numerous randomly oriented fractures filled with finely crystalline quartz and fibrous chalcedony. The fractures pass through phenocrysts and groundmass alike, and the groundmass is crushed and shattered in much the same manner as the quartz and feldspar phenocrysts.

A single specimen of dacite porphyry, containing phenocrysts of sodic andesine (An_{30-40}), was collected from the conglomerate and sandstone facies of the Hagman formation. This rock is somewhat more calcic than other rocks of this general type.

The estimated mode of typical hornblende-bearing dacite porphyry is given in table 4, and the chemical composition of a type specimen is given in table 5.

ANDESITES

The various types of andesite from Saipan differ widely in texture, volumetric mineral composition, and color, but chemically they are all much alike, as is indicated by a close correspondence in chemical composition (table 5). Although the andesites exhibit a fairly wide textural and mineral variation (chiefly with regard to accessory minerals and texture of the groundmass), they may be conveniently grouped into a reasonably small number of major rock types for purposes of petrographic description.

AUGITE-HYPERSTHENE ANDESITE

GENERAL FEATURES

This is the most abundant kind of andesite in the Hagman and Densinyama formations and forms approximately 50 to 60 percent of the larger fragments in the pyroclastic deposits. The general type also comprises four small massive andesite flows of the Hagman formation. The color of the rocks ranges through light gray, light greenish gray, light olive gray, brownish gray, reddish brown, and medium and dark gray. The light and dark rocks are of about equal abundance.

The wide variation in color from light to dark gray to nearly black is a particularly deceiving aspect of the andesites, and color (as distinct from color index) is of no practical use as a criterion for estimating composition or as a basis for field classification. Color in these rocks is apparently more a function of texture (principally grain size) than of composition. The light-colored rocks are generally coarsely porphyritic, containing large feldspar and pyroxene phenocrysts but only sparsely scattered femic constituents in the groundmass. The dark rocks, on the other hand, are ordinarily finer grained, the pyroxene phenocrysts are smaller, and the groundmass contains a greater density of femic constituents, giving the rock a darker color. The chemical composition of the light and dark rocks, however, is nearly identical, though the darker rocks commonly contain a slightly higher percentage of iron and magnesia.

In general, the augite-hypersthene andesites are massive, highly compact, coarsely and profusely porphyritic, and contain abundant large phenocrysts of labradorite and fewer large phenocrysts of hypersthene and augite. The phenocrysts form about 30 to 55 percent of the rock and are generally enclosed in a light to dark microcrystalline groundmass. The proportion of hypersthene and augite phenocrysts is variable. Commonly hypersthene phenocrysts are more abundant than augite phenocrysts, but the rocks range to types containing a greater proportion of augite phenocrysts than hypersthene phenocrysts. The two extremes are gradational through rocks containing nearly equal proportions of augite and hypersthene phenocrysts, although the medial rocks are rare.

PHENOCRYSTS

Plagioclase phenocrysts form about 20 to 45 percent of the rock, are generally subhedral to euhedral, are equant to slightly elongate, and are commonly moderately to highly zoned (pl. 30*A*, *B*). They are as much as 1 cm in length, but the maximum length is ordinarily about 5 or 6 mm, and the average length is about 2 to 3 mm. Commonly the plagioclase phenocrysts are formed of an intergrowth of several individual crystals. The cores of some of the larger phenocrysts are sodic bytownite (An_{70-80}), but more commonly the cores are calcic labradorite (An_{60-70}), and the rims are sodic labradorite (An_{50-55}). The average composition of the plagioclase phenocrysts in these rocks is between approximately An_{55} and An_{66}, as determined by specific-gravity measurements (table 2). The plagioclase phenocrysts are usually complexly zoned, and commonly the zoning is oscillatory or repetitive and rarely normal. In many rocks of this general type the plagioclase phenocrysts contain abundant small inclusions of dark-brown groundmass material (chiefly altered glass) and small microscopic grains of monoclinic pyroxene and magnetite. The inclusions generally are oriented in regular zones parallel to the internal zone boundaries of the phenocrysts. The larger phenocrysts, and many of the smaller feldspar grains in the groundmass, commonly show albite and carlsbad twinning. Pericline twinning is infrequently developed in the plagioclase.

In general, the plagioclase phenocrysts show only minor effects of reaction with the groundmass. Occasional phenocrysts in some of the rocks have ragged, serrate boundaries and are slightly rounded and embayed by the groundmass. Commonly the groundmass fills cracks and irregular openings in broken phenocrysts.

Hypersthene phenocrysts form about 1 to 12 percent of the rock, are generally elongate, prismatic, and euhedral, and in some of the lighter colored rocks are as much as 1 cm in length and 4 mm in width. In darker rocks the hypersthene crystals ordinarily have a maximum length of 5 to 6 mm and an average length of 2 or 3 mm. The hypersthene phenocrysts are generally unzoned and show no resorption effects with the groundmass. A few rocks, however, contain hypersthene crystals with narrow border rims of subcalcic augite (pl. 29*A*, *B*). This augite has an optic angle $2V$ of approximately 45° and a composition that is identical or nearly identical to that of the groundmass pyroxene. One of the textural varieties of augite-hypersthene andesite (specimens S654B, S679), which comprises 2 thin flows in the Hagman formation, contains hypersthene grains that are surrounded by narrow to wide (about 0.01 to 0.20 mm) irregular reaction rims of a mixture of finely granular hematite and small amounts of monoclinic pyroxene and possibly plagioclase feldspar. Small phenocrysts and groundmass grains, formerly hypersthene, are completely altered to granular hematite.

In section, the hypersthene phenocrysts are generally colorless or pale pink and weakly pleochroic. In thick sections the pleochroism is X=light brown or pale pink, Z=colorless or pale green, and Y=pale brown. Nine samples of hypersthene from varieties of augite-hypersthene andesite were studied in oil immersion and with the universal stage (table 3). Their composition, as determined from curves published by Kennedy (1947, p. 564), ranges between approximately $En_{67}Fs_{33}$ and $En_{63}Fs_{37}$.

Augite phenocrysts are dark green to greenish black, form about 1 to 10 percent of the rock, are elongate to equant, euhedral to subhedral and rarely anhedral, and are as much as 1 cm in length in the light-colored rocks. In the darker rocks the augite phenocrysts are generally between about 1 to 4 mm in longest dimension and average about 2 or 3 mm. Finely porphyritic augite-hypersthene andesites contain augite phenocrysts with lengths averaging about 1 mm. The larger phenocrysts are commonly elongate, prismatic, and euhedral with well-developed prismatic and pinacoidal faces terminated by {111} and {001}. In the majority of the rocks examined the augite phenocrysts are unzoned, but some of the rocks contain augite phenocrysts with narrow outer zones of augite and subcalcic augite having a composition approximating that of the groundmass augite—less calcic and probably slightly higher in iron content than the augite of phenocrysts and the cores of zoned phenocrysts. Hourglass zoning was not observed in the augite phenocrysts. In most of the rocks augite phenocrysts show no resorption effect other than occasional ragged, serrate edges, but in rocks in which hypersthene phenocrysts are strongly resorbed the augite crystals possess narrow reaction rims of an opaque mineral which is probably hematite.

In section the augite phenocrysts are colorless and nonpleochroic. Within single rocks and even within single crystals they are somewhat variable in composition, but the range in composition in rocks of the general type is not large. Nine samples of phenocryst augite from varieties of augite-hypersthene andesite were studied in oil immersion and with the universal stage (table 3). Their composition, as determined from optical property curves published by Kennedy (1947, p. 568), ranges from $Wo_{37}En_{41}Fs_{22}$ to $Wo_{33}En_{37}Fs_{30}$.

GROUNDMASS

The groundmass of the augite-hypersthene andesites is of variable texture and mineral composition. In general, the groundmass is light gray or light greenish gray to dark gray or dark greenish gray and, rarely, black; aphanitic, microcrystalline or crytocrystalline to hypohyaline and glassy; and microlitic and pilotaxitic. Only a few rocks were observed to have flow texture developed in the groundmass.

The commonest rocks have a groundmass of small crystals of sodic labradorite (more rarely, calcic andesine An_{45-55}), augite, subcalcic augite, hypersthene, magnetite, ilmenite(?), tridymite, cristobalite(?), and anorthoclase, and between these mineral grains there is generally a small amount of partly devitrified glass.

Plagioclase is the principal constituent of the groundmass and in holocrystalline rocks comprises about 40 percent of the groundmass. The plagioclase forms small elongate microlites mostly from about 0.1 mm to 0.01 mm in length but ranging down to submicroscopic size. The compositional range is from about An_{40-45} (rare) to An_{60} and most commonly is between An_{50} and An_{55}.

Augite and subcalcic augite are the common pyroxenes of the groundmass, and generally they form small equant grains ranging from about 0.5 mm across to submicroscopic dimensions, but in some rocks they are of uniform size and less than 0.05 mm in diameter. The groundmass augite has a variable composition, even in a single rock specimen. Among the various sections examined, the optic angle $2V$ ranges between approximately 40° and 50°, with the majority of grains (subcalcic augite) having optic angles between 40° and 45°.

Hypersthene is a common constituent in the groundmass of some of the augite-hypersthene andesites and forms small elongate prismatic crystals from about 0.02 to 1.0 mm in length. In a few rocks the small groundmass hypersthenes have reaction borders of magnetite and hematite or are entirely replaced by a dust-sized granular aggregate of magnetite and hematite.

Silica minerals, the most common of which are tridymite, quartz, and fibrous chalcedony, are present in the groundmass of the majority of the augite-hypersthene andesites. Tridymite is almost universally present and forms isolated crystals and aggregates of small wedge-shaped crystals commonly closely associated with small patches of intergrown granular quartz and chalcedony. The isolated crystals of tridymite are elongate and tabular and are generally less than 0.1 mm long.

Ordinarily they are embedded in the recrystallized glass of the groundmass. However, in many rocks the tridymite crystals are closely associated with a mineral of low index of refraction and low birefringence that is probably anorthoclase. In some rocks the tridymite crystals project into or are entirely included within small prisms of anorthoclase(?), and in others they appear to surround irregularly shaped interstitial fillings of this mineral (pl. 28*A*, *B*.). Tabular crystals of tridymite forming small microscopic patches in the groundmass commonly exhibit a characteristic wedge-shaped twinning (pls. 28*C*, 29*C*). Small anisotropic needlelike crystals embedded in groundmass glass of many andesites are probably cristobalite, although they cannot be positively identified as such. Quartz and chalcedony, although not abundant, are commonly present in finely crystalline and fibrous intergrowths with feldspar and are also intergrown with zeolites formed from the alteration of plagioclase. Finely crystalline quartz, plagioclase, and possibly anorthoclase(?) form small microscopic patches in and around feldspar phenocrysts. Opal and chalcedony are commonly found in the altered portions of the groundmass and may have developed largely from the alteration of interstitial glass.

Microscopic prisms and irregular interstitial fillings of anorthoclase (possibly in part potash oligoclase?) are present in the groundmass of some and possibly most of the andestites. Most of the grains and irregular fillings of this mineral are less than 0.05 mm in diameter, have a γ index of refraction considerably below 1.54, and have a low birefrigence. Commonly the grains enclose tiny needlelike crystals of tridymite, or they form an interstitial filling between elongate tridymite crystals. More rarely, microcrystalline grains of anorthoclase are associated with finely granular quartz and plagioclase at the borders of large plagioclase phenocrysts.

Accessory minerals of the groundmass include small equant and generally subhedral grains of magnetite and ilmenite, small elongate prismastic grains of apatite, and small elongate to equant grains of rutile. Equant crystals of a dark amber-colored mineral, believed to be rutile, are abundant in a single specimen of augite-hypersthene andesite (specimen S3B), where they are embedded in a cryptocrystalline and nearly opaque groundmass clouded with dust-sized particles of magnetite and ilmenite(?). The crystals are as much as 0.4 mm in diameter.

Within the general rock type the groundmass ranges from clear to pale-brown and darkly clouded glass to a felted or pilotaxitic mixture of plagioclase, pyroxene, tridymite, anorthoclase(?), magnetite, and ilmenite(?), with variable amounts of interstitial glass. Commonly the interstitial glass is partly or wholly devitrified and altered. Rounded microscopic patches of finely crystalline and radiating fibrous intergrowths, believed to be quartz and feldspar, are common. In some rocks the groundmass is composed of a weakly birefringent aggregate of devitrified glass containing randomly oriented submicroscopic grains of pyroxene and magnetite. In other rocks, especially fresh rocks unaffected by weathering, the interstitial material is a light-brown to yellow or nearly colorless glass, generally containing randomly oriented to parallel microscopic inclusions of monoclinic pyroxene and magnetite. A few rocks possess a groundmass of light-brown interstitial glass enclosing dark microscopic dendrites and crystallites of magnetite and possibly monoclinic pyroxene.

The typical mineral composition of augite-hypersthene andesite is given in table 4, and chemical compositions of type specimens of this rock are given in table 5.

ALTERATION

The majority of the rocks examined show some degree of alteration, part of which may be hydrothermal, but mostly the result of weathering. Feldspar phenocrysts are altering to kaolinite, calcite, and occasionally to zeolites (principally analcite). The alteration to kaolinite is most intense at the borders of crystals and along transverse cracks. Calcium carbonate is commonly present along with kaolinite, and the cores of the feldspar phenocrysts are preferentially altered to this mineral. However, kaolinite is the chief alteration product of the plagioclase feldspars, and in deeply weathered rocks the feldspar phenocrysts are completely altered to kaolinite or to a mixture of kaolinite and gibbsite(?).

Phenocrysts and smaller groundmass crystals of hypersthene are generally altered to light- and dark-green serpentine and chlorite(?) minerals. The alteration proceeds along transverse fractures and along crystal boundaries, and even the hypersthene of fresh rocks is commonly altered at the borders and has a core with remnant sections surrounded by green serpentine. The commonest alteration mineral is light green in section and has a low birefringence. This is most likely the antigorite variety of serpentine. A less common alteration mineral is pleochroic, grass green to dark green and yellowish brown in section, and has a higher birefringence. This may be a ferriferous chlorite. In some rocks the alteration is a light-green mineral with an extremely low birefringence—probably sepiolite(?). Dark-brown birefringent goethite is found with the serpentine in a few rocks. Some rocks contain large hypersthene phenocrysts altered to a mixture of light-green serpentine, goethite, and calcite.

An interesting aspect of the alteration of pyroxenes in these rocks is the marked stability of augite. Augite in the fresh rocks is unaltered and even in the more highly weathered rocks is only slightly altered to serpentine. It is common to find unaltered augite in rocks in which hypersthene phenocrysts are completely altered to serpentine and in which the groundmass consists of an aggregate of zeolites, quartz, opal, serpentine, chlorite(?), and calcite. This contrast in stability between augite and hypersthene is difficult to explain but is probably related in some way to the difference in structure and composition of the two minerals.

The groundmass of relatively fresh augite-hypersthene andesite is ordinarily somewhat altered. Zeolites are commonly present, and as nearly as can be determined in section and in oil immersion they are analcite, chabazite, gmelinite(?), heulandite, phillipsite, and possibly stilbite. In part the zeolites are of deuteric origin and form small microscopic and megascopic amygdules.

In the more highly altered rocks the groundmass contains irregular patches of zeolites which are the product of weathering, and commonly they are developed at the margins of feldspar phenocrysts. Clay minerals also are present as an alteration product of the glassy portions of the groundmass. Kaolinite and possibly other kaolin minerals are present in the weathered rocks, and a light-green weakly birefringent clay, thought to be montmorillonite, is common.

In deeply weathered andesites the alteration of primary minerals is complete, and these rocks are composed of clay minerals (chiefly kaolinite, montmorillonite, and nontronite(?), hydrous iron oxides (goethite and limonite), hematite, and zeolites. Alkalies, lime, and magnesium are removed except for small traces; ferrous iron is oxidized to ferric iron to produce hematite and hydrous ferric oxides; and some silica is removed and a large amount of water is added in the weathering process. The most notable concentrations are in alumina, ferric iron, and water (OH). The following analyses illustrate the marked change in composition effected by weathering. Specimen S67A is from the unweathered core of a spheroidally weathered boulder of augite-hypersthene andesite from the breccia-tuff facies of the Hagman formation, and specimen S67B is a portion of the thick weathered shell enclosing the fresh core. The boulder is about 5 to 6 feet in diameter and the weathered shell about 2½ feet thick. The analyses were made by A. C. Vlisidis and S. M. Berthold, U. S. Geological Survey.

	S67A	*S67B*
SiO_2	60.95	54.39
TiO_2	.54	.65
Al_2O_3	18.06	24.83
Fe_2O_3	2.41	5.15
FeO	2.61	.58
MnO	.08	.04
MgO	2.37	.58
CaO	8.16	.10
Na_2O	3.10	.44
K_2O	.58	.08
H_2O-	.76	2.42
H_2O+	.58	10.62
P_2O_5	.10	.04
	100.30	99.92

SECONDARY ROCK TYPES

QUARTZ-BEARING AUGITE-HYPERSTHENE ANDESITE

This rock type is fairly common in the Hagman and Densinyama formations and is similar in texture and general mineralogy to the augite-hypersthene andesites described above. It differs from the augite-hypersthene andesites proper in containing visible grains of quartz, which are mostly confined to the groundmass as isolated crystals, probably of primary origin.

The rocks are light to dark gray and greenish gray, massive, and coarsely porphyritic. Phenocrysts form about 20 to 40 percent of the rock and are calcic labradorite, elongate prismatic hypersthene, elongate to equant diopsidic augite, and scarce small equant to rounded quartz. The feldspar phenocrysts are as much as 5 mm across, the pyroxene phenocrysts are as much as 4 mm in length, and the quartz phenocrysts are as much as 1 mm in diameter.

The groundmass is cryptocrystalline to microcrystalline, generally has an intergranular texture, and is composed of plagioclase microlites, larger lath-shaped grains of plagioclase, equant grains of subcalcic augite, small prismatic grains of hypersthene, randomly scattered grains of magnetite and ilmenite(?), elongate laths of tridymite and cristobalite(?), and small grains of quartz. The mineral grains are enclosed in a cryptocrystalline interstitial base of devitrified and altered glass, which in part consists of secondary minerals—zeolites, opal, and a patchy intergrowth of fibrous quartz and feldspar. Small patches of finely granular quartz are also present.

The small quartz phenocrysts and groundmass grains are equant and rounded and have ragged, serrate edges against the interstitial material of the groundmass. They have evidently suffered strong resorption. The quartz grains are as much as 1.0 mm in diameter, but average mostly less than 0.1 mm.

The typical mineral composition of quartz-bearing augite-hypersthene andesite is given in table 4.

Inclusions of quartz-bearing augite-hypersthene andesite were found at one horizon in dacitic breccias of the Sankakuyama formation. They have a considerably different mineral composition and texture from the quartz-bearing andesites of the Hagman and Densinyama formations and warrant separate description. The inclusions are brownish-gray massive finely porphyritic rocks composed of subhedral to euhedral phenocrysts of highly zoned labradorite, quartz, augite, and serpentine-replaced hypersthene(?) enclosed in a cryptocrystalline groundmass. The phenocrysts range in length from less than 1 mm to as much as 3 mm and have an average length of about 1 mm. Plagioclase phenocrysts form about 5 percent of the rock and are highly zoned; the zoning is normal. Cores are medium to calcic labradorite (An_{60-65}) and rims are calcic andesine and andesine labradorite (An_{45-50}). The plagioclase phenocrysts are commonly intergrown composites of many small elongate individual crystals. Euhedral prismatic crystals, forming about 1 to 2 percent of the rock and as much as 1 mm in length, are replaced by weakly birefringent fibrous serpentine that is believed to be pseudomorphous after original hypersthene. Augite forms euhedral equant to slightly elongate prismatic crystals as much as 2 mm long and is not abundant, representing only about 1 percent of the rock. The mineral is a somewhat ferriferous augite with the approximate average composition $Wo_{36}En_{31}Fs_{30}$ (specimen S583, table 3). Quartz phenocrysts represent about 1 percent of the rock, are commonly decidedly rounded and embayed by the groundmass, and are generally cracked and broken, but clear and without strain shadows. They are as much as 2 mm in diameter.

The groundmass of the rock is formed principally of a felted aggregate of randomly oriented microlites of andesine labradorite (An_{45-50}), submicroscopic grains of monoclinic pyroxene less than 0.01 mm across, and small euhedral to anhedral crystals of magnetite and ilmenite(?) 0.01 to 1.0 mm in diameter. Less abundant, but nonetheless conspicuous, are minute slender needles and tabular grains of tridymite and cristobalite(?) and isolated prisms of anorthoclase(?) or perhaps potash oligoclase(?). Needles of cristobalite(?), and needles and tabular crystals of tridymite are commonly embedded in the interstitial glass, but in some rocks they form small irregular patches and apparently fill small interstices in the groundmass. The small needles of tridymite commonly surround isolated prisms or irregular patches of anorthoclase(?), which appears to have crystallized interstitially to the tridymite crystals. Rarely, small needles of tridymite project into or are included within the anorthoclase(?) prisms. The anorthoclase(?) has an index of refraction (estimated 1.52) considerably below that of balsam and a low birefringence. Between the mineral grains there is a small amount of colorless and light-brown interstitial volcanic glass charged with minute dark inclusions, and a colorless isotropic material, opal(?), with an index of refraction between 1.45 and 1.47, forms an interstitial filling in the groundmass and has partly replaced feldspar and hypersthene phenocrysts.

The estimated average mode of the quartz-bearing augite-hypersthene andesite inclusions is given below.

	Volume percent
Phenocrysts:	
Labradorite	5
Hypersthene (serpentine)	3
Augite	1
Quartz	1
Groundmass:	
Andesine-labradorite microlites	50
Monoclinic pyroxene (augite)	10
Tridymite and cristobalite	10
Anorthoclase	5
Opal(?)	2
Magnetite and ilmenite	3
Volcanic glass	10

QUARTZ-BEARING AUGITE-HYPERSTHENE ANDESITE PORPHYRY

This rock was recovered from a dacitic volcanic plug in association with fragments of hornblende-bearing dacite porphyry. It bears a close compositional resemblance to quartz-bearing augite-hypersthene andesites of the breccia facies of the Hagman formation. However, the rock has a distinctive coarsely porphyritic texture and contains a higher percentage of free quartz than the breccia-associated rocks.

The rock is dark gray, massive, and coarsely porphyritic. Phenocrysts of labradorite, augite, hypersthene, and quartz comprise about 30 to 40 percent of the rock and are enclosed in a dark partly glassy pilotaxitic groundmass.

The plagioclase phenocrysts are subhedral and commonly equant, are as much as 1 cm in diameter, and form about 15–20 percent of the rock. They are highly zoned and the zoning is normal. Cores range from bytownite (An_{75-80}) to labradorite (about An_{70}), and rims are sodic labradorite (An_{50-55}). The average composition, as determined by specific gravity measurements (specimen S141, table 2) is about An_{65}. Many of the larger plagioclase phenocrysts have a sievelike texture and contain abundant small and generally elongate inclusions of light-brown volcanic glass oriented parallel to zonal boundaries. In some phenocrysts the inclusions appear to be distributed throughout the entire crystal, but in general they are confined to the outermost zones. Plagioclase phenocrysts are generally idomorphic toward the groundmass and show no effects of resorption.

Augite phenocrysts are euhedral, equant to elongate, prismatic, as much as 3 mm long, and form about 5 to 10 percent of the rock. A few large augite phenocrysts are of irregular shape and have poikilitic texture, enclosing small rounded grains of feldspar and magnetite. Many of the augite phenocrysts are zoned. The cores of these are diopsidic augite. The outer rim of one of these zoned phenocrysts has a positive optic angle $2V$ of about 42°, and its composition probably corresponds closely with subcalcic augite of the groundmass. Many of the augite phenocrysts are composed of aggregates of several individual grains. The augite shows no effects of resorption.

Hypersthene phenocrysts are rare in the porphyry. They are small, euhedral, prismatic crystals averaging about 1 mm in length, and form about 1 to 2 percent of the rock. They exhibit no effects of resorption.

Quartz phenocrysts are subhedral to anhedral and are commonly well rounded by resorption (pl. 29*D*). Some are large and have a diameter of about 1 cm. They form 1 to 4 percent of the rock. Several of the quartz phenocrysts are red and may be stained with iron oxides, although this was not evident in section.

In contrast to the shattered quartz and feldspar phenocrysts and groundmass of the hornblende-bearing dacite porphyry plug rock, the quartz-bearing augite-hypersthene andesite porphyry fragments are unaffected by shearing stress, and crushing does not appear to be a general characteristic of the plug rocks as a whole.

The groundmass of the andesite porphyry is dark gray to nearly black and consists of a felty aggregate of small plagioclase microlites (labradorite, An_{50-60}) with lengths less than 0.2 mm, equant grains of subcalcic augite less than 0.2 mm in diameter and with an optic angle $2V$ of approximately 42° to 45°, and small magnetite grains surrounded by a light-brown glass base containing dark submicroscopic inclusions. This glass forms about 5 to 10 percent of the groundmass. The texture of the groundmass is intergranular tending toward intersertal.

The estimated mode of the rock is given in table 4.

AUGITE ANDESITE

Augite andesite comprises flow rocks of the Fina-sisu and Hagman formations, fragments in the pyroclastic deposits of the Hagman and Densinyama formations, and inclusions in the mixed dacitic pyroclastic-rock facies of the Sankakuyama formation.

Flows of augite andesite are light to dark olive gray, brownish gray, and greenish gray, massive to highly vesicular, and aphanitic to finely porphyritic. The rock contains small acicular phenocrysts of labradorite (average composition about An_{65}) having a maximum length of 3 mm and an average length of about 1 mm. The phenocrysts, which form about 1 to 5 percent of the rock, are subhedral to euhedral in outline, are elongate parallel to the *a* crystallographic axis, are weakly zoned, and show carlsbad and albite twinning.

The groundmass of the rock is aphanitic and microcrystalline and consists chiefly of small lath-shaped crystals and microlites of labradorite (An_{55-60}); less abundant and generally equant grains of augite, magnetite, and ilmenite(?); and exceedingly rare, small prismatic apatite crystals. The interstitial material between these mineral grains is a light-brown (in section) partly or wholly devitrified generally altered glass containing swarms of dark crystallites of monoclinic pyroxene(?), plagioclase(?), and tiny grains of magnetite and ilmenite(?). Silica minerals, common in the groundmass of other andesites, are not present. The texture of the groundmass is commonly intersertal, the glass mesostasis filling the interstices between plagioclase grains (pl. 28*D*).

The plagioclase grains of the groundmass range in length from about 0.2 mm to submicroscopic dimensions, are randomly oriented, and form an estimated 50 to 60 percent of the rock. Augite grains form an estimated 10 to 20 percent of the rock and are generally equant and less than 0.05 mm across, although a few elongate crystals of augite with lengths of as much as 1 mm are present in some rocks. They have the approximate composition $Wo_{37}En_{36}Fs_{27}$ (specimen S636A, table 3). Small equant subhedral to anhedral grains of magnetite and ilmenite(?) are scattered throughout the rock. They are as much as 0.1 mm across, although generally less than 0.05 mm in diameter, and form about 5 percent of the rock. Apatite forms small prismatic crystals embedded in the interstitial groundmass glass, and generally these crystals are less than 0.01 mm long.

The flows of augite andesite are generally highly vesicular at the top and moderately and minutely vesicular at the middle and base. The vesicles are ordinarily spherical or slightly flattened and ovoid, and are as much as 5 mm in maximum diameter at the tops of flows. In the more massive flow rock (middle and basal portions of flows) the vesicles are generally less than 1 mm in diameter and are rounded to uneven. They are commonly lined with a narrow coating of white, pink, and bluish-green zeolites, and a few were noted to be lined with calcite and some with chalcedony. The most common zeolites are chabazite (possibly gmelinite), heulandite, and analcite. A fibrous zeolite, possibly stilbite, is present in the vesicles along with the other zeolites, and a light-bluish-green mineral, possibly prehnite, forms thin coatings in the vesicles of some of the rocks.

The augite andesite flows are deeply weathered at the surface, and commonly to depths of tens of feet; no fresh rock is exposed. The interstitial glassy portions of the groundmass are readily altered to mixtures of clay materials, zeolites, and secondary silica. Plagioclase grains are altering to kaolinite and more rarely to a mixture of kaolinite and calcite. Augite grains are ordinarily very stable in the zone of weathering, but in deeply rotted rock they are altered at the borders to fibrous serpentine. Opal and chalcedony of secondary origin are present in several rocks and are mostly confined to the altered interstitial glass of the groundmass, but they also appear to be forming from the alteration of plagioclase. In the upper portions of the weathered zone original rock-forming minerals are completely destroyed and the rock consists of a variety of clay minerals (chiefly kaolinite, montmorillonite, and nontronite?), hydrous iron oxides (goethite, limonite), and hematite, though relict igneous texture is still preserved because of the differential alteration—plagioclase grains alter to white kaolinite and give the rock a relict porphyritic appearance.

The estimated mode of typical augite andesite flow rock is given in table 4, and the chemical composition of a type specimen of the rock is given in table 5.

A second type of augite andesite, not found among the flow rocks, is a light-gray to light-greenish-gray massive coarsely porphyritic andesite. Texturally the rock is similar to light-colored varieties of augite-hypersthene andesite, but it differs from these rocks in that augite is present to the exclusion of hypersthene. Phenocrysts are highly zoned calcic labradorite and euhedral to subhedral diopsidic augite, the latter as much as 8 mm in length. The groundmass has an intergranular texture and is composed of tiny microlites of feldspar between which are scattered grains of monoclinic pyroxene, tridymite, magnetite, ilmenite(?), and apatite. Interstitial to the mineral grains is a small amount of partly devitrified colorless glass. Secondary minerals include zeolites, silica minerals (opal and chalcedony), and clay minerals.

Inclusions of augite andesite in the breccias and tuffs of the Sankakuyama formation are a fraction of an inch to 6 inches across. They are dark grayish brown, massive, and finely porphyritic and are composed of phenocrysts of labradorite, diopsidic augite, and smaller crystals of magnetite enclosed in a fine-grained groundmass. The phenocrysts comprise only about 5 percent of the rock, are from less than 1 mm to as much as 3 mm long, and have an average length of about 1 mm.

Plagioclase phenocrysts in the inclusions are subhedral and highly zoned, with cores of bytownite (about An_{75}) and rims of labradorite (about An_{55-60}); the zoning is normal. Both albite and carlsbad twinning are common. Augite phenocrysts are equant to somewhat elongate and are as much as 2 mm long. The augite phenocrysts are unzoned, slightly rounded, and a few possess narrow reaction rims of a finely granular birefringent mineral that is probably monoclinic pyroxene. The augite phenocrysts (specimen S235, table 3) are slightly pleochroic in section with Z=greenish blue, Y=light brownish green, and X=light green. Their approximate composition is $Wo_{40}En_{29}Fs_{31}$. Subhedral crystals and small equant grains of magnetite as much as 0.5 mm across are scattered throughout the rock and form approximately 3 or 4 percent of the rock volume.

The groundmass of the augite andesite inclusions is composed of a felted aggregate of randomly oriented microlites and lath-shaped crystals of labradorite (about An_{50-55}) from submicroscopic size to about 0.1 mm in longest dimension, small elongate prismatic crystals of monoclinic pyroxene with a length from about 0.01 to 0.1 mm, small grains of magnetite and ilmenite(?) generally less than 0.05 mm across, and small elongate and tabular crystals of tridymite less than 0.1 mm in length. Minute needles of extremely low refrigence may be cristobalite. Anorthoclase is probably present in small amounts interstitially, although it was not recognized in the groundmass. The mineral grains are surrounded by a light-brown interstitial volcanic glass containing swarms of tiny dark opaque inclusions which are probably magnetite.

The approximate average mode of the augite-andesite inclusions is given below.

	Volume percent
Phenocrysts:	
Labradorite	4
Augite	1
Groundmass:	
Labradorite microlites	55
Monoclinic pyroxene	15
Magnetite and ilmenite	3
Tridymite and cristobalite	2
Volcanic glass	20

HYPERSTHENE ANDESITE

A porphyritic hypersthene andesite from the shore of Laulau Bay on Saipan (breccia facies of Hagman formation) has been described by Tsuboya (1932, p. 208–211), but apparently this rock type is rare in the volcanic formations of Saipan, for it was not found among the many specimens of andesite collected by the writer. Tsuboya's rock consists of phenocrysts of calcic labradorite and hypersthene in a brownish aphanitic groundmass. The groundmass is composed of a glass base containing lath-shaped plagioclase and hypersthene grains, the latter stained by brown iron oxides (hematite?). No mention is made of monoclinic pyroxene in the groundmass, and probably it is not present, for the high alumina content of the rock would indicate that most of the calcium probably went into the feldspars during crystallization. Plagioclase phenocrysts in this rock are highly zoned, with cores of bytownite (An_{78}) and outer zones of calcic labradorite, and the crystals exhibit both albite and pericline twinning. Hypersthene phenocrysts are euhedral, prismatic, and strongly pleochroic (in section?), with Z=light green, Y=brownish yellow, and X=brown. Iron oxides (hematite? and magnetite?) are disseminated in the margins of the hypersthene phenocrysts. An analysis of this specimen is given in table 5.

CHEMICAL COMPOSITION OF THE MAJOR ROCK TYPES

The chemical compositions and norms of major types of andesite and dacite of Saipan are given in table 5. Columns 12 and 13 of the table give the average chemical compositions and norms of these rocks. All the analyses are new except for two hitherto published analyses (columns 4 and 10). Because it is uncertain that the augite andesite described by Kaiser (1903, p. 120) is from Saipan, and because it does not conform well with the modern analyses, it was omitted in computing the average composition of andesite from Saipan and is not included in the variation diagrams.

In general, the volcanic rocks of Saipan are characterized by a high silica content, a high alumina content with respect to the sum of the alkalies and lime, and a low potash content compared with the average andesite-dacite-rhyolite series of the world. The dacites are exceptionally high in silica and are peraluminous (the molecular proportion of alumina in the rocks exceeds the sum of the molecular proportions of soda, potash, and lime). The most silicic dacite contains almost 50 percent quartz in the norm. The andesites of Saipan are strongly oversaturated with silica, are moderately aluminous or peraluminous, and have a high lime content (excluding the analysis given by Kaiser) compared with average world andesite. Normative plagioclase in the andesites of Saipan is highly calcic, and no normative composition is more sodic than An_{50} (again excluding the augite andesite of Kaiser). Phenocrysts of plagioclase are exceedingly abundant as compared with those of mafic constituents, and this feature, together with the high anorthite content of the plagioclase, can be correlated with the high content of Al_2O_3 and CaO in the bulk composition of these rocks. All the andesites of Saipan contain an appreciable amount of quartz in the norm, which is largely attributable to the presence of silica minerals in the groundmass of these rocks, although in some rocks the excess silica is occult in interstitial glass.

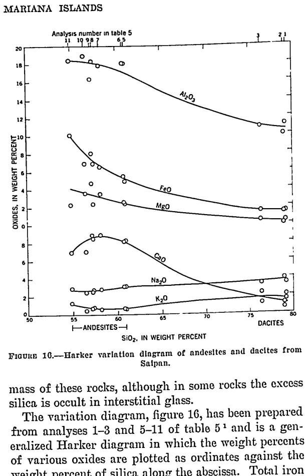

FIGURE 16.—Harker variation diagram of andesites and dacites from Saipan.

The variation diagram, figure 16, has been prepared from analyses 1–3 and 5–11 of table 5[1] and is a generalized Harker diagram in which the weight percents of various oxides are plotted as ordinates against the weight percent of silica along the abscissa. Total iron is plotted as FeO. The andesite end of the diagram shows a wide scattering of points for the various oxides, exclusive of alkalies and lime, and the curves through this region of the diagram are highly generalized.

Because of the wide scattering of values for the oxides involved, and the pronounced break between the composition of the andesites and dacites of Saipan, the true location of the curves for the various oxides is uncertain, and therefore the alkali-lime index cannot be stated accurately. However, it is in the vicinity of 65, placing the rocks as a whole in the calcic series of Peacock (1931), and in this and other respects they are closely akin to volcanic rocks of the Izu Peninsula region of Japan (see fig. 20).

The ACF diagram of figure 17 shows the composition of the analyzed rocks of Saipan in terms of three components where A, C, and F are the molecular amounts:

$$A=Al_2O_3-K_2O-Na_2O,\ C=CaO,$$

and

$$F=MgO+FeO+MnO-Fe_2O_3-TiO_2.$$

[1] Analyses 8 and 11 are slightly weathered andesites in which ferrous iron has been largely oxidized to the ferric state with the formation of limonite. Analysis 2 is a dacite in which most of the ferrous iron has been oxidized to form hematite. In order to place these rocks more nearly in their proper position within the variation diagrams, they are plotted with a ferrous and ferric iron content recalculated to a proportion consistent with that of fresh andesites and dacites. Specifically, one-half of the molecular amount of Fe_2O_3 in the original analyses (analyses 2, 8, and 11) has been converted to FeO, the H_2O content of the andesites has been reduced to the normal content of fresh rocks, and the analyses recalculated to 100 percent. These modified values of analyses 2, 8, and 11 also have been used to compute the average compositions of Saipan andesite and dacite plotted on the diagrams of figures 17, 21, and 22, and the plotted averages thus do not represent the averages given in columns 12 and 13.

TABLE 5.—*Chemical analyses and norms of volcanic rocks from Saipan and Guam*

	1	2	3	4	5	6	7	[1] 8	9	10	[1] 11	12	13	[1] 14
Analysis (weight percent)														
SiO_2	70.20	79.00	76.39	63.58	60.95	60.80	58.19	57.38	57.20	56.45	51.21	78.20	57.45	60.84
TiO_2	.23	.18	.11	.71	.54	.48	.46	.62	.54	.01	1.35	.17	.66	.72
Al_2O_3	11.05	9.01	10.75	14.57	18.06	18.13	17.82	18.36	16.35	18.97	17.20	10.58	17.84	12.56
Fe_2O_3	.52	1.18	.29	1.52	2.41	2 03	2.50	4.88	2.23	3.61	7.59	.66	3.61	3.13
FeO	.90	.22	1 12	5.92	2.61	3.53	4.08	2.26	5.93	3.56	3.24	.75	3.60	3.49
MnO	.02	.02	.07	------	.08	.09	.10	07	.14	.10	.10	.01	.10	.13
MgO	.36	None	.30	1.60	2.37	2.54	3.46	2.40	4.65	3.55	2.14	.22	3.02	3.44
CaO	2.06	64	1.13	4.58	8.16	8.18	8.90	8.48	8.85	7.02	6.54	1 28	8.02	8.17
Na_2O	3.40	3.88	3.34	4.86	3.10	3.12	2.80	2.76	2.50	2.50	2.75	3.54	2.79	2.69
K_2O	1 58	1.20	2.29	2.02	.58	.60	53	.74	.68	.43	1.05	1 60	.66	.82
H_2O-	.53	------	.32	------	76	.34	81	------	.34	1 14	3.77	.28	1 02	.79
H_2O+	.27	3.98	3.91	.31	.58	.40	.47	1.30	.56	1.68	2.47	2.72	1.07	.73
P_2O_5	.13	.07	.16	.34	.10	.11	.09	.02	.36	.07	.32	.12	.15	.14
CO_2	------	------	------	------	------	------	------	.57	------	------	------	------	------	2.14
Total	100.25	100.31	100.18	100.01	100.30	100.35	100.21	99.84	100.33	99.69	99.73	100.25	99.99	99.79
Norms (weight percent)														
Quartz	48.00	49.74	43.98	14.52	20.30	19.00	15.90	18.72	14.22	17.52	14.70	47.52	17.10	25.26
Orthoclase	9.45	7.23	13.35	11.68	3.31	3.31	2.78	4.45	3.89	2.22	6.12	10.01	3.89	5.00
Albite	28.82	33.01	28.30	40.87	26.20	26.20	23.58	23.60	20.96	20.96	23.06	29.87	23.58	23.06
Anorthite	10.01	3.06	5.56	12.23	33.64	33.64	31.75	35.30	31.41	35.03	30.86	6.12	34.19	19.46
Diopside:														
Wollastonite	------	------	------	3.60	2.90	2.90	3.94	1.28	3.71	------	------	------	2.32	3.12
Enstatite	------	------	------	1.20	2.00	1.70	2.40	1.10	2.10	------	------	------	1.60	2.20
Ferrosilite	------	------	------	2.51	.66	1.06	1.32	------	1.45	------	------	------	.53	.66
Hypersthene:														
Enstatite	.90	------	------	2.80	3.90	4.60	6.20	4.90	9.50	7.20	5.00	------	5.90	6.40
Ferrosilite	.92	------	1.85	5.94	1.32	2.90	3.30	------	6.60	2.04	------	.53	2.11	2.24
Magnetite	70	.23	.40	2.09	3.48	3.02	3.71	5.57	3.25	5.34	6.73	.93	5.31	4.41
Ilmenite	30	.30	.15	1.37	1.06	.91	91	1.22	1.06	1.22	2.58	.30	1.22	1.37
Hematite	------	.96	------	------	------	------	------	.96	------	------	3.04	------	------	------
Apatite	Tr	Tr	Tr	67	Tr	Tr	Tr	Tr	.67	Tr	.67	Tr	Tr	Tr
Sillimanite	------	1.62	------	------	------	------	------	------	------	------	------	.32	------	------
Cordierite	------	------	2.01	------	------	------	------	------	------	4.67	.81	1.43	------	------
Calcium carbonate	------	------	------	------	------	------	------	1 32	------	------	------	------	------	4.90
Normative feldspar (molecular percent)														
Orthoclase	19	16	27	17	5	5	4	7	7	4	10	21	6	10
Albite	61	77	61	65	43	43	40	39	38	37	40	66	40	50
Anorthite	20	7	12	18	52	52	56	54	55	59	50	13	54	40
Normative pyroxene (molecular percent)														
Wollastonite	------	------	------	22	25	21	22	------	15	------	------	------	17	20
Enstatite	------	------	------	29	60	53	55	------	55	------	------	------	66	64
Ferrosilite	------	------	------	49	15	26	23	------	30	------	------	------	17	16

[1] Weathered rock.

1. Hornblende-bearing dacite porphyry; block in dacitic volcanic plug, 0.75 mile east of Point Flores, northwest Saipan. Specimen S139. A. C. Vlisidis and S. M. Berthold, analysts.
2. Dacite; thin flow in Sankakuyama formation, summit of Mount Achugau, northeast-central Saipan. Specimen S317. F. A. Gonyer, analyst.
3. Dacite vitrophyre; thin massive layer in flow breccia of Sankakuyama formation, 0.25 mile south of Kalabera, northeast Saipan. Specimen S448. A. C. Vlisidis and S. M. Berthold, analysts.
4. Augite andesite; Magpi ruin, north Saipan. Klüss, analyst (Kaiser, 1903, p. 120).
5. Augite-hypersthene andesite; block in andesite breccia of Hagman formation, Sabanan Talofofo, north-central Saipan. Specimen S67A. A. C. Vlisidis and S. M. Berthold, analysts.
6. Augite-hypersthene andesite; block in andesite breccia of Hagman formation, Sabanan Talofofo, north-central Saipan. Specimen S37 A. C. Vlisidis and S. M. Berthold, analysts.
7. Augite-hypersthene andesite; block in andesite breccia of Hagman formation, Sabanan Talofofo, north-central Saipan. Specimen S107. A. C. Vlisidis and S. M. Berthold, analysts.
8. Augite-hypersthene andesite; flow in Hagman formation, lower course of Talofofo Creek, north-central Saipan. Specimen S15. F. A. Gonyer, analyst.
9. Augite-hypersthene andesite; block in andesite breccia of Hagman formation, 0.75 mile east of Point Flores, northwest Saipan. Specimen S135. A. C. Vlisidis and S. M. Berthold, analysts.
10. Hypersthene andesite; block in andesite breccia of Hagman formation, Laulau Bay, southeast Saipan. S. Tanaka, analyst (Tsuboya, 1932, p. 211).
11. Augite andesite; flow in Fina-sisu formation, northern As Lito, southwest Saipan. Specimen S636A. Leonard Shapiro and S. M. Berthold, analysts.
12. Average dacite of Saipan; average of analyses 1, 2, and 3.
13. Average andesite of Saipan; average of analyses 5, 6, 7, 8, 9, 10, and 11.
14. Augite basalt; pillowed flow, east flank of Mount Santa Rosa, northeast Guam. Specimen G-S48-85A. Leonard Shapiro and S. M. Berthold, analysts.

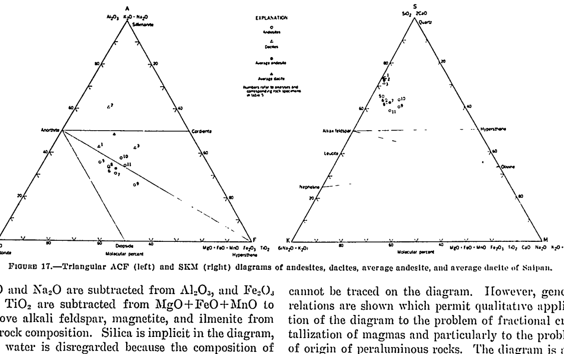

FIGURE 17.—Triangular ACF (left) and SKM (right) diagrams of andesites, dacites, average andesite, and average dacite of Saipan.

K_2O and Na_2O are subtracted from Al_2O_3, and Fe_2O_3 and TiO_2 are subtracted from $MgO+FeO+MnO$ to remove alkali feldspar, magnetite, and ilmenite from the rock composition. Silica is implicit in the diagram, and water is disregarded because the composition of the rocks is considered only in terms of water-free (dry) components. The corners and midpoints of the sides of the diagram represent various mineral phases as shown, and the composition of any rock can be expressed in terms of three normative mineral phases, depending on where it falls in the diagram. The lines (joins) connecting the points representing the various minerals form subsidiary triangles within the diagram which may represent separate ternary chemical systems, the joins representing phase boundaries between the separate systems, and the minerals at the corners of each subsidiary system representing stable (compatible) mineral assemblages.

Rocks that lie in the anorthite-cordierite-hypersthene and sillimanite-anorthite-cordierite triangles are peraluminous. In general, felsic members of calc-alkaline rock associations tend to lie in the peraluminous triangles, whereas mafic and alkalic rocks lie in the anorthite-diopside-hypersthene triangle or off the diagram (negative A) in the case of some alkalic rocks. The analyzed dacites of Saipan tend to lie in the peraluminous anorthite-cordierite-hypersthene triangle, and the andesites, with two exceptions, lie in the anorthite-diopside-hypersthene triangle near the anorthite-hypersthene join.

The location of the boundary curves of the various mineral fields and the shape of the liquidus surface within the ACF triangle are not known, and therefore the course followed by a crystallizing liquid (magma) cannot be traced on the diagram. However, general relations are shown which permit qualitative application of the diagram to the problem of fractional crystallization of magmas and particularly to the problem of origin of peraluminous rocks. The diagram is also useful in comparing members of rock series and rock provinces.

The SKM diagram of figure 17 shows the composition of the analyzed rocks of Saipan in terms of three components where S, K, and M are the molecular amounts: $S=SiO_2-2CaO$, $K=6(Na_2O+K_2O)$, and

$$M=MgO+FeO+MnO-Fe_2O_3-TiO_2-CaO-Na_2O-K_2O+Al_2O_3.$$

The diagram is a modification of the von Wolff (QLM) triangle (von Wolff, 1923, p. 35–45; Johannsen, 1939, p. 110) as devised by James B. Thompson of Harvard University. In the diagram, the horizontal line at 50 represents, as in the standard von Wolff triangle, the silica-saturation line. Above this line all rocks contain an excess of silica (oversaturated rocks) and minerals that are fully saturated with silica, and below this line all rocks are deficient in silica (undersaturated) and contain one or more minerals with less silica than is required for saturation. Saturated rocks lie on or slightly above or below the line. The end points of the horizontal line at 50 represent normative alkali feldspar and hypersthene, rather than the normative total feldspar and total pyroxene of the von Wolff triangle. The left line of the triangle comprises the leucocratic (sialic) constituents alkali feldspar, leucite, and nepheline, and the right line of the triangle comprises the melanocratic (femic) constituents hypersthene and olivine. The principal advantage of the SKM diagram over the von

Wolff triangle is that the lines connecting normative minerals become valid as phase boundaries with the removal of the lime-bearing feldspar and pyroxene. The diagram is thus a partial graphic solution of the norm, and the composition of any rock can be expressed in terms of a combination of three normative mineral components, depending on where it falls in the diagram. The andesites and dacites of Saipan lie in the upper triangle of the diagram formed by the lines connecting quartz, alkali feldspar, and hypersthene.

Anorthite, diopside, magnetite, and ilmenite are removed from the rock composition as plotted on the diagram by subtracting the molecular amounts of SiO_2, FeO, and MgO contained in these minerals from the S and M components of the diagram. Thus, twice the amount of CaO (less CaO in apatite) in any rock is the amount of normative silica in anorthite and diopside and is accordingly subtracted from total silica; Fe_2O_3 in any rock is the amount of normative FeO in magnetite and is accordingly subtracted from total $FeO+MgO$ in the rock; TiO_2 in any rock is the amount of normative FeO in ilmenite and is accordingly subtracted from total $MgO+FeO$ in the rock; and the quantity $CaO-(Al_2O_3-Na_2O-K_2O)$ in any rock is the amount of CaO in diopside, which in turn equals the amount of $MgO+FeO$ in diopside, and is therefore subtracted (the expression then becomes

$$-CaO-Na_2O-K_2O+Al_2O_3)$$

from total $MgO+FeO$ in the rock. The component K, representing total alkalies, is taken as six times the total alkali content to bring the position of alkali feldspar up to the midpoint of the left side of the diagram. The removal of anorthite, diopside, magnetite, and ilmenite from the rock composition has the effect of placing individual rocks in their proper position in the diagram with respect to the true proportion of normative minerals in the rocks.

The SKM diagram is useful in comparing rocks of various petrographic provinces and in the study of differentiation in a rock series by crystal fractionation.

COMPARISON WITH VOLCANIC ROCKS OF OTHER PACIFIC ISLANDS AND WITH DALY'S AVERAGE ROCK TYPES

TINIAN, ROTA, AND GUAM

Volcanic rocks presumed to be of late Eocene age are exposed beneath Miocene limestones in north-central Tinian at Mount Lasso and in the south-central part of the island of Carolinas Hill. The rocks of Mount Lasso consist of deeply weathered andesitic pyroclastic rocks which bear a close resemblance to the more highly weathered parts of the breccia-tuff facies of the Hagman formation on Saipan. At Carolinas Hill, the rocks are of hornblende-bearing andesitic sandstones and pebble conglomerates containing fragments of hornblende-augite andesite and pyroxene andesite. The hornblende andesites are generally less mafic and perhaps somewhat more silicic than the pyroxene andesites of Saipan.

On Rota, volcanic rocks of supposedly late Eocene age are exposed in a steep escarpment along the south side of the island and in smaller outcrops atop and around the edges of a central limestone plateau. They resemble the volcanic rocks of Saipan, Tinian, and Guam. Yoshii (1936, p. 18–19) describes specimens of hornblende-augite andesite, hypersthene-augite andesite, and augite-andesite tuff from this island.

Tertiary volcanic rocks are exposed over a wide area on Guam. According to J. T. Stark and S. O. Schlanger (oral communication, January 1954), these rocks may be divided into two sequences: an older sequence of folded and faulted basaltic and andesite pyroclastic rocks and minor basalt flows of late Eocene age, and a younger succession of gently inclined, eastwardly dipping olivine-bearing pillow basalt flows and basaltic and andesitic pyroclastic rocks of Miocene age. The Eocene volcanic rocks are exposed over several tens of square miles in the southern half of the island and in three small inliers on the northern limestone plateau at Mount Santa Rosa, Mataguac Hill, and Palia Hill. The Miocene volcanic rocks crop out over a wide area in the extreme southern part of Guam and overlie the older volcanic rocks with pronounced angular unconformity. The combined stratigraphic thickness of the Eocene and Miocene succession is several thousand feet.

The pyroclastic rocks of Guam are principally breccias and tuffs and water-laid volcanic conglomerates, tuffaceous sandstone, and shales. The entire volcanic succession, including the basalt flows, is believed by Stark to be of submarine origin. The principal lithic differences between the volcanic rocks of Guam and those of Saipan are the abundance of pillow basalt flows, the presence of basaltic fragments in the pyroclastic rocks, the absence of large masses of dacitic rocks, and the possible absence of subaerially deposited volcanic rocks in the sequence on Guam. Hypersthene dacite, containing abundant phenocrysts of quartz and probably approaching the composition of the dacitic rocks of Saipan, is found on Guam only as scattered accessory inclusions in andesitic conglomerate beds of the Eocene series at Mount Santa Rosa and near the former village of Fena (now flooded by waters of the Fena Reservoir) in the south-central part of the island (Cloud, Schmidt, and Burke, 1956). Aside from these basic differences, however, equivalent rocks of the two islands are generally much alike. Volcanic rocks of

Guam are plotted on the ACF and SKM diagrams of figure 18, from which it is evident that the chemical compositions of various effusive rock types of Guam and Saipan are in close agreement.

A chemical analysis of basaltic flow rock from Guam is given in table 5. Although the rock has an exceptionally high content of silica it is considered a basalt, for the actual content of silica in fresh rock from this flow is probably much less than is indicated by the analysis, a large amount of silica having been introduced in the form of chalcedony, which fills irregular cavities in the rock.

PALAU, YAP, AND BONIN ISLANDS

The Palau Islands form a short arcuate island group centered at about long 134°30′ E. and lat 7°35′ N. (fig. 11). The island chain is about 100 miles long in a generally north-south direction and consists of 10 large islands and several hundred smaller islands and minute islets. The larger islands in the northern part of the group are mainly formed of volcanic rocks; the larger islands in the southern part of the group and the smaller islands and islets are composed of coral-algal and clastic limestones. The largest island of the Palau group is Babelthuap, about 30 miles long in a north-south direction. Volcanic rocks are exposed over most of Babelthuap and the nearby islands of Koror, Arakabesan, and Malakal.

According to an unpublished report by Gilbert Corwin, to which he has kindly given permission to refer, the volcanic rocks of Babelthuap, Koror, Arakabesan, and Malakal are of late Eocene and possibly in part of early Oligocene age. They consist mainly of pyroclastic rocks but include minor intercalated flows. The rocks are mostly andesitic, but the petrogenic series of Palau comprises a much greater and more complete range of types and is generally more mafic than that of Saipan. Rock types from the Palau Islands described by Corwin include olivine-augite basalt, hypersthene-bearing augite basalt, hypersthene-augite basalt, hornblende-bearing pyroxene gabbro, augite-hypersthene andesite, hornblende-pyroxene andesite, hornblende dacite, and biotite dacite. The basaltic rocks are primarily confined to the lower part and the dacites and andesites to the upper part of the volcanic succession.

Basaltic rocks, and rocks intermediate between calcic andesite and silicic dacite, such as hornblende andesite and hornblende dacite, are unknown on Saipan. The volcanic rocks of the Palau Islands are plotted on the ACF and SKM diagrams of figure 18, from which it may be seen that the andesites and silicic dacites of Palau are similar in composition to the andesites and dacites of Saipan.

The Yap island group, situated at about long 138°08′ E. and lat 9°30′ N. (fig. 11), about 530 miles south-southwest of Guam, includes 4 principal islands—Yap, Gagil-Tomil, Map, and Rumong. These islands form a compact group 16 miles long and 8 miles wide and are of special interest geologically, for they consist mainly of metamorphosed basement rocks. Rock specimens from the Yap island group have been described briefly by Kaiser (1903, p. 93–110), Koert and Finckh (1920, p. 5–10), Tsuboya (1932, p. 207–208), Tayama (1935, p. 25–38), and Yoshii (1936, p. 38–50).

Metamorphic rocks are exposed on all of the main islands and underlie about three-fourths of the land area. The most common rock of the basement sequence is a green amphibolite schist consisting of actinolite, albite, and accessory titanite and magnetite (Tsuboya, 1932, p. 207). Other rock types of this sequence, described by Yoshii (1936, p. 38–50), include epidote amphibolite, green schist, talc schist, diopside-calcite hornfels, hornblende-feldspar hornfels, hornblende sandstone, olivine pyroxenite, diallage peridotite, hornblendite, serpentine, uralite diabase, norite, and gabbro. C. G. Johnson (written communication, June 8, 1954), who carried out a detailed geologic study of the Yap island group in 1948, reports that the mafic and ultramafic igneous rocks mostly occur as fragments in amphibolite-schist breccia and conglomerate of Tertiary age which overlie the basement rocks on the larger islands. On Gagil-Tomil, Johnson found small bodies of gabbro and serpentine. He did not find outcrops of the other types of mafic and ultramafic rock listed by Yoshii.

In addition to mafic and ultramafic rocks, the Tertiary amphibolite-schist breccia has yielded fragments of granitic rock. The occurrence of this rock type at Yap was first mentioned by Kaiser (1903, p. 107), who recorded the presence of small fragments of amphibole (hornblende?) granite and amphibole (hornblende?) syenite in amphibolite-schist breccia on Map. Johnson (written communication, June 8, 1954), in his later study, also found fragments of "granite" or granitelike rock in the breccia on Map.

The basement rocks of the Yap island group are strongly folded and faulted, and the schistosity of the rocks trends north-northeastward, parallel to the direction of trend of the larger structural features of the Yap arc. Hess (1948, p. 432) believes that the metamorphic rocks are probably of Mesozoic age and that the mafic igneous rocks, which intrude the metamorphosed sequence, are considerably younger and related to an early Tertiary orogeny that formed the Yap trench and arc.

The rocks of the basement complex are overlain un-

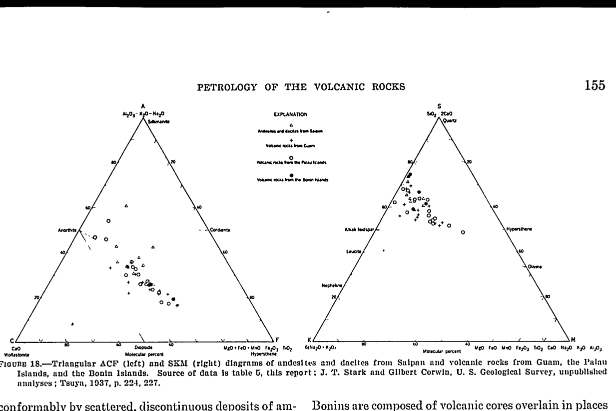

FIGURE 18.—Triangular ACF (left) and SKM (right) diagrams of andesites and dacites from Saipan and volcanic rocks from Guam, the Palau Islands, and the Bonin Islands. Source of data is table 5, this report; J. T. Stark and Gilbert Corwin, U. S. Geological Survey, unpublished analyses; Tsuya, 1937, p. 224, 227.

conformably by scattered, discontinuous deposits of amphibolite-schist breccia (possibly of tectonic origin), conglomerate, sandstone, siltstone, and marl—the Map formation—and this sequence is overlain by an extensive deposit of volcanic breccia and tuff known as the Tomil agglomerate (C. G. Johnson, letter to P. E. Cloud, Jr., May 29, 1952). The fine-grained clastic beds of the Map formation have yielded larger Foraminifera which W. S. Cole (letter to C. G. Johnson, December 9, 1952) refers to the Miocene (Tertiary f_1 of the Indonesian classification). Marl beds of this sequence contain Radiolaria of probable Oligocene or lower Miocene age according to W. R. Riedel (written report to P. E. Cloud, Jr., November 14, 1952). However, it appears to Riedel that the Radiolaria are contained in lumps of reworked material somewhat older than the matrical sediment, suggesting that the marl might be slightly younger than the included fauna. The relationship of the amphibolite-schist breccia to the sedimentary rocks has not been established, but Johnson (written communication, June 8, 1954) considers the deposit as part of the Map formation and of probable Miocene age, though perhaps somewhat older than the clastic sequence. Although fossils have not been found in the Tomil agglomerate, Johnson believes that it is of Miocene age and slightly younger than the rocks of the Map formation. Yoshii (1936, p. 14, 16) describes augite andesite and andesitic tuff from the Tomil agglomerate which are similar in their mineralogy to varieties of andesite on Saipan.

The Bonin Islands lie east and north of the Volcano Islands and are centered at approximately long 147°30′ E. and lat 26°30′ N. (fig. 11). The larger islands of the Bonins are composed of volcanic cores overlain in places by Miocene and younger limestones. Eocene limestones are reportedly associated with the volcanic sequence on Haha Jima (Yoshiwara, 1902, p. 297, 300–301; Tsuya, 1937, p. 222–223, 225). The volcanic rocks consist of flows, agglomerates, tuff breccias, and tuffs, and some of the tuffs are water laid and contain Camerinid Foraminifera, signifying a late Eocene age.

According to Tsuya (1937, p. 223–228), the major volcanic rock types of the Bonin Islands are two-pyroxene (augite-hypersthene) andesite, olivine-bearing augite-hypersthene andesite, quartz-bearing augite-hypersthene andesite, aphyric augite-pigeonite andesite, olivine-augite-bronzite andesite (boninite), andesite perlite, and quartz-bearing augite-hypersthene andesite or pyroxene dacite.

Compositions and norms of andesitic rocks from various localities in the Bonin Islands are given by Tsuya (1937, p. 224, 227), and three superior analyses from this report are plotted on the ACF and SKM diagrams of figure 18. The andesites of the Bonin Islands have less alumina and lime and a slightly higher average potash content than the andesites of Saipan, and they are therefore not so rich in calcic plagioclase as their counterparts on Saipan, though in other respects they are generally similar. A specimen of augite-hypersthene andesite described by Tsuya (1937, p. 223) has a mineral composition and texture much like that of some varieties of andesite from Saipan, and, according to Tsuya, this is the most abundant type of rock in the volcanic sequence of the Bonin Islands. The rock is porphyritic with phenocrysts of zoned plagioclase (anorthite to calcic labradorite), augite, and hypersthene enclosed in a groundmass containing medium labradorite, augite, pigeonitic (subcalcic) augite, silica minerals, and magnetite. The quartz-bearing two-pyroxene andesite, or pyroxene dacite, of the Bonin Islands, also described by Tsuya (1937, p. 228), is a porphyritic rock containing phenocrysts of labradorite, augite, hypersthene, and indented quartz and is petrographically similar to the quartz-bearing pyroxene andesites of Saipan. Some of the andesites of the Bonin Islands, however, contain small olivine phenocrysts, and other andesites contain pigeonite in the groundmass and have a normative pyroxene composition that appears to be considerably higher in ferrosilite than that of the andesites of Saipan. So-called boninite is a olivine-augite-bronzite andesite.

Contrary to published reports, basement rocks older than the volcanic series are not known to be exposed on any of the Bonin Islands. The presence of serpentine at Kurose, Ototo Jima, in the Chichi Jima group, was mentioned by Yoshiwara (1902, p. 297) on the basis of a report by Susuki (1885), and this was later interpreted by Hess (1948, p. 430) as representing serpentinized periodotite of the pre-Eocene basement series. Yoshiwara did not, however, specify the relationship of the serpentine to the volcanic rocks and limestones, but merely stated that "Mr. Susuki has described serpentine from Kurose in Ototo-jima." From the translation of Susiki's report (1885), on file with the U. S. Geological Survey, it is evident that his report of serpentine in the Bonin Islands was misinterpreted. The only mention of serpentine by Susuki (p. 7) is to the effect that it forms an alteration product in augite andesite—"Frequently the weathered surface of this rock being smooth, presents greasy luster, and has altered into serpentine, * * *. Sometimes the crystal (augite) keeps its original form and has altered into serpentine."

NORTHERN MARIANA AND VOLCANO ISLANDS

The northern Marianas form a regular arcuate chain of active and recently active Quaternary volcanoes composed of basaltic and andesitic flows and pyroclastic rocks. The writer has made a preliminary examination of rocks from five of the northern islands which indicates that basaltic rocks are abundant on northern Pagan and southern Agrihan, and andesites are abundant on Alamagan, Sarigan, and Anatahan. The principal rock types from these islands are olivine-bearing augite-hypersthene (bronzite) basalt, olivine-bearing augite basalt, hypersthene-augite basalt, augite basalt, olivine-bearing augite-hypersthene andesite, and augite-hypersthene andesite.

Yoshii (1936, p. 14–22) and Tayama (1936b) report andesite as a common rock type of the northern Mariana Islands, and Yoshii describes augite andesite, hypersthene-augite andesite, and olivine-augite andesite from southern Pagan, and olivine basalt, olivine andesite, and hypersthene-augite andesite from Maug. Tanakadate (1940, p. 220) lists 2 analyses of hypersthene-augite andesite, and Kaiser (1903, p. 117) lists 1 analysis of augite-hypersthene andesite from the south coast of Pajaros, the northernmost island of the chain.

Chemical compositions and norms of major volcanic rock types of the northern Mariana Islands are given in table 6, and these rocks are plotted on the ACF and SKM diagrams of figure 19. A common rock type of

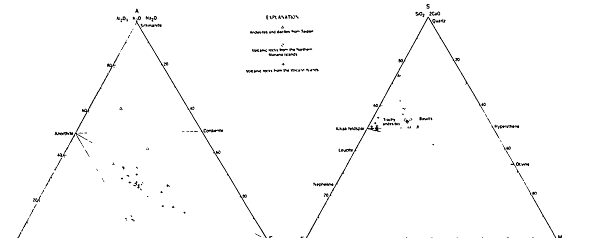

FIGURE 19.—Triangular ACF (left) and SKM (right) diagrams of andesites and dacites from Saipan and volcanic rocks from the northern Mariana and Volcano Islands. Source of data is tables 5 and 6, this report; Macdonald, 1948, p. 1016

the islands of Alamagan, Pagan, and Agrihan, in the central part of the northern Marianas chain, is olivine-bearing pyroxene basalt (table 6). This rocks bears a fairly close compositional resemblance to Tertiary and Quaternary basalts of the Izu Peninsula region of Japan, which are described below, but more nearly resembles basalt of the Huzisan (Fujiyama) volcano (table 10), which has a somewhat higher average potash

TABLE 6.—*Chemical analyses and norms of volcanic rocks from the northern Mariana Islands*

	1	2	3	4	5	6	7	8	9	10	11	12
Analyses (weight percent)												
SiO_2	49.89	50.30	50.52	50.87	50.99	51.46	53.09	52.80	53.94	57.00	51.01	54.58
TiO_2	.80	1.06	1.04	.95	.97	------	.80	.86	------	------	.94	.70
Al_2O_3	18.89	18.12	16.94	15.46	16.98	17.66	16.28	21.39	19.59	17.47	17.19	19.48
Fe_2O_3	3.28	4.50	2.70	4.32	3.39	2.62	4.52	2.10	2.69	4.59	3.62	3.13
FeO	6.74	6.66	8.59	8.20	8.29	8.18	4.71	6.22	6.65	4.43	7.32	5.77
MnO	.19	.21	.22	.21	.21	.20	.19	.14	.17	------	.20	.15
MgO	4.74	4.80	5.37	5.55	4.74	4.57	6.00	2.40	2.44	3.23	5.11	2.69
CaO	11.81	10.80	10.75	10.64	10.03	11.00	10.20	10.50	9.80	8.51	10.75	9.60
Na_2O	2.44	2.50	2.68	2.63	2.90	2.40	2.57	2.76	2.67	2.98	2.59	2.80
K_2O	.61	.70	.76	.71	.78	.63	.88	.62	.67	1.15	.72	.81
H_2O-	.06	.13	.05	.02	.06	.07	.07	.06	.10	} .21	.06	.08
H_2O+	.10	.23	.13	.24	.30	.32	.43	.10	.15		.25	.12
P_2O_5	.25	.16	.18	.24	.24	.12	.25	.15	.12	.19	.20	.15
Total	99.80	100.17	99.93	100.04	99.88	99.23	99.99	100.10	98.99	99.76	99.96	100.06
Norms (weight percent)												
Quartz	1.68	3.60	0.18	2.34	1.74	2.94	6.78	6.30	8.64	12.78	2.88	9.42
Orthoclase	3.34	3.89	4.45	3.89	4.45	3.34	5.00	3.34	3.89	6.67	3.89	5.00
Albite	20.44	20.96	22.53	22.53	24.63	20.44	21.48	23.58	22.53	25.15	22.01	23.58
Anorthite	38.92	36.14	31.97	28.08	31.14	35.86	30.58	44.20	39.58	30.86	33.36	38.09
Diopside:												
Wollastonite	8.24	7.31	8.93	10.32	7.66	7.77	8.35	3.36	3.83	4.76	8.35	3.94
Enstatite	4.50	4.40	4.60	5.70	3.90	3.50	6.00	1.40	1.50	2.90	4.70	1.90
Ferrosilite	3.43	2.51	4.09	4.22	3.56	4.22	1.58	1.98	2.38	1.58	3.30	1.98
Hypersthene:												
Enstatite	7.30	7.60	8.80	8.20	7.90	7.80	9.00	4.60	4.60	5.20	8.10	4.80
Ferrosilite	5.02	4.62	8.05	6.07	7.26	9.11	2.38	6.20	7.79	2.77	5.94	4.88
Magnetite	4.64	4.48	3.94	6.26	4.87	3.71	6.50	2.08	3.94	6.73	5.34	4.41
Ilmenite	1.52	2.13	1.98	1.82	1.82	------	1.52	1.67	------	------	1.82	1.37
Apatite	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
Normative feldspar (molecular percent)												
Orthoclase	5	6	7	7	7	5	9	5	6	10	6	7
Albite	34	36	40	43	42	36	39	34	36	42	39	37
Anorthite	61	58	53	50	51	59	52	61	58	48	55	56
Normative pyroxene (molecular percent)												
Wollastonite	28	27	25	29	25	24	29	19	19	26	27	22
Enstatite	47	50	44	45	44	40	60	40	36	52	47	44
Ferrosilite	25	23	31	26	31	36	11	45	45	22	26	34

1. Olivine-bearing augite basalt; pahoehoe flow, 2,000 feet north of Bandeera Peninsula, northwest Pagan. Specimen P5. Leonard Shapiro and S. M. Berthold, analysts.

2. Olivine-bearing augite basalt; pahoehoe flow, central crater of Mount Pagan, northern Pagan. Analysis by Imp. Japanese Geol. Survey (Tanakadate, 1940, p. 220).

3. Augite basalt; thin flow, promintory at landing beach, southern Agrihan. Specimen AG4. Leonard Shapiro and S. M. Berthold, analysts.

4. Olivine-bearing augite basalt; aa flow, floor of caldera, 2,500 feet east of Bandeera Peninsula, northwest Pagan. Specimen P8. Leonard Shapiro and S. M. Berthold, analysts.

5. Olivine-bearing augite basalt; thin flow, base of caldera wall, 6,000 feet southeast of Bandeera Peninsula, northwest Pagan. Specimen P6. Leonard Shapiro and S. M. Berthold, analysts.

6. Olivine-bearing augite basalt; pahoehoe flow, central crater of Mount Pagan, northern Pagan. S. Tanaka, analyst (Tanakadate, 1940, p. 220).

7. Olivine-bearing augite basalt; pahoehoe flow, 1,500 feet southwest of native village, southern Alamagan. Specimen AL7. Leonard Shapiro and S. M. Berthold, analysts.

8. Augite-hypersthene andesite; aa flow, south coast of Farallon de Pajaros. Analysis by Imp. Japanese Geol. Survey (Tanakadate, 1940, p. 220).

9. Augite-hypersthene andesite; aa flow, foot of volcanic cone, southeast Farallon de Pajaros. S. Tanaka, analyst (Tanakadate, 1940, p. 220).

10. Augite-hypersthene andesite; Farallon de Pajaros. Eyme, analyst (Kaiser, 1903, p. 117).

11. Average basalt; average of analyses 1, 2, 3, 4, 5, 6, and 7.

12. Average andesite; average of analyses 8, 9, and 10.

content than the basalt of Izu. The andesites of Pajaros (table 6) are somewhat higher in iron and potash and lower in silica and magnesia than average andesite of Saipan. The molecular ratio of MgO to FeO (all iron calculated as FeO) is approximately 0.56 in the average andesite of Pajaros and 0.80 in the average andesite of Saipan. Aside from these minor differences, however, there is a close similarity betwen the andesites of the northern Mariana Islands and those of Saipan.

The Volcano Islands, or Kazan Retto, are active and recently active volcanic islands which lie to the south and slightly to the west of the Bonin Islands, between lat 24°–26° N. and long 141°–142° E. (fig. 11). The middle member of the three islands of this group, Iwo Jima, is composed entirely of trachyandesite flows and pyroclastic rocks, described by Tsuya (1936, p. 472–479; 1937, p. 316–320) and Macdonald (1948, p. 1009–1018) as augite and augite-hornblende trachyandesites. Tsuya (1936, p. 479) also describes rare inclusions of augite syenite in tuff beds on Iwo Jima. Trachyandesites in the form of pumice and obsidian were erupted from the submarine cone Sin Iwo Jima, located 3 miles northwest of Minami (South) Iwo Jima, during violent explosive activity in 1904 and again in 1914. Kita (North) Iwo Jima is built of flows and pyroclastic rocks composed of augite basalt and augite-olivine basalt (Tsuya, 1937, p. 282–284). The nature of the volcanic rocks of Minami Iwo Jima is not known. Southward from the Volcano Islands, the submarine ridge on which the islands are situated is deeply submerged (fig. 12), but several sharp peaks along the crest of the ridge here are probably submerged inactive volcanoes.

The trachyandesites of the Volcano Islands are distinctly more alkalic than the ordinary andesites of the Izu Peninsula region of Japan and the andesites of the Bonin, Mariana, and Palau Islands. The lavas of Iwo Jima are also richer in alkalies and poorer in lime than Daly's average world andesite (Daly, 1933, p. 16). They have been compared to the trachytes of the Hawaiian Islands, but their composition is more like that of the Hawaiian oligoclase andesites (Macdonald, 1948, p. 1017). The rocks of the Volcano Islands, analyses of which are given by Macdonald (1948, p. 1016), are plotted on the ACF and SKM diagrams of figure 19.

The pyroxene basalt of Kita Iwo Jima shows no apparent alkaline characteristics and has a chemical composition that is closely similar to typical basalts of the Izu Peninsula region of Japan (see figs. 19, 20).

IZU PENINSULA REGION OF JAPAN AND IZU ISLANDS

The Izu Peninsula lies southwest of the city of Tokyo and extends southward from the southern coast of central Honshu, forming the western shore of Sagami Bay (fig. 11). The peninsula is situated in the southern part of the so-called Fossa Magna, a great structural depression trending southeastward across central Honshu.

The surface rocks of the Izu Peninsula region are mostly of volcanic derivation and are separated into a complex rock sequence of early Miocene(?) to late Pliocene age (Neogene), and a younger sequence of dominantly Quaternary volcanoes and complex volcanic fields generally referred to as the Fuji (Huzi) volcanic zone.

The Tertiary (Neogene) volcanic sequence of Izu consists of various rock types that range from olivine basalt to biotite liparite (rhyolite). Table 7 presents this sequence in a simplified form.

The Quaternary volcanic sequence of Izu ranges in age from early Pleistocene to Recent and comprises a complex interrelated group of volcanoes and volcanic fields. Table 8 gives the sequence in its simplest form. Fujiyama is the only member of this group of volcanoes known to have been active in historic time.

The Izu Islands lie in a nearly straight line along the 140th meridian south of Sagami Bay (fig. 11) and form a chain of active and recently active Quaternary volcanoes that are the southward continuation of the Fuji volcanic zone. Seven of these volcanoes have been active in historic time. Ōshima was active in late 1951 and again in early 1952. Most recently (September 1952), violent eruptions occurred at Myojin reef, in the vicinity of Beyonesu Gan (Bayonnaise Rocks), from a submarine volcanic cone (Niino and others, 1953).

Tsuya (1937, p. 277–316) describes the following major rock types from the Izu Islands: olivine basalt, augite-olivine basalt, olivine-augite-hypersthene andesite, olivine-bearing augite-hypersthene andesite, hypersthene andesite, pyroxene plagioliparite (dacite, soda rhyolite), hornblende plagioliparite, hornblende-bearing hypersthene plagioliparite, biotite plagioliparite, and potash liparite (rhyolite). Kodushima and Niishima are the two liparitic (dacitic, rhyolitic) volcanoes of the island group.

Chemical compositions and norms of Tertiary and Quaternary porphyritic rocks from the Izu Penisula and Izu Islands are given by Tsuya (1937, p. 235–315), and Kuno (1950b, p. 1000–1002, 1004–1006) lists analyses of rocks from Hakone Volcano. The basalts and andesites of the Izu region are notably rich in CaO and poor in alkalies, compared with the average basalt and andesite of the world, and the rocks are characteristically rich in calcic plagioclase, are relatively low in mafic mineral constituents, and have a significantly large amount of quartz in the norm. According to Kuno (1950b, p. 1003) not a single example is known in which excess silica does not appear in the norm of these rocks. The average alkali-lime index of the petrogenic series of Izu is about 65.4 (Tsuya, 1937, p. 343).

TABLE 7.—*Sequence of Tertiary volcanic rocks of the Izu Peninsula region, Japan* [1]

Age	Izu Peninsula [2]	Hakone Volcano and adjacent areas [3]	
		Group, series, or formation	Character
Pliocene	Pyroxene dacite	Hata basalt group.	Flows and tuffs of olivine basalt and augite-hypersthene andesite.
	Pyroxene andesite.	Aziro basalt group.	Flows and pyroclastic rocks of olivine-bearing pyroxene basalt and hypersthene-augite andesite.
	Basalt.	Hatu-sima basalt group.	Flows and minor pyroclastic rocks of olivine-rich basalt and hypersthene andesite.
	Hornblende-pyroxene dacite (Hiyekawa beds).	Tensyô-san basalt group.	Flows and pyroclastic rocks of olivine-pyroxene basalt, basic pyroxene andesite, and hornblende-pyroxene andesite.
	Pyroxene andesite.	Ainohara andesite group.	Flows and pyroclastic rocks of pyroxene and olivine-pyroxene andesite.
		Inamura andesite group.	Pyroclastic rocks and minor flows of pyroxene andesite.
		Asigara beds.	Volcanic conglomerate, sandstone, and shale with interbedded flows and pyroclastic rocks of pyroxene andesite and pyroxene-hornblende andesite and dacite.
Miocene	Pyroxene andesite.	Sukumo-gawa andesite group.	Flows and pyroclastic rocks of pyroxene andesite.
	Hornblende dacite, biotite plagioliparite, potash liparite (Simoda beds).	Haya-kawa tuff breccias. Atami tuffs.	Tuff breccias, tuffs, and lapilli tuffs of pyroxene quartz dacite and pyroxene-hornblende-quartz dacite.
	Dacite, pyroxene andesite, calcareous tuffs, and *Miogypsina*- and *Lepidocyclina*-bearing limestone.	Hudô Tunnel basalt group.	Olivine-bearing pyroxene basalt flows.
	Propylite series (Yugasima beds). Dacite. Liparite. Andesite. Basalt.	Yugasima series. Misaka series.	Greenish flows and pyroclastic rocks of pyroxene andesite and basalt.

[1] The correlation between the rocks of the Izu Peninsula and those of Hakone Volcano and adjacent areas, as given in the table, is approximate. The exact correlation is unknown

[2] After Tsuya, 1937, p. 230.

[3] After Kuno, 1950a, p. 264, 266–268.

The analyses of andesites and dacites from Saipan (table 5) are in close agreement with their counterparts amongst the rocks of Japan, though the andesites of Saipan are somewhat lower in ferrous iron and magnesia than the andesites of Izu. Kuno (1950b, p. 993) divides the rocks of the Hakone region of the Izu Peninsula into a pigeonitic rock series and a hypersthenic rock series, the majority of the rocks falling into the first category and containing pigeonite in the groundmass. The andesites of Saipan do not carry pigeonite, the characteristic pyroxenes being hypersthene, augite, and subcalcic augite, and therefore the rocks conform more closely to members of the hypersthenic rock series of the Hakone region.

The dacites of Saipan resemble silicic dacites of the volcanoes of the Izu Peninsula and of Niishima and Kodushima in the Izu Islands. However, the dacites of Saipan are slightly higher in silica and lower in alumina and alkalies than their Japanese equivalents.

ACF and SKM diagrams of andesites and dacites from Saipan, Tertiary and Quaternary rocks from the Izu Peninsula region of Japan and the Izu Islands, and average rocks of the Hawaiian Islands are presented in figure 20. These diagrams indicate that the rocks of Saipan and those of the Izu Peninsula region and the Izu Islands are chemically and mineralogically very similar. The andesites of Saipan have a slightly lower pyroxene content than the andesites of Japan and are correspondingly somewhat richer in plagioclase and quartz. This agrees with the lower content of magnesia and ferrous iron and the higher content of alumina and lime in the andesites of Saipan. The dacites of Saipan

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TABLE 8.—*Sequence of Quaternary volcanic rocks of the Izu Peninsula region, Japan* [1]

Age	Volcano or formation	Character
Recent	Fuji volcano.	Olivine and pyroxene basalts with minor aphyric andesite.
Middle and Upper Pleistocene	Omura volcano.	Olivine and pyroxene basalt.
	Amagi volcano.	Complex volcano; olivine basalt, pyroxene andesite, hornblende dacite.
	Hakone volcano.	Complex volcano; olivine basalt, pyroxene andesite, pyroxene dacite, olivine-hypersthene andesite.
	Asitaka volcano.	Olivine and pyroxene andesite and minor olivine-augite-hypersthene basalt.
	Tensi volcano.	Olivine basalt and olivine-bearing pyroxene andesite.
	Yugawara volcano.	Basalt and pyroxene andesite.
	Taga volcano.	Olivine and pyroxene basalt and olivine and pyroxene andesite.
	Usami volcano.	Olivine and pyroxene andesite.
Lower Pleistocene	Sino-tanna beds. Sino Hata beds. Ono beds. Zyo beds.	Gravel, sand, mudstone, sandy tuff, tuffaceous shale, tuff, and tuff breccia containing fossil leaves and diatoms.
	Kuno's Hata and Aziro beds.	Basalt and pyroxene andesite flows and pyroclastic rocks.

[1] Modified from Tsuya, 1937, p. 250, 252–308; Kuno, 1950a, p. 265, 268–274.

and the dacites of Izu and the Izu Islands (Tsuya's plagioliparites) are peraluminous and contain cordierite and sillimanite in the norm. One of the plagioliparites from Izu and several from the Izu Islands are extremely high in alumina relative to alkalies and lime and, like one of the dacitic rocks from Saipan, fall above the anorthite-cordierite join in the ACF diagram (fig. 20). The dacites of Saipan are slightly richer in quartz and lower in alkali feldspar content than the Japanese dacites of equivalent character, and this is correlative with the higher content of silica and lower content of alumina and alkalies in the dacites of Saipan.

Although slight differences may be pointed out between the rocks of Saipan and those of the Izu volcanoes, it is well to emphasize that the chemical and mineralogical properties of individual rocks within the two geographic provinces are nearly identical, and, although widely separated in time of origin (the Japanese rocks are of post-Oligocene and mostly of post-Pliocene age), this close correspondence in composition indicates an origin under similar environmental conditions. The volcanoes of Izu, however, like the Quaternary volcanoes of the northern Mariana Islands, have produced great volumes of basalt, whereas this mafic rock is apparently absent in the volcanic sequences of Saipan, Tinian, and possibly also Rota, in the southern Marianas. Basaltic rocks are also unreported from the older Tertiary volcanic sequences of the Bonin and Yap island groups bordering the Philippine Sea. This feature may be of special significance, for it tends to suggest either that basaltic magmas were not produced in the period of early Tertiary volcanism which gave rise to these particular insular volcanic rocks or that, if they were produced, they lie below the volcanic rocks exposed at the surface of the islands. The presence of basalts on Guam and on the Palau Islands indicates the possibility that the volcanic rocks of Saipan, Tinian, and Rota and of the Bonin and Yap islands may actually represent the uppermost part and comprise the latest products of a volcanic succession that includes basaltic rocks at depth. However, if this is true, it is odd that basaltic inclusions are not found in the volcanic deposits of these islands.

HAWAIIAN ISLANDS

It is generally recognized that the volcanic rocks of the Pacific Ocean area may be grouped into two geographically distinct petrographic provinces: the basalt-andesite-dacite-rhyolite association of the Pacific margin (called the circum-Pacific province), and the olivine-basalt trachyte association of the island groups lying within the Pacific Basin (called the intra-Pacific province). The boundary between these two provinces is commonly referred to as the andesite line (see fig. 11), and throughout much of its length it marks a zone of petrologic, structural, and physiographic transition that is believed to be of fundamental importance to the consideration of the origin and distribution of Pacific rocks.

The rocks of the Hawaiian Islands form a prime ex-

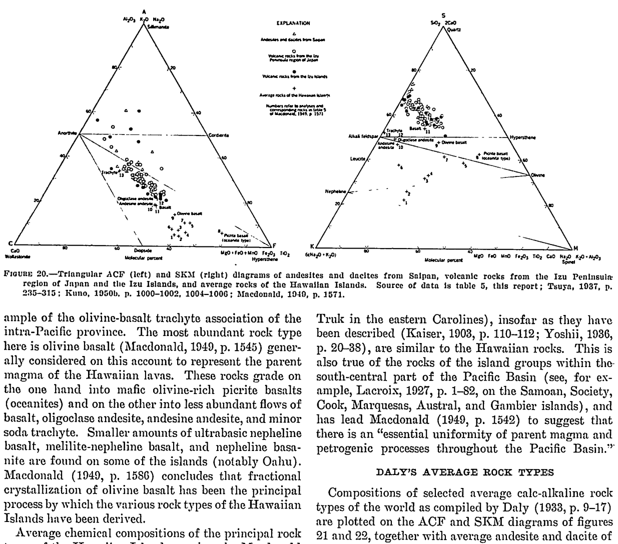

FIGURE 20.—Triangular ACF (left) and SKM (right) diagrams of andesites and dacites from Saipan, volcanic rocks from the Izu Peninsula region of Japan and the Izu Islands, and average rocks of the Hawaiian Islands. Source of data is table 5, this report; Tsuya, 1937, p. 235–315; Kuno, 1950b, p. 1000–1002, 1004–1006; Macdonald, 1949, p. 1571.

ample of the olivine-basalt trachyte association of the intra-Pacific province. The most abundant rock type here is olivine basalt (Macdonald, 1949, p. 1545) generally considered on this account to represent the parent magma of the Hawaiian lavas. These rocks grade on the one hand into mafic olivine-rich picrite basalts (oceanites) and on the other into less abundant flows of basalt, oligoclase andesite, andesine andesite, and minor soda trachyte. Smaller amounts of ultrabasic nepheline basalt, melilite-nepheline basalt, and nepheline basanite are found on some of the islands (notably Oahu). Macdonald (1949, p. 1586) concludes that fractional crystallization of olivine basalt has been the principal process by which the various rock types of the Hawaiian Islands have been derived.

Average chemical compositions of the principal rock types of the Hawaiian Islands, as given by Macdonald (1949, p. 1571), are plotted on the ACF and SKM diagrams of figure 20. The majority of the basic and intermediate rocks of the Hawaiian Islands are undersaturated with respect to silica and are decidedly more mafic and generally richer in alkalies compared to equivalently named circum-Pacific types. The more felsic differentiates—andesites and trachytes—are likewise richer in mafic constituents, richer in akalies, and much lower in silica than the andesites, dacites, and rhyolites of the volcanic arcs from Japan to Palau. The alkali-lime index of the Hawaiian rocks is in the vicinity of 54 (Macdonald, 1949, p. 1570), placing the province as a whole in the alkali-calcic series.

Rocks of other islands within the north-central part of the Pacific Basin (for example, Kusaie, Ponape, and Truk in the eastern Carolines), insofar as they have been described (Kaiser, 1903, p. 110–112; Yoshii, 1936, p. 20–38), are similar to the Hawaiian rocks. This is also true of the rocks of the island groups within the south-central part of the Pacific Basin (see, for example, Lacroix, 1927, p. 1–82, on the Samoan, Society, Cook, Marquesas, Austral, and Gambier islands), and has lead Macdonald (1949, p. 1542) to suggest that there is an "essential uniformity of parent magma and petrogenic processes throughout the Pacific Basin."

DALY'S AVERAGE ROCK TYPES

Compositions of selected average calc-alkaline rock types of the world as compiled by Daly (1933, p. 9–17) are plotted on the ACF and SKM diagrams of figures 21 and 22, together with average andesite and dacite of Saipan, average groundmass of andesite and dacite from Saipan, and average basalt of the Izu Peninsula region of Japan. Average andesite and hypersthene andesite of the world are lower in alumina and lime and much richer in alkalies, especially potash, than the average andesite of Saipan. Although the absolute silica content is about the same in the average andesites of the world and the average andesite of Saipan, the latter carries more quartz in the norm, presumably because of its high content of lime and alumina which goes into the formation of calcic plagioclase. Average dacite and rhyolite of the world have a higher content of alumina and alkalies and a much lower content of silica than the average dacite of Saipan. In general, the average rocks of the world are markedly less calcic and higher in alkalies than equivalent rock types of Saipan, and

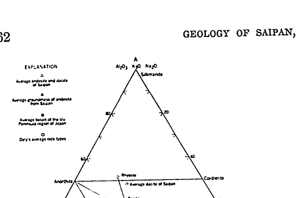

FIGURE 21.—Triangular ACF diagram of average andesite and dacite of Saipan, average groundmass of andesite from Saipan, average basalt of the Izu Peninsula region of Japan, and Daly's average rock types. Source of data is tables 5, 9, and 10, this report; Daly, 1933, pp. 9–17.

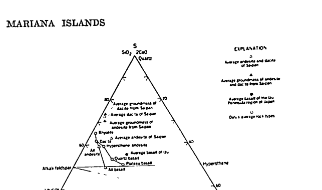

FIGURE 22.—Triangular SKM diagram of average andesite and dacite of Saipan, average groundmass of andesite and dacite from Saipan, average basalt of the Izu Peninsula region of Japan, and Daly's average rock types. Source of data is tables 5, 9, and 10, this report; Daly, 1933, p. 9–17.

the rocks of Saipan have a noticeably higher content of normative quartz. Among Daly's average rocks, only plateau basalt appears to have a close resemblance to the average basalt of Izu (see figs. 20, 22).

SUMMARY AND CONCLUSIONS

The andesites and dacites of Saipan generally are close in composition to volcanic rocks of other islands in the system of arcs extending from Japan to the Palau Islands. They bear a close structural, petrographic, and compositional resemblance to early Tertiary volcanic rocks exposed over large parts of the Bonin Islands; the sister islands of Tinian, Rota, and Guam in the southern Marianas; and the Yap and Palau Islands. They are also similar in composition to andesites and dacites of the late Tertiary and Quaternary volcanoes of the Izu Peninsula region of Japan, the Izu Islands, and the northern Mariana Islands. It therefore appears that the great bulk of the volcanic rocks produced throughout the region from Izu south to Palau belong to a common rock suite and form a well-defined petrographic province. Within this province the rocks range from basalts of tholeiitic type through calcic andesite to silicic dacite and rhyolite, comprising a volcanic association characterized by a high silica and alumina, a high lime, and an exceptionally low potash content. Quartz is universally present in the norm and greatly increases in amount toward the salic end, attaining as much as 49 percent in the dacites of Saipan. The composition of normative feldspars is markedly calcic in the basic members of the rock province, the plagioclase of basalts averaging about An_{70} and that of andesites about An_{55}.

Throughout the oceanic area between Japan and the Palau Islands, the general continuity of rock composition is broken only at Iwo Jima, the largest of the Volcano Islands, which is formed of flows and fragmental deposits of trachyandesite. These rocks are distinctly more alkalic than the ordinary andesites in this part of the Pacific.

Exclusive of the trachyandesites of Iwo Jima, the volcanic rocks of the island arcs from Honshu to the Palau Islands (the rocks of the western part of the circum-Pacific province) comprise a calcic basalt-andesite-dacite-rhyolite kindred that is in marked contrast to the typical picrite-basalt olivine-basalt trachyte association of the islands lying within the confines of the Pacific Basin proper (the intra-Pacific province). The rocks of the western part of the circum-Pacific province lie in a tectonically active region, presumably floored by sial. They appear to have been a normal accompaniment to the orogeny that formed the island-arc system, the rocks presumably originating through petrogenetic processes of a different nature than those that produced the lavas of the Pacific Basin. The volcanic rocks of the intra-Pacific province, on the other hand, lie in a tectonically stable region, in which a sialic crustal layer is presumably absent.

They are believed to have originated by fractional crystallization of oceanic olivine basalt. The marked difference in composition of the volcanic rocks of these two provinces is taken as a reflection of origin under geologically dissimilar conditions. The broad uniformity of composition of the rocks within each of the separate provinces is considered a reflection of origin under similar geological conditions.

PETROGENESIS

The oldest rocks among the andesites and dacites of Saipan, whose relative age is known, are accessory inclusions of augite andesite and quartz-bearing augite-hypersthene andesite in dacite breccias and tuffs of the Sankakuyama formation. These inclusions are at least older than the dacite breccias in which they are found and in all probability are older than the entire sequence of dacitic rocks that comprises the Sankakuyama formation. The next younger rocks are the dacites, including dacite porphyry plug rocks. The dacites are succeeded by andesites of the Hagman, Densinyama, and Fina-sisu formations. The Densinyama formation contains rocks derived from the Sankakuyama and Hagman formations (dacites and andesites) as well as fragments of chert, limestone, and silicified pyritic rocks. The Fina-sisu formation consists of augite-andesite flows and andesitic tuffs. The fragmental rocks of the Hagman formation, particularly the widespread breccia deposits, are made up in large part of accessory blocks of andesite, many of which have probably come from great depth and which could therefore actually be older than the dacites of the Sankakuyama formation. However, the bulk of the fragmental andesites, and the andesite flows, are undoubtedly younger than the dacites. The observable sequence within the volcanic deposits of Saipan is therefore a simple rock association whose line of descent has been andesite–dacite–andesite.

Although much is known about the composition and stratigraphic relationships of the rocks composing the exposed part of the volcanic core of Saipan, these rocks form only the uppermost part of the total complex of volcanic rocks beneath the island—a succession that is probably many thousands of feet thick. Lacking knowledge of the nature of the underlying volcanic rocks, the problem of origin of the andesites and dacites of Saipan is considered by means of analogy with the more extensive rock sequence of the Izu Peninsula region of Japan. Extending the consideration of petrogenesis beyond the limits of Saipan permits conjecture regarding the nature of a parent magma for the andesites and dacites and the treatment of fractional crystallization of the parent material as a possible means of origin of these rocks.

COMPOSITIONAL VARIATION OF THE ROCKS

VARIATIONS BETWEEN AND WITHIN MAJOR ROCK TYPES

It should be clear from data presented that there is a wide gap in composition between the andesites and dacites of Saipan. Rocks intermediate in composition between these two extremes were not found in the volcanic succession.

The andesites are represented by a considerable variety of mineralogical types, which is both a reflection of differences in the physicochemical conditions under which the rocks crystallized and small differences in chemical composition. Actually, any sort of regular linear variation in bulk chemical composition among the andesites of Saipan is not great and is not particularly well defined. Instead, variation in bulk composition appears to be of a somewhat haphazard nature, reflecting a random variability in the content of certain oxides, notably iron, magnesia, silica, and alumina. The variability of the chemical composition of the andesites is well illustrated by the scattering of points representing these oxides in the Harker variation diagram (fig. 16), in which few of the points for iron, magnesia, and alumina fall on or near the curves of linear variation. This compositional variation of the andesites is also shown by the scattering of points representing analyzed rocks on the ACF and SKM diagrams (fig. 17).

For the most part, the random variation of the oxide composition of the porphyritic andesites is probably a reflection of the fact that they do not represent compositions of true magmatic liquids but are, rather, magmatic liquids plus variable amounts of accumulated and incorporated crystals, which accounts for their displacement from smooth variation curves. In addition, and probably to a lesser degree, the random variability in composition of the andesites is related to differences in the state of weathering of the analyzed rocks, and the randomness of the oxide composition of fresh rocks would not therefore be so great as is indicated by the variation diagrams.

The dacites of Saipan comprise several distinctive textural types of rock—flow rock, vitrophyre, perlite, and porphyry—which are closely alike in chemical composition (table 5). The content of lime in the dacite porphyry, and therefore the anorthite content of feldspar of this rock, is somewhat higher than that of either dacite flow rock or dacite vitrophyre.

COMPARISON BETWEEN BULK AND GROUNDMASS COMPOSITION OF PORPHYRITIC ANDESITES AND DACITES

The calculated chemical compositions of the groundmasses of analyzed andesites and dacites from Saipan are given in table 9, together with the volume percent of phenocrysts in the rocks, and the average groundmass compositions are also listed. The groundmass compositions were computed by subtracting the oxide content of phenocrysts (calculated to weight percent) from the bulk composition of the rocks and recalculating the remainder to 100 percent. The volume percent of phenocrysts was determined on single thin sections, using a point-counter stage. Because of the error in computing the volume percent of phenocrysts in the rocks from a single section, and because the chemical composition of the phenocrysts is not known accurately, the calculated groundmass compositions probably do not represent more than a general approximation of the actual composition of the groundmass of the andesites and dacites.

However, despite their evident inaccuracy, the calculated groundmass compositions are not greatly unlike natural rock types, and in a general way they indicate real differences that exist between groundmass and bulk composition. The bulk compositions are decidedly lower in silica, mostly higher in alumina, and tend to be lower in Fe_2O_3 than the groundmass. Magnesia and FeO have diverse relationships. Magnesia and FeO.

TABLE 9.—*Volume percent of phenocrysts, bulk chemical composition, and calculated chemical composition of the groundmass of analyzed porphyritic andesites and dacites from Saipan*

Constituents	Andesites							Dacites				
	S135	S15 [1]	S107	S37	S67A	Average bulk composition	Average groundmass composition	S448	S317 [2]	S139A	Average bulk composition	Average groundmass composition
Phenocrysts (volume percent) [3]												
Plagioclase	26.75	30.05	44.30	39.00	34 35			3.0	4 2	11.9		
Quartz								1.5	2.8	5.7		
Hypersthene	.95	8.90	10.30	4.00	2.15					8		
Augite	8.50	3.10	2.65	.80	1.25					3		
Hornblende												
Magnetite	1.05	1 65	.85	.20	.65							
Groundmass	62.75	56.30	41.90	56.00	61 60			95.5	93.0	81.3		
Bulk composition (weight percent)												
SiO_2	57.20	58.34	58.19	60.80	60.95	59.09		76.39	78.79	79.20	78.13	
TiO_2	.54	.63	.46	.48	.54	.53		11	.18	23	.17	
Al_2O_3	16.35	18.66	17 82	18.13	18.06	17.80		10.75	9.92	11 05	10.57	
Fe_2O_3	2.23	2.48	2.50	2.03	2.41	2.33		.29	59	52	.47	
FeO	5.93	4.54	4.08	3.53	2.61	4.13		1.12	75	90	.92	
MnO	04	07	10	09	.08	.10		.07	02	02	04	
MgO	4.65	2.44	3.46	2.54	2.37	3.09		.30	None	36	.22	
CaO	8.85	8.61	8.90	8.18	8.16	8.54		1.13	.64	2.06	1.28	
Na_2O	2.50	2.81	2.80	3.12	3.10	2.87		3.34	3.87	3.40	3.54	
K_2O	.68	.76	.53	.60	.58	.63		2.29	1 20	1.58	1 69	
H_2O	.90	.64	1.28	.74	1.34	98		4 23	3.97	80	3.00	
P_2O_5	.36	.02	.09	11	10	.14		16	.07	13	.12	
Total	100.33	100.00	100.21	100.35	100.30	100.23		100.18	100.00	100.25	100.15	
Calculated composition of groundmass (weight percent)												
SiO_2	62.92	66.69	70.75	69.10	69.16		67.73	79.86	82.45	81 62		81.31
TiO_2	89	1 13	1.05	.87	90		99	.12	.20	.29		.20
Al_2O_3	13.88	17.73	12.09	11 33	12.66		13.54	10.98	10.00	10.07		10.35
Fe_2O_3	1.52	.68	3.61	3.21	2.75		2 35	.32	67	.25		.41
FeO	5.93	1.87	1.28	3.96	2.40		3.09	1 23	85	.80		.96
MnO								.08	.02	02		.04
MgO	4 64	.07	03	2.20	2.53		1 89	33		.33		.22
CaO	6.04	7 52	6.70	5.07	5.50		6.17	1 09	49	1.69		1.09
Na_2O	2.68	3.08	3.19	3.21	3.25		3.08	3.38	3.96	3.06		3.47
K_2O	91	1 19	98	85	68		92	2.43	1 28	1 71		1.81
H_2O												
P_2O_5	59	04	.22	.20	.17		.24	18	08	.16		.14
Total	100.00	100.00	100.00	100.00	100.00		100.00	100.00	100.00	100.00		100.00

[1] The bulk composition of specimen S15 is recalculated from the original analysis (table 5, column 8). One-half the molecular amount of Fe_2O_3 in the original analysis has been converted to FeO, the H_2O content reduced to the normal content of fresh rock, the CO_2 removed, and the analysis recalculated to 100 percent.

[2] The bulk composition of specimen S-317 is recalculated from the original analysis (table 5, column 2) One-half the molecular amount of Fe_2O_3 in the original analysis has been converted to FeO, and the analysis recalculated to 100 percent.

[3] 2,000 counts were made on each specimen of andesite and 1,000 counts were made on each specimen of dacite to obtain the volume percent of phenocrysts.

particularly magnesia, in every instance should be lower in the groundmass composition. Lime is considerably higher in the bulk compositions, and soda and potash are for the most part slightly higher in the groundmass, which is the expected relationship.

Normative feldspar of the porphyritic rocks is more calcic than that of the groundmass, and the content of normative feldspar (volume and weight percent) in the porphyritic rocks is greater than that of the groundmass. The pyroxenes, however, show anomalous relationships, which can probably be correlated with the diverse relationships shown by magnesia and FeO. Normative pyroxene of the groundmass of the andesites appears to be generally richer in calcium and magnesium and lower in ferrous iron than the bulk composition, and the content of normative pyroxene is somewhat less in the groundmass than in the bulk composition. The content of normative magnetite and ilmenite is higher in the groundmass.

The principal differences between the bulk composition and groundmass composition of the porphyritic andesites appear to be due to the large amount of calcic plagioclase phenocrysts, which constitute from about 20 to 45 percent of these rocks by volume, and to the relatively high proportion of pyroxene phenocrysts in the rocks. The erratic variation in composition, and the coarsely and profusely porphyritic nature of the rocks, coupled with their high content of calcic feldspar and pyroxene phenocrysts, are features that suggest that the bulk composition of the rocks may at least in part represent magma plus a certain amount of accumulated plagioclase and pyroxene crystals.

From a petrogenetic standpoint, the most significant features of the groundmass compositions are that the groundmass of both the andesites and dacites appears to be decidedly more silicic than the bulk composition, and the groundmass of the andesites appears to be strongly deficient in alumina relative to alkalies and lime. These relationships are considered further in the following section on origin of the volcanic rocks of Saipan.

EVIDENCE OF CONTAMINATION

Direct evidence of contamination of the magmas and lavas involved in the evolution of the volcanic rocks of Saipan is almost lacking. Xenoliths of basement rocks of a felsic or mafic nature, which might indicate material possibly assimilated by the lavas, were not found in the volcanic succession.

Contamination of some of the andesitic rocks with silica is perhaps indicated in andesites that contain quartz crystals as phenocrysts and groundmass grains. The quartz crystals in these rocks are highly corroded and also commonly embayed by the groundmass, and strong resorption has evidently occurred. This indicates that the quartz crystals were not in chemical equilibrium with the surrounding groundmass liquid and were therefore possibly of foreign derivation. However, loss of equilibrium may be related to extrusion, for corroded quartz crystals are characteristic of lavas in general.

There is no direct evidence of contamination of the dacitic rocks of Saipan.

ORIGIN OF THE ROCKS

NATURE OF A PARENT MAGMA

Although the andesites and dacites of Saipan might be members of a larger rock sequence that includes basaltic and intermediate rock types, this has not been established. Basalts and intermediate rock types are not found as flows on Saipan, nor do they occur as fragments in the pyroclastic deposits. This might suggest that basaltic rocks are absent throughout the entire volcanic section beneath the island.

However, as evidenced in the volcanic associations of Japan, Guam, and the Palau Islands, calcic andesites and silicic dacites of similar composition to the rock types of Saipan are related to porphyritic and aphyric basaltic rocks, and the aphyric basaltic rocks, at least in part, probably represent the ancestral or parent magma types of these regions. It is not unreasonable to assume, therefore, that the andesites and dacites of Saipan may represent members of a rock sequence that includes basaltic rocks and other intermediate types, even though these latter rocks were not found in the volcanic formations of Saipan.

Kuno (1937, p. 189–208; 1950b, p. 1012; 1953, p. 269) assumes that the primary magma of north Izu and Hakone, in Japan, has the composition of a slightly undersilicated olivine basalt—comparable to the olivine basalt magma type of Kennedy (1933, p. 241)—consisting of calcic labradorite or sodic bytownite, augite, olivine, and iron ore. The closest approach to this mineral composition in the Hakone region, however, is found in the basalts of type IIIb→c (Kuno, 1950b, p. 986, 1012; 1953, p. 269–270), which are actually somewhat oversaturated with silica. Kuno believes the undersilicated olivine basalt magma gives rise to two distinct rock series of tholeiitic magma type: a pigeonitic rock series formed chiefly through simple fractional crystallization of olivine basalt magma, and a hypersthenic rock series formed through reaction with and assimilation of overlying or adjacent granitic material of the sial in the olivine basalt magma. The andesites and dacites of Saipan are more nearly akin to members of the hypersthenic rock series.

On the other hand, undersilicated basaltic rocks of the nature of average Hawaiian olivine basalt, as well as other basalts with characteristics of the olivine basalt magma type of Kennedy, are not present among the calc-alkaline volcanic-rock associations of the Izu Peninsula region of Japan and the island-arc system that extends from Honshu to Palau. Consequently, it appears doubtful that magmas of this nature were involved in the genesis of the calc-alkaline volcanic rocks of this area. This conclusion is further sustained by the general absence of dacitic and rhyolitic lavas within the oceanic area of the Pacific Basin, which strongly suggests that lavas of this composition do not originate by simple fractionation of undersaturated oceanic olivine basalt. The differentiation of oceanic olivine basalt in a salic direction leads, instead, to the formation of oligoclase andesites and trachyte or quartz trachyte.

Aside from the absence of undersilicated olivine basalt in the calc-alkaline volcanic series of the Izu Peninsula region, and the absence of calc-alkaline rocks among the lavas of the Pacific Basin, the case for rejecting a magma of this composition as the primitive magma from which the tholeiitic basalt of Izu has developed is somewhat strengthened from other lines of evidence. It can be seen from the SKM diagram (fig. 20) that separation and removal of olivine and some proportion of hypersthene from a liquid (magma) with the composition of average Hawaiian olivine basalt causes the composition of the liquid to move toward the alkali feldspar side of the diagram, and in this way (assuming coordinate removal of calcic plagioclase) the andesine and oligoclase andesites and trachyte of the Hawaiian Islands might be derived, as is so postulated by Macdonald (1949, p. 1575). It also appears reasonable that the slightly oversilicated basalt of the Hawaiian Islands, an average analysis of which is plotted on the diagrams of figure 20, may originate by separation and removal of olivine in more than its stoichiometric proportion. However, as shown in figure 23, average Hawaiian olivine basalt has a normative feldspar composition considerably less calcic than the average basalt of Izu or the average andesite of Saipan, which clearly rules out the possibility of derivation of the basalts of Izu or the andesites of Saipan from a magma with the composition of average Hawaiian olivine basalt either by fractional crystallization or assimilation of rock material. Assimilation of granitic material by a magma of the composition of average Hawaiian olivine basalt, a material which by definition would contain alkali feldspar and which would therefore enrich the olivine basalt magma in alkalies, could never give rise to a differentiate with the composition of the average basalt of Izu. The derivation of average Izuian basalt from average Hawaiian olivine basalt is thus primarily a problem of alkali impoverishment and oversaturation with silica. The latter condition might conceivably result by removal of olivine in more than its stoichiometric proportion by crystal settling, but the mechanics of alkali impoverishment cannot be satisfactorily explained by crystal fractionation or assimilation.

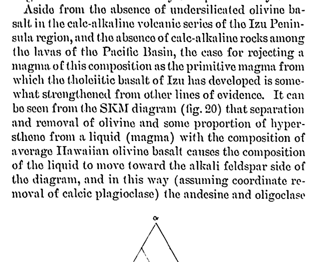

FIGURE 23.—Composition of normative feldspar of average andesite of Saipan, average basalt of the northern Mariana Islands, average olivine basalt of the Hawaiian Islands, and average basalt of the Izu Peninsula region of Japan.

The foregoing evidence strongly suggests that the tholeiitic magma type of the Izu Peninsula region probably developed independently of olivine basalt magma, and this conclusion is reached by Turner and Verhoogen (1951, p. 199) concerning the general relationship between olivine basalt and tholeiitic magmas.

The composition of average Hawaiian olivine basalt and the composition of various basalts of tholeiitic type are given in table 10. Among these types, the average basalt of Izu, because of its low content of alkalies, particularly potash, corresponds more closely to a parent type for the andesites and dacites of Saipan than any of the others.

FRACTIONAL CRYSTALLIZATION AND ASSIMILATION

Assuming that the volcanic rocks of Saipan are genetically related to a parent tholeiitic magma of the nature of average Izuian basalt, it is possible to consider whether the andesites and dacites of Saipan are the result of fractional crystallization or contamination of such a parent magma.

In the considerations that follow, the author has calculated the composition of the smallest amounts of material that must be subtracted from and added to

TABLE 10.—*Average chemical composition of olivine basalt from the Hawaiian Islands and basalts of tholeiitic magma type from various parts of the world*

	1	2	3	4	5	6	7
SiO_2	48. 35	50. 53	50. 61	50. 79	51. 01	51. 07	53. 31
TiO_2	2. 77	1. 49	1. 91	2. 65	. 94	. 94	1. 14
Al_2O_3	13. 18	17. 87	13. 58	13. 96	17. 19	17. 70	18. 38
Fe_2O_3	2. 35	3. 58	3. 19	2. 11	3. 62	3. 23	2. 60
FeO	9. 08	7. 62	9. 92	11. 27	7. 32	8. 06	5. 35
MnO	. 14	. 21	. 16	. 22	. 20	. 21	. 21
MgO	9. 72	4. 94	5. 46	4. 88	5. 11	4. 96	5. 18
CaO	10. 34	9. 74	9. 45	8. 48	10. 75	10. 56	8. 33
Na_2O	2. 42	2. 73	2. 60	2. 98	2. 59	2. 11	3. 68
K_2O	. 58	. 76	. 72	1. 24	. 72	. 37	. 79
H_2O	------	. 43	2. 13	. 83	. 31	. 85	. 62
P_2O_5	. 34	. 26	. 39	. 61	. 20	. 12	. 32
Total	99. 27	100. 16	100. 12	100. 02	99. 96	100. 18	99. 91

1. Olivine basalt of Hawaii; average of 53 analyses (Macdonald, 1949, p. 1571).
2. Basalt of Huzi San (Fujiyama), average of 8 analyses (Tsuya, 1937, p. 307).
3. Basalt of the Deccan Plateau; average of 11 analyses (Washington, 1922, p. 774).
4. Basalt of Oregon, plateau type; average of 9 analyses (Washington, 1922, p. 779; Thayer, 1937, p. 1622).
5. Basalt of northern Marianas; average of 7 analyses (table 6, this report).
6. Basalt of Izu; average of 29 analyses (Tsuya, 1937, p. 235–301; Kuno, 1950b, p. 1000–1002, 1004–1006).
7. Olivine basalt of Oregon, average of 9 analyses (Thayer, 1937, p. 1622, 1623).

possible parent magmas to form the andesitic and dacitic lavas of Saipan. Basic to calculations of this sort are the assumptions that potash is not removed from the subtracted fraction and that magnesia is not introduced in the added fraction, although neither of these conditions is likely to obtain in natural processes of magmatic differentiation. Moreover, the smallest amount of material added or substracted is generally found to be of very unusual composition and not such as would be expected to separate as crystals from a parent magma. The composition of an intermediate amount of material, which may approach a reasonable magmatic composition, can, of course, be calculated, but because there are an infinite number of such intermediate compositions obtainable, the meaning of such calculations is questionable. For these reasons the subtraction and addition method of analysis of magmatic differentiation must be used advisedly and with extreme caution in attempting to reach definite conclusions regarding the origin of lavas.

It should also be noted that throughout this theoretical treatment the porphyritic rocks of Saipan are treated as representing magmatic liquids, and that the bulk compositions of porphyritic rocks of Izu were used in computing the average composition of the parent Izuian basalt. Whether these rocks actually represent the composition of magmatic liquids is open to question, and probably a more accurate analysis would result if groundmass compositions were used instead. However, the calculated compositions of the groundmass of porphyritic andesites from Saipan (table 9) are erratic and cannot be relied upon as being representative of the groundmass compositions. For this reason the bulk compositions of the porphyritic rocks are alone considered in the treatment of fractional crystallization.

The compositions and norms of the smallest amount of material which must be removed from and added to the average basalt of Izu to yield the average andesite of Saipan is shown in columns 1 and 2 of table 11. The composition and norm of the smallest amount of material which must be removed from the average basalt of Izu to yield the average dacite of Saipan is given in column 3.

TABLE 11.—*Composition of material subtracted from average basalt of Izu to yield average andesite and dacite of Saipan, and composition of material added to average basalt of Izu to yield average andesite of Saipan* [1]

	1	2	3
Compositions (weight percent)			
SiO_2	45. 60	70. 75	45. 60
Al_2O_3	17. 80	19. 00	19. 70
Total iron as FeO	14. 90	. 45	13. 40
MgO	6. 90	. 00	6. 20
CaO	13. 20	4. 40	12. 85
Na_2O	1. 40	4. 15	1. 90
K_2O	. 00	1. 25	. 00
Amount subtracted (percent)	44	----------	78
Amount added (percent)	----------	39	----------
Norms (weight percent)			
Quartz	----------	32. 28	----------
Orthoclase	----------	7. 23	----------
Albite	12. 05	35. 11	16. 24
Anorthite	42. 26	21. 96	45. 04
Diopside:			
Wollastonite	9. 74	----------	7. 89
Enstatite	4. 90	----------	3. 70
Ferrosilite	4. 62	----------	4. 09
Hypersthene.			
Enstatite	5. 30	----------	. 60
Ferrosilite	4. 88	. 26	. 66
Fosterite	4. 90	----------	7. 84
Fayalite	5. 10	----------	9. 59
Magnetite	6. 03	. 23	6. 50
Cordierite	----------	2. 75	----------
Feldspar:			
Orthoclase	----------	11	----------
Albite	23	56	28
Anorthite	77	33	72

[1] Only the principal oxides have been used in the calculation, and all iron has been calculated as FeO. However, in the norms, iron is distributed between FeO and Fe_2O_3 in the same proportion as in the parent basalt, and magnetite is calculated as a normative component.
1. Composition of smallest amount of material which, subtracted from average basalt of Izu, yields average andesite of Saipan.
2. Composition of smallest amount of material which, added to average basalt of Izu, yields average andesite of Saipan.
3. Composition of smallest amount of material which, subtracted from average basalt of Izu, yields average dacite of Saipan.

The norms of the material removed from the basalt to form the andesite and dacite consist of calcic plagioclase, diopside, hypersthene, olivine, and magnetite. All of these minerals might be expected to crystallize in the basaltic magma at high temperatures, although the monoclinic pyroxene would be augite rather than diopside. The proportion of material removed, which represents the proportion of material crystallized from the parent basalt, is 44 percent to yield the andesite and 78 percent to yield the dacite. This also appears reasonable. The average composition of the feldspar is An_{77} in the material subtracted to form the andesite and An_{72} in the material subtracted to form the dacite. The composition of plagioclase in the material subtracted to form the andesite corresponds well to the calcic plagioclase phenocrysts actually found in the basalts of Izu. On the other hand, derivation of the andesite, and especially the dacite, by removal of a minimal amount of material from the basaltic magma, requires that olivine be subtracted in amount greater than its stoichiometric proportion in the rock to yield either the andesite or the dacite, and that both olivine and diopside (augite) be removed in amounts greater than their stoichiometric proportion in the rock to yield the dacite. Removal of olivine in some amount greater than its stoichiometric proportion might reasonably be assumed to take place at elevated temperatures, but it is doubtful that either olivine or diopside (augite) could be removed from the parent basalt in the amount required to form the dacite.

Other difficulties involved in deriving the volcanic rocks of Saipan by such a simple mechanism of fractional crystallization are that normative diopside (augite), hypersthene, and olivine in the subtracted material are more iron rich than actual phenocrysts of these minerals in the basalts of Izu, and the change in the average feldspar composition from An_{77} in the material subtracted to form the andesite to An_{72} in the mineral subtracted to yield the dacite is not as great a change in sodium content as would be expected in normal crystallization of the basalts of Izu. However, the high iron content of the ferromagnesian minerals in the material subtracted to form the andesite may be a consequence of not assuming the right order of oxidation state for iron, and if a change in the oxidation state is postulated to put more ferrous iron into magnetite, the iron content of the ferromagnesian minerals can be made compatible with the actual composition of phenocrysts in the basalts of Izu.

The amount and composition of the smallest amount of material which when added to the average basalt of Izu yields a rock with the composition of average andesite of Saipan is given in column 2 of table 11. The norm of this material consists essentially of quartz, andesinic plagioclase, and aluminous minerals. Material of this composition might conceivably be derived by selective assimilation of mineral material in andesitic and dacitic rocks of a sialic crust through which the parent basalt may have risen, but it is not such as would be expected to crystallize from the basalt. The proportion of added material (39 percent of the resultant mixture or an amount equal to more than one-half the volume of the original magma) assumed to have been dissolved by the magma is, however, quite improbable. Derivation of the dacites by solution of foreign rock material in a basaltic magma would require assimilation of even a more highly siliceous and aluminous material in an amount many times greater than the volume of the original magma. It thus appears that the andesites and dacites cannot be derived solely through simple enrichment of the basaltic magma, either by selective fusion (assimilation) of contaminating wall-rock material or by assimilation of crystals formed in another part of the magma body.

In summary, the data given in table 11 appear to indicate that the andesites of Saipan might have originated through simple fractional crystallization of a magma with the composition of average Izuian basalt, the dacites of Saipan can doubtfully be ascribed to a pure differentiation process, and the andesites and dacites of Saipan could not have originated through simple assimilation of foreign rock material in a parent basalt magma.

Assuming that the andesites were derived by fractional crystallization of a parent basalt, the possibility may be considered that the dacites originated through a process of differentiation of a magma with the composition of average andesite. The compositions and norms of the smallest amounts of material which must be subtracted and added to the average andesite of Saipan to yield the average dacite of Saipan are given in table 12. The material added consists of siliceous feldspathic material of very unusual composition (quartz and potassium-rich albitic feldspar), and it is very doubtful whether any such mixture of known igneous or sedimentary rocks could approach such a composition. Moreover, even were it granted that such a mixture is available, it would require assimilation to the extent of 93 percent of the resultant magma (nearly 13 times the amount of the original magma) in order to produce the required change. Any less siliceous material would have to be assimilated in still greater amount. It is therefore highly unlikely that the dacites could have been derived solely by solution of foreign rock in a magma with the composition of the average andesite of Saipan.

Supposing that the change from andesite to dacite was effected by subtraction of crystals (crystal fractionation), the smallest amount of material that would have to be removed from the andesite (table 12) is 61 percent of the melt and consists of basic plagioclase, olivine, diopside, and hypersthene. All except olivine are common as phenocrysts in the andesites of Saipan,

TABLE 12.—*Composition of material subtracted from and added to average andesite of Saipan to yield average dacite of Saipan* [1]

	1	2
Compositions (weight percent)		
SiO_2	46.00	82.50
Al_2O_3	23.10	10.28
Total iron as FeO	10.50	.90
MgO	4.90	.00
CaO	12.60	.75
Na_2O	2.50	3.75
K_2O	.00	1.82
Amount subtracted (percent)	61	
Amount added (percent)		93
Norms (weight percent)		
Quartz		52.26
Orthoclase		10.56
Albite	20.96	31.44
Anorthite	51.71	3.61
Diopside:		
Wollastonite	4.52	
Enstatite	2.70	
Ferrosilite	1.58	
Hypersthene:		
Enstatite	1.30	
Ferrosilite	.79	.53
Fosterite	5.74	
Fayalite	3.47	
Magnetite	6.73	.70
Cordierite		.92
Feldspar:		
Orthoclase		22
Albite	30	70
Anorthite	70	8

[1] Only the principal oxides have been used in the calculation, and all iron has been calculated as FeO. However, in the norms, iron is distributed between FeO and Fe_2O_3 in the same proportion as in the parent andesite, and magnetite is calculated as a normative component.

1. Composition of smallest amount of material which, subtracted from average andesite, yields average dacite.

2. Composition of smallest amount of material which, added to average andesite, yields average dacite.

although the monoclinic pyroxene is actually an aluminous augite rather than diopside. It is doubtful that olivine could be removed from the andesite in the proportion indicated, and it must be assumed that, if olivine is not separated, the material removed must then have a more siliceous composition, in which case the subtracted fraction would comprise more than 70 percent by weight of the melt.

Derivation of the peraluminous dacites by removal of a minimal amount of material from the andesitic melt also requires removal of diopside (augite) in an amount greater than its actual stoichiometric (normative) proportion in the rock, the residual melt thereby gaining an excess of alumina (relative to alkalies and lime) by subtraction of lime from the system which would otherwise combine with alumina to form anorthite. However, there is little basis for believing that such a process is an important factor in the development of highly peraluminous rocks such as the dacites of Saipan.

As shown in the ACF diagrams of figures 17, 18, and 20, the salic (felsic) members of calc-alkaline rock associations are generally peraluminous. The peraluminous character of the rocks is difficult to account for by a process of simple fractional crystallization. For example, it can be seen from the ACF diagrams that if the anorthite-cordierite-hypersthene and anorthite-diopside-hypersthene triangles represent separate ternary systems, the anorthite-hypersthene join may coincide approximately with a thermal high on the liquidus surface of these systems, in which case removal of crystals could not cause the composition of the melt to pass into the peraluminous triangles. However, the fact that a specimen of augite andesite from Saipan as well as several augite-bearing rocks from the Izu Peninsula region are slightly peraluminous and fall within the anorthite-cordierite-hypersthene triangle may indicate that the anorthite-hypersthene join does not correspond with a thermal high (at least not in the vicinity of these peraluminous andesites) and that the field of crystallization of diopside (augite) extends across the join into the peraluminous triangle. Should this be true, crystallization and subsequent removal of diopside (augite) from a melt with the composition of average andesite of Saipan would probably cause the melt to change along a path in the direction of average dacite of Saipan, toward a possible diopside-anorthite-cordierite eutectic in the peraluminous triangle. The melt might therefore become slightly peraluminous by removal of diopside in slight excess of its normative proportion. The position of the possible diopside-anorthite-cordierite eutectic is not known, but if it should lie close to the anorthite-hypersthene join, as seems probable, then it is doubtful that other than slightly peraluminous rocks could be produced by removal of excess diopside (augite).

The mineral relations in the andesites of Saipan give no indication that removal of diopside (augite) is the means through which the rocks have become peraluminous, for it appears that calcic plagioclase has mostly crystallized early along with augite in the andesites and in some instances may have begun to crystallize before augite. It may also be noted that the calculated groundmass compositions of analyzed andesites from Saipan (table 9) are in every instance strongly deficient in alumina relative to alkalies and lime. This appears to indicate that the course of fractionation of these rocks with respect to alumina is in a direction away from the anorthite-hypersthene join, with crystallization starting in the anorthite field and the melt subsequently moving toward a possible eutectic in the anorthite-diopside-hypersthene triangle of the ACF diagram. This relationship may be inferred from the ACF diagram of figure 21, on which the average groundmass composition of the andesites of Saipan is plotted along with the average bulk composition.

On the other hand, the groundmass compositions listed in table 9 provide evidence that, at least to some extent, simple strong fractionation of the andesitic magmas might have played an important role in the evolution of the dacitic magmas. The groundmass compositions of the andesites and dacites are decidedly more silicic than the bulk compositions, and it may be seen from the SKM diagram of figure 22, on which the average groundmass compositions are plotted, that the course of fractionation of the average andesite of Saipan is toward and approaches the composition of the average dacite. In this connection, it is worth mention that the course of fractionation of the average dacite appears to be in the same direction (with respect to silica) as that of the average andesite. Were the groundmass of the dacites actually less silicic than the phenocrysts (less silicic than the bulk composition), a course of fractionation of the dacites in a direction opposite to that of the andesites would be indicated, suggesting that these rocks bear little or no genetic relationship to each other.

The chief property of the dacites of Saipan, and of the petrogenic series of Saipan as a whole, which is most difficult to account for through a mechanism of simple fractional crystallization of a basaltic magma, is the high silica content of the rocks. In general, fractional crystallization of oversilicated basaltic magma leads to residua rich in alkali feldspar plus quartz, and Bowen (1937, p. 11–13) has stated that the salic members of a differentiation series containing more than 80 percent of normative salic minerals (excluding anorthite) should have a composition that approximates mixtures in the experimentally investigated system nepheline-kaliophilite-silica. Under these conditions, as a consequence of fractional crystallization, the compositions of the residual magmas should change toward those compositions represented by mixtures lying within the region of the low-temperature trough of the system, and the maximum content of normative quartz of even the most salic differentiates should not be in excess of about 35 percent by weight. However, the plotted positions of the dacites of Saipan fall far outside (above and to the left) the trough of this triangle (fig. 24).

On the basis of the foregoing analysis it appears doubtful that the dacites of Saipan could have originated by pure differentiation of a magma with the composition of average andesite of Saipan, and that processes other than fractional crystallization probably have contributed to their formation. To account for

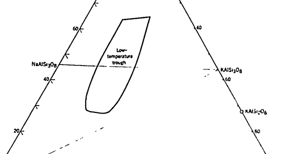

FIGURE 24.—Position of dacites of Saipan with respect to the low-temperature trough of the system nepheline-kaliophilite-silica.

these highly silicic and peraluminous rocks, providing they are indeed related to the andesites, it seems necessary to assume some special process such as perhaps extreme fractionation of an andesitic magma coupled with assimilation of significant amounts of siliceous and aluminous crustal material.

Objections may also be raised that salic magmas such as the dacites of Saipan could be derived from basic magmas without the development of rocks of intermediate composition.

RELATIONSHIP OF VOLCANISM TO THE DEVELOPMENT OF THE MARIANA ARC

It has long been recognized that volcanism is a normal accompaniment to the structural development of the island arcs which rim the Pacific Ocean, and this suggests that volcanism and structural evolution of the arcs are interrelated phenomena. The arcuate alinement of the Mariana Island chain parallel to the bordering marginal deep known as the Mariana trench affords a good illustration of this structural-volcanic relationship in which igneous activity is probably contemporaneous with orogeny (see fig. 12).

The doubly arcuate arrangement of the Mariana Islands into an older outer (eastern) arc and a younger inner (western) arc (fig. 12) implies that a shift in the locus of volcanism has taken place, the locus having been displaced from near the crest of the present Mariana ridge westward to the backslope of the ridge in the southern part of the chain. This shift was apparently accompanied by little change in the chemical nature of the eruptive products, except that the older eastern volcanic arc (southern Marianas) appears to have produced a greater volume of andesitic rocks and has produced dacitic rocks, whereas the younger western arc (northern Marianas) has produced mafic basaltic and andesitic rocks which are somewhat richer in potash than the older lavas.

To some extent, the above relationships may be a reflection of changing conditions in the structural environment in which the volcanic rocks of the Mariana Islands originated. The early Tertiary rocks—basalts, andesites, and dacites—of the southern Mariana Islands may relate to the initial development of a crustal downwarp or tectogene, beneath the Mariana trench, a type of structure which has been postulated to account for the linear and arcuate oceanic deeps (see Cloud, Schmidt, and Burke, 1956).

Westward shift of the locus of volcanism in the Marianas to the backslope of the Mariana ridge may have resulted through later migration of simatic material away from the tectogene or downbuckle, on the concave side of the evolving arc, in response to an increase in the curvature of the arc, as suggested by Umbgrove (1947, p. 191). The appearance of major amounts of basaltic rocks in the northern Marianas (the inner volcanic arc) may be a direct result of the shift in the locus of volcanism away from the downbuckle beneath the Mariana trench. Such a shift would not only result in displacement of the point of origin of the mafic magmas laterally away from the downbuckle, but would also place the environment at greater depth within the simatic substratum, a position where there would, perhaps, be less chance of contamination with sialic material.

The possible mode of origin of lavas in an environment of this sort has been described as follows by Turner and Verhoogen in Igneous and Metamorphic Petrology (1951, p. 222–224):

In some provinces, and at some stage or other in the history of most provinces, great volumes of andesite, and in some cases dacite and rhyolite, have been erupted over large areas with little or no accompanying olivine basalt. This contrasts sharply with the characteristically small volumes of trachytic, phonolitic, or rhyolitic differentiates that accompany floods of basaltic lavas in provinces of quite different character where basaltic magma is generally believed to be the parent material. It would be surprising if, in the tectonic environment provided by a zone of active folding, great volumes of andesitic and rhyolitic differentiates were habitually squeezed up from the depths without considerably greater volumes of undifferentiated basaltic magma welling up simultaneously. A second difficulty raised by the pure differentiation hypothesis concerns the alternate, and in some cases simultaneous, eruption of fine-grained olivine basalt and glassy rhyolite in comparable amounts from the same volcano, without appearance of lavas of intermediate (andesitic) composition. This condition is illustrated by the Newberry volcano. A distinct but much narrower compositional break between the more basic and more siliceous members of volcanic series is by no means uncommon, and could be explained by assuming that some special mechanism of fractional crystallization, such as gas streaming, is effective in separating the last liquid fractions from the mass of early-formed crystals. Such are the breaks between andesite and dacite in the present association, and between mugearite (or trachyandesite) and trachyte in the lavas of oceanic islands. To account for the basalt rhyolite combination of such volcanoes as Newberry, it seems necessary to assume either some drastic mechanism of differentiation, *e. g.*, unmixing of magmas into immiscible rhyolitic and basaltic liquid fractions, or independent origin and uprise of the two kinds of magma.

With such anomalies in mind, the authors suggest that some of the features of andesites and rhyolites ascribed by orthodox opinion to fractional crystallization of basaltic magma in the depths may really be due to differential fusion of basaltic and other rocks beneath or within the sial. Students of tectonic geology have brought forward convincing evidence indicating that downward thickening of a "granitic" upper layer (sial) accompanies orogenic folding. If, following orthodox petrological opinion, we were to assume that temperatures in an underlying basic layer are periodically raised sufficiently to allow complete fusion, *i. e.*, generation of basaltic magma, then surely, in view of the relatively low temperatures required for complete melting of granite, we would also be obliged to admit the probability of local melting within the sial itself. Presumably this would be particularly liable to occur within the thickened portion of the sial, locally depressed below the level elsewhere reached by the basic or ultrabasic substratum. According to this or any other current hypothesis of the deep structure of fold mountains, deep-seated generation of basaltic magma is likely to be accompanied by nearby development of andesitic and rhyolite magmas, either by complete or by partial fusion of rocks of varied composition. Where folding is active, there is ample opportunity for filter-pressing and segregation of the magmas so formed and for mixing and blending of magmas en route to the surface. These processes, modified by differentiation wherever magma temporarily is held in a closed chamber, are surely complex enough to account for the wide variation observed in the products of eruption at the surface Nor is it difficult to imagine why volcanic series in which andesites and rhyolites are so conspicuous are confined to the continents and attain their most spectacular development along the Pacific margin, where for long ages the rocks of the sial and adjacent underlying basic material have almost continuously been kneaded together.

Varied processes such as the above may account for the development of the extreme compositional gap between the andesites and dacites of Saipan without the development of intermediate rock types, as well as the observed absence of basaltic rocks on Saipan. Evidence was presented in an earlier section of this report to show that the volcanic rocks of Saipan probably could not originate by simple differentiation alone, and that some such process as assimilation of sialic material by a basaltic or andesitic magma is necessary to form magmas with the composition of silicic dacite.

CONCLUSIONS

The close analogy of the volcanic rocks of Saipan with volcanic associations in Japan and in the Palau Islands—associations that comprise gradational series ranging from basalts of tholeiitic type to silicic dacites—suggests that the andesites and dacites of Saipan may possibly represent members of a larger rock sequence that includes ancestral basalts, even though the latter rocks do not appear in the volcanic formations of Saipan.

While it is not unreasonable to suppose that basic magmas might have played a parent role in the evolution of the andesites and dacites of Saipan, many features of the rocks are difficult to reconcile with simple differentiation of a primary basaltic magma. On the basis of elementary considerations regarding the nature and amount of material which must be removed from or added to parent rocks to yield average andesite and dacite of Saipan, and on the basis of graphical analyses using chemical and petrographic data, the following inferences appear valid.

1. The andesites and dacites could not have originated solely through simple assimilation of foreign rock material in a parent basaltic magma.
2. The andesites of Saipan might have originated by simple fractionation of a magma with the composition of average tholeiitic basalt of Izu, but the more reasonable mechanism of origin from such a parent magma is by removal of pyroxene and feldspar components coupled with assimilation of small amounts of siliceous, feldspathic material.
3. The dacites of Saipan doubtfully could have originated by simple fractional crystallization of basic magmas. Characteristic properties of the dacites which cannot be correlated with simple differentiation are the high silica content and peraluminous nature of the rocks. On the other hand, the course of fractionation of the andesites with respect to silica, as indicated by the groundmass composition of the andesites, is toward and approaches the composition of the dacites. This tends to suggest that fractional crystallization of the andesitic magmas might have been an important factor in the evolution of the dacitic magmas.
4. Providing the dacites are derivatives of ancestral basaltic or andesitic magmas, it seems necessary to assume assimilation of significant amounts of siliceous and aluminous crustal material to account for their composition.

Although the origin of the andesites and dacites of Saipan may be explained by basaltic differentiation and assimilation, there is no clear-cut evidence of contamination of the rocks, suggesting that perhaps some special process might have contributed to their formation. The absence of basalts on Saipan, and the wide compositional gap between the andesites and dacites without the development of rocks of intermediate composition, may indicate that the andesitic and dacitic magmas originated independently.

The general similarity of the volcanic rocks throughout the structural belt of island arcs along the eastern border of the Philippine Sea indicates that the rocks have developed under similar geological conditions, and that there is a close interrelation in this region between volcanism and orogeny. In such an environment it is not unreasonable to expect that petrogenetic processes such as differential fusion and perhaps independent origin of femic and salic lavas might result. These processes, probably operating in conjunction with differentiation (fractional crystallization) in the tectonic environment, may explain the origin of the widely variable calcic and silicic rocks of Saipan.

THE PETROGENETIC SIGNIFICANCE OF THE ANDESITE LINE

The andesites and dacites of Saipan properly lie within the western part of the circum-Pacific province in which the characteristic volcanic-rock association is basalt, andesite, dacite, and rhyolite or some combination of these types. The circum-Pacific province is petrographically and geographically distinct from the adjacent intra-Pacific or Pacific Basin province in which the characteristic rock association of the island groups (for example, the Hawaiian Islands) is olivine basalt and smaller amounts of its differentiation products such as oligoclase andesite and trachyte. The petrologic boundary between these two provinces is well defined around much of the Pacific border, and it is this boundary that has been called the andesite line (see fig. 11) by various writers.

The already discussed differences between the area of the Pacific Basin and the regions bordering it cannot be overemphasized in terms of significance for petrogenesis and the development of the two widely contrasting rock suites of the circum-Pacific and intra-Pacific provinces. The pyroxene basalt, pyroxene andesite, dacite, and rhyolite association of the circum-Pacific province and the picrite basalt, olivine basalt, trachyte association of the intra-Pacific province are to a large extent a reflection of the differing structural environments in which the two rock associations originated. In the Pacific border region igneous activity has been broadly contemporaneous with orogeny, and the volcanic rocks have developed under conditions and processes largely controlled by orogenic folding of a sialic crustal layer. In such an environment normal evolution of contrasting volcanic rock types by differentiation of magmas has been modified by assimilation of sialic material or by special processes such as independent evolution of magmas of varying compositions by complete or partial fusion of rocks of varied composition. Conversely, in the area of the Pacific Basin, a sialic crust is presumably absent, igneous activity is not known to be related to orogenic folding, and the volcanic rocks have originated by fractional crystallization of primary olivine basalt magma.

The significance of the andesite line, from the standpoint of petrogenesis, is that it separates a region in which rock evolution and rock compositions are related to orogeny and the presence of a sialic layer (the circum-Pacific province) from a region in which rock evolution and rock compositions are related to crustal stability and the absence of a sialic layer (the intra-Pacific or Pacific Basin province).

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PLATES 26–30

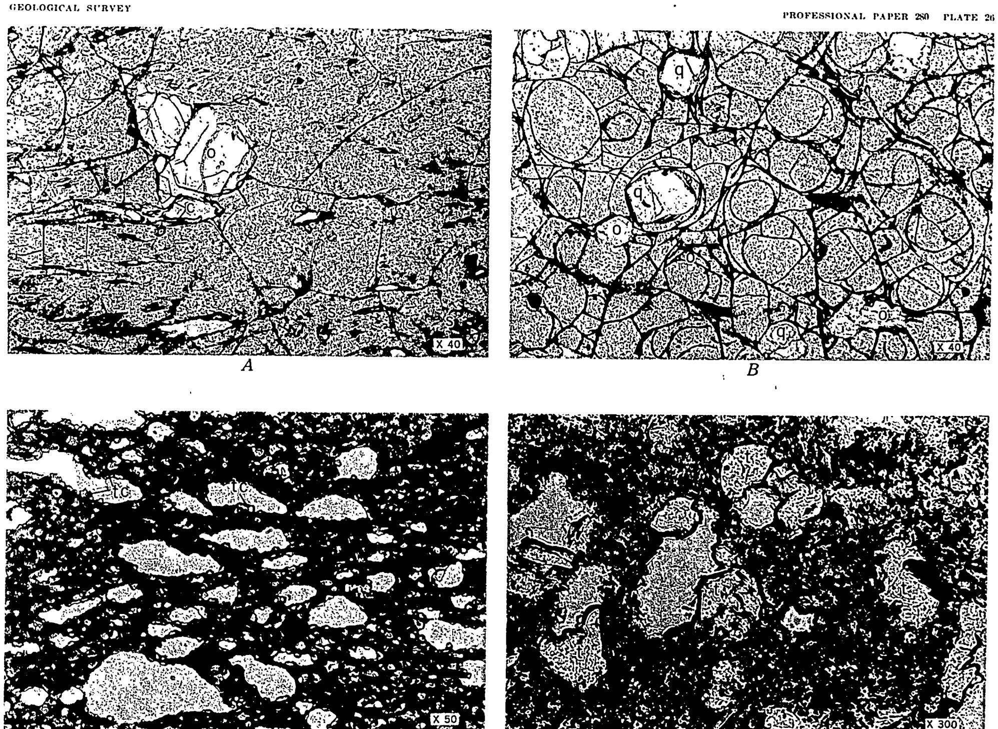
PLATE 26

A. Dacite vitrophyre (specimen S448). Small spherulites (*s*) and phenocryst of oligoclase (*o*) in groundmass of dacitic glass enclosing oligoclase microlites. Elongate vesicles are lined with cristobalite (*c*). Thin, massive layer in breccia facies of Sankakuyama formation.

B. Dacite perlite (specimen S571). Phenocrysts of oligoclase (*o*) and quartz (*q*) in groundmass of fractured dacitic glass enclosing oligoclase microlites. Typical perlitic texture. Fragment in breccia facies of Sankakuyama formation.

C. Dacite (specimen S293). Vesicular dacite with groundmass (dark) of partly recrystallized glass enclosing oligoclase microlites and grains of magnetite and hematite. Large, elongate vesicles are lined with tridymite and cristobalite? (*tc*), and smaller vesicles are filled with these minerals. Thin flow in Sankakuyama formation.

D. Dacite (specimen S230A). Tridymite (*t*) in small cavities in groundmass of dacitic glass, plagioclase microlites, and grains of magnetite and hematite. Middle portion of thick flow in Sankakuyama formation.



PHOTOMICROGRAPHS OF DACITES FROM SAIPAN

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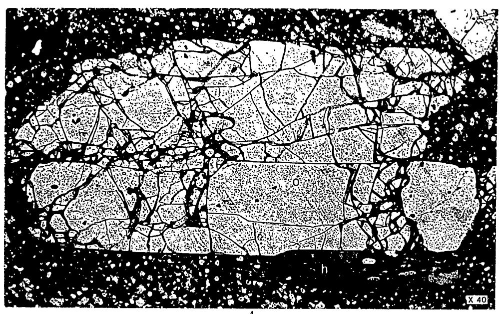
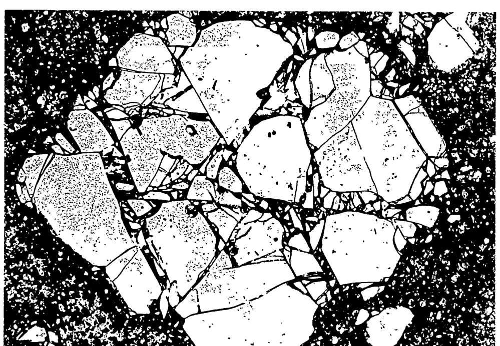


A



B

PHOTOMICROGRAPHS OF DACITES FROM SAIPAN

PLATE 27

A. Hornblende-bearing dacite porphyry (specimen S139). Shattered phenocryst of oligoclase (*o*) and phenocryst of hornblende (*h*) in groundmass of partly recrystallized dacitic glass, spherulites, silica minerals, and magnetite grains. Groundmass material fills interstices between broken feldspar fragments. Block in dacitic volcanic plug.

B. Hornblende-bearing dacite porphyry (specimen S139). Shattered phenocryst of quartz with groundmass material filling interstices between broken quartz fragments. Same rock as plate 27*A*.

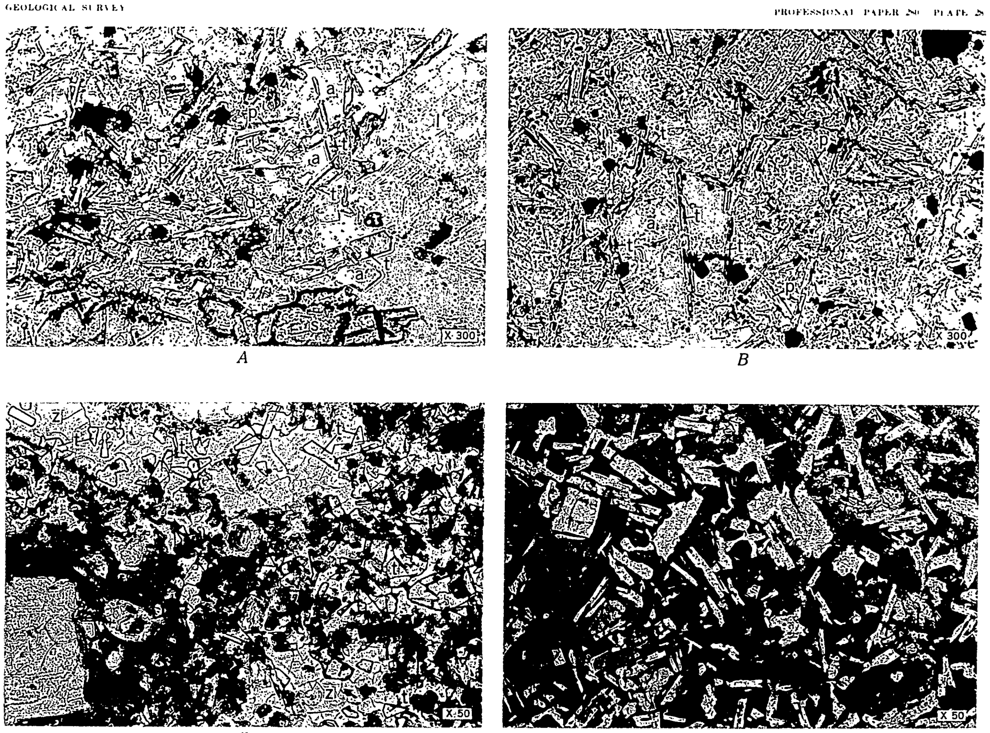
PLATE 28

A. Augite-hypersthene andesite (specimen S121). Irregular filling of anorthoclase (*a*) interstitial to network of elongate tridymite crystals (*t*), plagioclase microlites (*p*), and subcalcic augite (*s*). Large crystals are labradorite (*l*). Dark grains are magnetite. Block in breccia facies of Hagman formation.

B. Augite-hypersthene andesite (specimen S16). Mesh of tridymite needles (*t*) and plagioclase microlites (*p*) enclosing irregular areas of anorthoclase (*a*). Dark grains are magnetite. Block in breccia facies of Hagman formation.

C. Augite-hypersthene andesite (specimen S07A). Wedge-shaped crystals of tridymite (*t*) and interstitial filling of zeolite? (*z*) in druse adjacent to large labradorite phenocrysts. Block in breccia facies of Hagman formation.

D. Augite andesite (specimen S582). Groundmass of elongate labradorite crystals, equidimensional augite crystals, magnetite grains (black), and interstitial glass. Intersertal texture. Thin flow in Fina-sisu formation.



PHOTOMICROGRAPHS OF ANDESITES FROM SAIPAN

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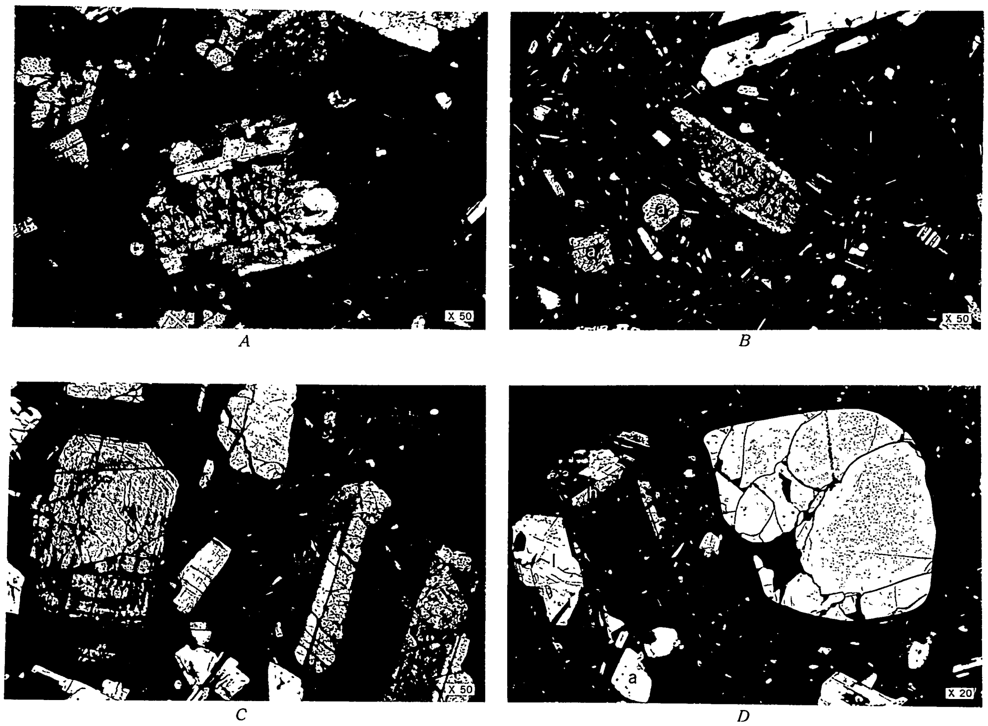


PHOTOMICROGRAPHS OF ANDESITES FROM SAIPAN

PLATE 29

A. Augite-hypersthene andesite (specimen S608B). Phenocryst of hypersthene (central part of crystal) with broad rim of subcalcic augite in parallel intergrowth. Boulder in conglomerate-sandstone facies of Densinyama formation. Nicols crossed.

B. Augite-hypersthene andesite (specimen S43). Phenocrysts of labradorite (*l*), augite (*a*), and hypersthene (*h*); the hypersthene (*h*) has a rim of subcalcic augite. Block in breccia facies of Hagman formation. Nicols crossed.

C. Augite-hypersthene andesite (specimen S21). Wedge-shaped crystals of tridymite in small cavity between large labradorite phenocrysts. Block in breccia facies of Hagman formation. Nicols crossed.

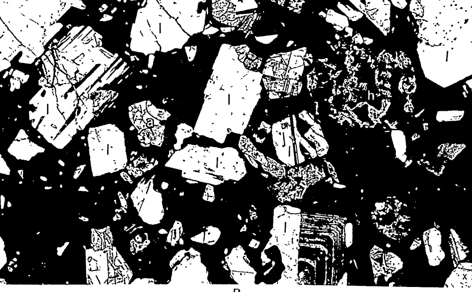
D. Quartz-bearing augite-hypersthene andesite porphyry (specimen S141). Rounded xenocryst(?) of quartz and smaller phenocrysts of labradorite (*l*), zoned augite (*a*), and hypersthene (*h*) in groundmass of labradorite microlites, monoclinic pyroxene, tridymite, anorthoclase, and andesitic glass. Block in dacitic volcanic plug. Nicols crossed.

PLATE 30

A. Augite-hypersthene andesite (specimen S37). Phenocrysts of zoned labradorite (*l*) and smaller grains of labradorite (*pl*) and hypersthene (*h*) in microcrystalline groundmass of plagioclase microlites, grains of subcalcic augites, magnetite, tridymite, anorthoclase, and andesitic glass. Hypersthene phenocrysts are altering to chlorite. Note density of plagioclase phenocrysts. Block in breccia facies of Hagman formation. Nicols crossed.

B. Augite-hypersthene andesite (specimen S107). Phenocrysts of labradorite (*l*), hypersthene (*h*), and augite (*a*) in groundmass of nearly opaque glass enclosing crystallites (not observable) of monoclinic pyroxene and magnetite. Hypersthene phenocrysts are altering to mixture of serpentine and chlorite. Note density of plagioclase phenocrysts. Block in breccia facies of Hagman formation. Nicols crossed.

A



B

PHOTOMICROGRAPHS OF ANDESITES FROM SAIPAN

Petrography of the Limestones

By J. HARLAN JOHNSON

GEOLOGICAL SURVEY PROFESSIONAL PAPER 280-C

A study of the composition, organic constituents, and relative importance of the limestones of Saipan

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GEOLOGY OF SAIPAN, MARIANA ISLANDS

PETROGRAPHY OF THE LIMESTONES

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ABSTRACT

The limestones of Saipan are clastic and consist mainly of foraminiferal tests, debris of the lime-secreting algae, and calcareous shells and exoskeletons of animals. In a few, volcanic material is present. The animals which contributed most to limestone building are corals and Foraminafera; the important plants are coralline algae and *Halimeda*. Other organisms represented are echinoids, mollusks, and dasycladacean algae. The groundmass may consist of fine organic debris, calcareous paste, crystalline calcite, or fine sand and volcanic debris.

The limestones are tuffaceous limestones and calcareous tuffs, detrital limestones, bioclastic limestones, and constructional limestones. The bioclastic limestones include foraminiferal, algal-foraminiferal, coral-algal, and algal limestones. The algal-foraminiferal and the coral-algal limestone are the most common The constructional limestones are old reefs or biostromes that contain corals and algae in position of growth.

Recrystallization has altered some of the limestones, which range in age from Eocene to Recent.

INTRODUCTION

The Saipan limestones are all clastic limestones of Cenozoic age (see chart). The larger clastic particles are the tests of Foraminifera or fragments of the calcareous skeletons of algae and other organisms imbedded in a groundmass of fine mechanical debris, calcareous precipitate, or crystalline calcite.

The following classification of grain sizes, used at the Colorado School of Mines (Low, 1951, p. 17–18), was used in this chapter: coarse, 2.00 mm; medium, 2.00–0.25 mm; fine, 0.25–0.05 mm. Below the range of visibility with 12X power are two classes: sublithographic, dull luster, earthy, opaque; and lithographic, porcelaneous, semitranslucent.

Field localities are shown on a special locality-finding map (pl. 4). Locality numbers, arranged in numerical order at the lower right corner of this map, may be found by reference to grid coordinates. The letter prefix of these numbers indicates the collector—B for Burke, C for Cloud, S for Schmidt. A complete description of the field numbering system is given in Chapter A, page 39. This locality-finding map is intended to be used in connection with the generalized geologic map (pl. 2) at the same scale.

The petrographic studies of thin sections of the limestones were directed toward recognition of the organisms and organic debris of which the limestone was built, in order to determine their relative importance and the conditions of the deposition and ecology. In determining percentages, the ordinary crossgrid whipple plate was used and actual counts were made of the area of a slide occupied by the different types of organisms.

PRINCIPAL LIMESTONE-BUILDING ORGANISMS

Calcareous algae and Foraminifera are the principal builders of the Saipan limestones. The relative percentage of each varies with time of deposition and location, but together they commonly form as much as 75 percent of the rock. The fossil calcareous algae of Saipan include representatives of 3 families and 15 genera which are listed below.

Rhodophyta (red algae)
- Family Corallinaceae (coralline algae)
  - Division 1.—Subfamily Melobesieae? (crustose corallines)
    - *Archaeolithothamnion*
    - *Dermatolithon*
    - *Goniolithon*
    - *Lithothamnion*
    - *Lithophyllum*
    - *Lithoporella*
    - *Mesophyllum*
    - *Porolithon*
  - Division 2.—Subfamily Corallinae (articulate corallines)
    - *Amphiroa*
    - *Arthrocardia*
    - *Cheilosporum*
    - *Corallina*
    - *Jania*

Chlorophyta (green algae)
- Family Codiaceae
  - *Halimeda*
- Family Dasycladaceae
  - *Cymopolia*

CORALLINE ALGAE

The coralline algae comprise two distinct groups of the red algae, the crustose and the articulate, which have developed different growth structures and become adjusted to different environmental conditions.

The crustose corallines form solid, stony structures which range from thin crusts to thick, massive branching forms. Some attain considerable size, specimens a foot or more across having been observed in and around the tropical reefs. On the other hand, the articulate corallines ordinarily develop small, delicate, bushy structures, seldom more than a few inches across. The crustose coralline algae have developed many growth forms. In Chaper E, Calcareous Algae, these have been discussed under the following types: Thin crusts which are attached to and cover or partially cover other organisms or organic debris; thin laminae which grow loose or unattached on the ocean bottom; crusts which develop warty protuberances, mammillae, or short, stubby branches; and strongly branching forms. In the limestones, one commonly finds the thin crusts entire and in position of growth. In some, small nodular masses are formed of superimposed crusts or alterations of these encrusting algae with encrusting Foraminifera (pl. 31, fig 2). The other growth types are commonly represented by broken and worn fragments. Their form may be elongate, ovoid, or irregular. In hand specimens they are easily recognized by their white chalky to porcelaneous texture. They occur in all the limestones. In thin section they may be recognized by the fine cellular structure commonly in definite layers and by the dark color. The calcium carbonate particles precipitated by the algae are so fine that they show no crystalline structure and appear dark. The characteristic structures of the common genera are shown on plate 31, figure 2, and plate 32, figure 3. Algae of this type are commonly associated with Foraminifera and coral. The actual percentage of such algae in the rock specimens studied varies greatly according to the specimen, but in relative abundance they commonly rank first or second and in volume second or first among organisms present.

Remains of the articulate corallines are surprisingly common and widespread in the Saipan limestones. Their presence can be recognized in a large majority of the slides studied, although only a moderate proportion of the limestones contain them in large number. In the Mariana and Tanapag limestones (Pleistocene), they appear to be represented primarily by the genus *Amphiroa* (pl. 35, fig. 4); although some contain material identified as *Jania*. In the Miocene and Eocene limestones, no *Amphiroa* were observed; *Corallina* is the commonly represented genus in them, while *Jania* occurs throughout but in minor numbers. Plants of this type develop usually as small bushy structures, each composed of clusters of delicate fronds which are made up of numerous segmented portions. The fronds are small, thin, and delicate, and the living plant is quite flexible. With the death of the plant, they break into individual segments. Most of the fragments seen in the thin sections are separated segments. Occasionally, pieces containing several connected segments occur. With the aid of a magnifying lens, these segments can be observed in many of the limestones, and they can be separated and washed out of some of the more marly and shaly facies. In thin section, they can be readily recognized by the shape of the fragment and general structure. Characteristically they are composed of curved layers of relatively long, narrow cells. The cells in general are much longer than in the crustose corallines. The skeletal material shows dark in the sections. They commonly occur associated with certain groups of Foraminifera and at places with *Halimeda*. Only rarely are they found in the same rock with abundant remains of the crustose forms. In a few samples of the limestones studied, they occur in sufficient abundance to be the predominant rock-building organism. However, in many instances where numerous specimens were observed in a slide, they did not form a large percentage of the rock.

CALCAREOUS GREEN ALGAE

In the Saipan limestones, two types of calcareous green algae have been observed—the codiaceans, represented primarily by *Halimeda*, and the dasycladaceae, represented by *Cymopolia*.

Halimeda occur in great numbers locally (pl. 34). They grow attached to the bottom as small bushy plants several inches high. Each bush is composed of many branches or fronds, each of which is segmented. Many of the segments resemble small models of the prickly pear (*Opuntia*) leaf. The young and growing forms are bright green. As they grow older, they become more and more encrusted with lime and assume a grayish appearance. After the death of the plant, the branches tend to break into separate segments which bleach white or light gray. These can be observed in many of the hand specimens of limestones (pl. 34, fig. 2). In thin section, the segments may assume a number of outlines depending on the angle of the section. Commonly they are long and slender, but occasionally a section parallel to the flat surface may show wide, lobate forms. The microstructure is distinctive. The central portion of the leaf consists of coarse tubes which branch into smaller and smaller tubes as the outer part of the segment is approached, ordinarily ending in very

fine tubes perpendicular to the edge of the segment (pl. 34, figs. 1, 3). The calcification starts at the outer surface and works inward. Where it is complete, the microstructure of the entire segment is preserved. If only the outer rim is calcified, it, only, is preserved. *Halimeda* is commonly associated with Foraminifera and locally with the crustose coralline algae. More rarely they may be associated with articulate coralline algae. In certain facies, they are so abundant as to be the predominant rock-forming organism, and the rocks are spoken of as *Halimeda* limestones (pl. 34, figs. 1, 2).

Dasycladaceans were recognized in a number of slides of limestones of both Miocene and Eocene age, but only the genus *Cymopolia* has been identified. The plants develop as small, brushlike or club-shaped structures from a fraction of an inch to several inches high. The individual fronds consist of a series of beadlike, club-shaped, or cylindrical segments. Each individual frond consists of a relatively thick central stem from which develop whorls of primary branches which are arranged like the spokes of a wheel. From these may develop secondary and even tertiary branches. Calcification consists of a precipitation of calcium carbonate around the central stem and primary branches. Occasionally it becomes thick enough to enclose the secondary and tertiary branches, forming a moderately compact crust. After the death of the plant, such crusts may be preserved as external casts of the central stem and branches which may or may not be filled with secondary calcite or fine calcareous paste. The fossils in hand specimens can be recognized with a low-power glass or the naked eye and they may be washed from shaly, chalky, or marly facies. In thin section, they have a very characteristic structure with a central stem and radiating primary branches. Certain echinoid spines in perpendicular section have a similar gross structure. Among the dasycladacean algae, however, the calcium carbonate is fine-grained and is not precipitated in optical continuity as in the echinoids. The dasycladacean algae may occur with Foraminifera and *Halimeda;* they have been observed only rarely with articulate coralline algae. In the Saipan limestones, they are of no importance as rock builders.

FORAMINIFERA

Foraminifera are abundant in most of the limestones from Saipan; in bulk and abundance they rank first to third among the rock-building organisms there. They include large, moderately deep-dwelling benthonic forms (pl. 32, fig. 4; pl. 35, fig. 1), small shallow-water types (pl. 35, fig. 2), and planktonic species. Structurally, they tend into two types. Most of the smaller Foraminifera are made up of radial calcite fibers. These fibers when oriented parallel to the crosshairs extinguish under crossed nicols. The larger Foraminifera are characterized by a compact shell structure which is nearly opaque under crossed nicols (Cayeux, 1916, p. 352–375). The Foraminifera are described and discussed in Chapters H and I.

The Foraminifera are associated with almost all of the other types of organisms noted in the limestones of Saipan. Many of the limestones are essentially algal-foraminiferal limestones, the 2 groups of organisms together at places making up as much as 75 to 90 percent of the rock mass (pl. 35, figs. 1, 3).

CORALS

Rock-building corals are abundant, varied, and widespread in many of the warm seas. They may be encrusting, branching, or may grow as compact heads.

The tropical limestone-building corals have a skeleton of minute crystals of calcium carbonate (Vaughan and Wells, 1943, p. 31–35). The majority of the reef-building corals secrete skeletons of aragonite. In the common tropical corals, the tabulae and dissepiments are formed of parallel crystals which grow at right angles to the surface (pl. 31, figs. 6, 7). The septa have more complicated structures. Fibrous crystals form prismatic or cylindrical columns of tiny fibers which radiate from a common axis, giving a feathery appearance in longitudinal section. In most of the fossil corals, the original aragonite has changed to calcite. The coral skeletons recrystallize easily, and much of the fossil material shows some degree of recrystallization (Johnson, 1951, p. 32–39).

Corals are commonly associated with calcareous algae and Foraminifera (pl. 32, figs. 1, 5). It is difficult to estimate their real importance in the Saipan limestones. Large colonies and fragments of coral can commonly be seen on outcrops of the post-Miocene limestones. In thin sections of the nonreef facies, fragments of coral are seen only occasionally (pl. 32, fig. 5). Also, as the coral fragments are typically large in comparison to the size of a thin section (pl. 34, fig. 3), most samples containing them were rejected in picking pieces for sectioning. Thus, the amount of coral material in the slides is not a fair indication of the amount in the rock. It is clear from the field studies reported in Chapter A that they have been important contributors to most of the younger limestones and are dominant locally. They are, however, relatively much less important than either the calcareous algae or the Foraminfera in the Miocene and Eocene limestones.

ACCESSORY LIMESTONE-BUILDING ORGANISMS

In addition to the important rock-building organisms mentioned above, remains of the hard parts of a number of other animals are commonly observed in thin section. However, these do not occur in sufficient quantity to form an appreciable percentage of the rock. The most important of these accessory rock builders are the echinoderms and mollusks, described below.

In addition, remains of several other groups of organisms were observed in trace amounts. These organisms included bryozoans, worms, ostracods, fragments of crustaceans, and fish teeth and bones.

ECHINODERMS

Echinoderms are common in the present seas around Saipan. The phylum is there represented by echinoids, holothurians, and several kinds of starfish. Remains of all these groups have been recognized in the limestones.

The echinoids are the most abundant and most easily recognized. The calcite of their spines is arranged in optically oriented bands that show up prominently in thin sections (pl. 31, figs. 3–5). Recognizable starfish plates are relatively uncommon in thin sections of the Saipan rocks. Holothurians have embedded in their thick skin numerous tiny spines and peculiarly shaped calcareous plates. These are occasionally recognized in the thin sections of the limestone.

Remains of echinoderm tests have been observed in all facies of all the limestones and may occur with any or all of the other organisms recorded. They are most commonly observed in the algal-foraminiferal limestones. Their total volume is insignificant as compared to the bulk of the limestone.

MOLLUSKS

The mollusks are abundantly represented in the present seas around Saipan. In the limestones studied, fragments of the shells of both pelecypods and gastropods have been observed (pl. 33, fig. 3).

The pelecypod shell is composed of three or more distinct layers: commonly an outer scleraprotein or conchin layer and calcareous middle and inner layers. The outer layer is ordinarily thin and is generally worn off in fossil shells. The middle layer is composed of closely packed polygonal prisms of calcium carbonate, disposed perpendicularly to the surface of the shell (pl. 31, fig. 1). It is called the prismatic layer and constitutes the outer layer in all the fossil fragments observed. The prisms are secreted by the free edges of the mantle lobes, hence growth takes place only on the margins of the shell. The inner layer of the shell is composed of thin laminae of calcite or aragonite, arranged roughly parallel to the surface of the mantle, and is usually called the laminated layer. It is secreted by the entire outer surface of the mantle, hence grows continuously during the life of the shell, and each laminae extends little beyond the previous one. If thin and crumpled, it gives a pearly luster to the shell. If thick and relatively smooth, the shell surface has a porcelaneous appearance.

Differences in the crystallographic organization of the calcium carbonate shell are found between genera. For example, among the oysters, both the prismatic and laminated layers are composed of calcite, whereas in some other groups, the layers are entirely aragonite; in others the outer prismatic layer is calcite and the laminated layer is aragonite. This original composition has a great deal to do with the manner in which the shell is preserved, as aragonite is much less stable and more easily dissolved than calcite. (See Bøggild, 1930, and Mackay, 1952, for details of the structure.)

Gastropod shells consist of an organic base impregnated with calcite or aragonite. Ordinarily they, also, show three or more distinct layers comparable in a general way to those of the pelecypods. The calcareous bulk of the shell is formed of very thin laminae composed of microscopic prisms of calcium carbonate oriented obliquely to the surface of the shell with a different orientation in each lamination. In a few genera the calcium carbonate is largely calcite, but in most genera aragonite predominates. Many of the fossil shells show evidence of secondary inversion of aragonite to calcite with considerable loss of the original structure. Usually, the aragonite prisms are very small and slender. The fact that the majority of gastropod shells are formed of a high proportion of aragonite probably explains their susceptibility to solution and frequently poor preservation.

Many of the limestones contain small, usually badly broken and worn fragments of molluscan shells, but they are rarely abundant. However, at a number of places shells are abundant in the late Pleistocene Tanapag limestone (pl. 33, fig. 3).

UNIDENTIFIED ORGANIC DEBRIS

Almost all of the thin sections studied contained some organic fragments which, because of lack of distinguishing structural features, recrystallization, or organic destruction, could not be identified. Recrystallization and destructive organisms such as boring worms and other animals and fine penetrating filaments of algae tend to destroy the original structures.

GROUNDMASS

The fine groundmass between the coarse organic debris makes up a large percentage of the rock, although the amount varies considerably. It may range from about 15 percent to as much as 85 percent. Four types of groundmass were observed in different limestones:

very fine organic debris, calcareous paste, crystalline calcite, and fine sand and volcanic debris.

FINE ORGANIC DEBRIS

The very fine organic debris represents small, commonly minutely macerated fragments of foraminiferal tests, shells, calcareous algae, and so on, the same material as the large organic fragments but much more finely triturated (pl. 35, figs. 2 and 4).

CALCAREOUS PASTE

The calcareous paste represents extremely fine particles of calcareous material which shows little or no structure. Such a groundmass occurs in limestones of all ages in many parts of the world. Its origin has been discussed by many writers and there is no clear concensus as to origin. The various suggestions on the matter have been recently summarized by G. W. Crickmay (1945, p. 233–235) in the report of the petrography of the limestones from Lau, Fiji. The suggested origins include altered fine organic debris, physicochemical precipitates (Johnson and Williamson, 1916), biochemical precipitates (Bavendamm, 1913, p. 597; Drew, 1914, p. 7–45), and extremely fine end products from the abrasion of shells in the littoral zone. Quite possibly some of the calcareous paste in the Saipan limestones have been developed in all those ways. However, the writer suggests that much of it may have been deposited by algae, especially green and blue-green types. Many such algae deposit calcium carbonate as extremely fine particles so tiny that they appear dark in thin sections. Such fine precipitate is found in most limestones rich in algae. Wood (1941, p. 192) has called it algal "dust."

In rocks formed largely of calcareous paste, the most common fossils are Foraminifera and red algae. Echinoid fragments may be present, but in very small quantity. Corals and molluscan debris, if present, are usually fragmentary and badly worn. During studies around Guam and Palau in 1952, the writer found that in many places behind the outer part of the reef, green algae occurred in considerable abundance with corals and coralline algae. Among the limestone slides studied, some showed vague suggestions of threads or fibers, which the author interprets as indicative of algal precipitation. These observations lead him to the belief expressed above that algal precipitate is the source of much of the material in the calcareous paste.

CRYSTALLINE CALCITE

Crystalline calcite is very common in the groundmass of Saipan limestones. In some it is fine to medium grained, and the whole groundmass has a more or less granular appearance. Granular calcite may fill the spaces between fossils and the coarser organic debris, as well as the cavities in fossils. In other limestones, a coarser, crystalline calcite surrounds fossils and similar objects. In some specimens the optical axes are oriented in phase with the prismatic material in the shells. In others, the calcite forms aureoles or bands around the outside of the fossils, with the calcite prisms more or less perpendicular to the edges of the fossils. Coarse crystalline material may fill vugs in the rock and former cavities in fossils.

The crystalline calcite not only is of several types but apparently was formed at several widely separated times. One gets the impression that most of the granular calcite formed rather early, probably almost contemporaneously with deposition, as much of this calcite coating as seen in section completely rings the clastic particles. If these entire rings are assumed to represent continuous sheaths, this suggests that the coating formed while the particles could still be moved on the sea bottom. If formed after the rock was well compacted, it would not entirely sheath the clastic particles but would fill the interspaces without coating the contact surfaces of the particles.

The coarser crystalline calcite is later and probably is related to the recrystallization of the rock which appears to be connected with the present chemical weathering of the surface material. This will be considered further in the discussion on recrystallization of the limestones.

FINE SAND AND VOLCANIC DEBRIS

A few of the limestones contain appreciable amounts of noncalcareous matter in the groundmass (pl. 32, fig. 2). This is particularly true of the calcareous bands in the Hagman formation and the limestones in the Densinyama formation, but it is also true of some of the limestones in the Donni sandstone member and the tuffaceous facies of the Tagpochau limestone. The material ranges from pure silica sand to but slightly altered volcanic sediments; much of it appears to be weathered volcanic ash. Some has been altered to clay. The rocks range from nearly pure limestones containing a small amount of pyroclastic material to calcareous tuffs in which pyroclastic material predominates. The tuffaceous limestones and calcareous tuffs range in color from gray to brown, the shade depending largely on the amount of pyroclastic material present.

CEMENTATION

The Saipan limestones vary greatly in the amount and nature of the cementation, ranging from soft chalky marls to aphanitic compact well-cemented limestones. Typically, lithification of the limestone involved an introduction of calcium carbonate as fine granular particles. The carbonate is usually either quite fine (particles generally about 0.005 mm across), very rarely in plumose crystalline masses, or in large crystals. The latter imply secondary recrystallization. In some thin sections there appears to have been a little recrystallization of the paste along with the introduction of the granular calcite, but typically this does not happen. Commonly, well-preserved small fossils and fragments of organic debris occur in the midst of granular calcite. Most of the fossils surrounded by the granular calcite show sharp, clean-cut outlines, quite different from the more irregular and indefinite outlines found with the recrystallized groundmass. In some specimens cementation locally was surprisingly complete, yet they contain well-preserved fossils, as for example in a number of specimens of the pink and white Eocene limestones.

RECRYSTALLIZATION

Many of the limestones show evidence of recrystallization, which ranges from very little to almost complete. However, the amount of thoroughly recrystallized limestone is small and is typically restricted to the weathered surfaces. The recrystallization involves both the groundmass, the fossils, and the coarse organic debris. Characteristically, it starts in the groundmass and proceeds until most or all of the groundmass is replaced by coarse crystalline calcite. Then the fossils are attacked from the outer edges or from cavities within the mass.

At first crystals develop and grow along the margins of the shells and foraminiferal tests and work forward in optical continuity into the groundmass. Gradually, the fossils become more and more indistinct until finally they are indicated only by marginal lines of "dust," color bands, or textural differences in the groundmass. Not all of the organic remains are equally affected; some alter more quickly and more thoroughly than others. Roughly, they may be arranged in the following order of decreasing susceptibility to crystallization: Corals, mollusks, pelagic Foraminifera, beach-type Foraminifera, larger Foraminifera, echinoids, and calcareous red algae. Among the green algae the Dasycladaceae are much more susceptible to alteration than the red coralline algae, but commonly *Halimeda* are less susceptible. Dasycladaceae commonly alter before any of the Foraminifera. The larger Foraminifera, coralline algae, and echinoids offer about equal resistance to recrystallization. Typically they are found with slightly altered structures after most of the other fossils are reduced to the order of solubility of the shells and skeletal fragments.

Solubility appears to be determined largely by the chemical composition, particularly the presence of magnesium carbonate, which reduces solubility; the form of the calcium carbonate, whether aragonite or calcite; and the nature of the shell structure, whether compact, porous, coarsely prismatic, or very fine textured. Thus, corals and many mollusks, particularly gastropods, which are made up largely of aragonite fibers, are much more soluble than those animals which have calcite shells.

The shell structure largely determines the nature and form of the recrystallization. Prismatic shells at first become more coarsely prismatic. Later the prismatic structure becomes more and more indistinct and is gradually replaced by granular calcite. Compact shells or skeletons, as of the larger Foraminifera and the calcareous coralline algae, become more transparent and optically more distinctly birefringent. The echinodermal material which is made up largely of crystal plates becomes flecked with small grains of calcite and finally changes to a granular aggregate of calcite, or, more rarely, the individual crystals grow into very large crystalline aggregates. Ultimately the fossils are so altered that their indentification becomes impossible. The calcareous paste usually is the first part of the rock to recrystallize as it is more susceptible to recrystallization than fossil fragments other than corals and certain of the mollusks, particularly gastropods. The original paste is dark colored and extremely fine grained. Commonly the grain size of the calcite particles is less than 0.005 millimeters. The recrystallized granules are from 10 to 100 times as large, frequently 20 to 25 times. Recrystallization seems to be spotty and irregular. It appears to be closely related to weathering, either present or past.

INTRODUCTION OF OTHER MINERALS

Accompanying recrystallization there is generally an introduction of other minerals such as iron oxide, silica, manganese oxides, and phosphate. However, the total amount of such alteration is small, spotty, and very localized. The most spectacular examples were observed in some of the outcrops of the Mariana limestone and some of the *Halimeda*-rich Mariana limestone specimens. The *Halimeda* have been discolored and in some cases largely replaced by iron oxide or more rarely by phosphate.

CLASSIFICATION OF THE SAIPAN LIMESTONES

The Saipan limestones are broadly divisible into four classes, though actually all graduations from one to the other may be found. These classes are tuffaceous limestones and calcareous tuffs (pl. 32, fig 2); detrital limestones; bioclastic limestones (pl. 32, fig. 1–4); and constructional limestone, commonly the coral-algal type (pl. 32, fig. 5).

TUFFACEOUS LIMESTONES AND CALCAREOUS TUFFS

The Eocene rocks exposed on Saipan are mainly pyroclastic rocks, some of which accumulated in marine waters and contain calcareous material and even well-preserved fossils. The amount of calcareous material ranges from very low to very high, that is, from a volcanic tuff containing a slight amount of calcium carbonate to nearly pure limestones slightly contaminated with volcanic material.

Much higher in the section are tuffaceous Miocene limestones which may contain 12 to 15 percent or more reworked volcanic material. However, in most of the specimens selected for study the percentage of volcanic material was low, 3 to 5 percent.

A typical representative is a specimen from locality C132, which contains rounded fragments of corals, larger Foraminifera, and crustose coralline algae. All are considerably rounded and worn and are associated with less worn fragments of articulated coralline algae in a groundmass of clear crystalline calcite. The organic debris forms 45 to 52 percent of the rock, the volcanic material forms 3 to 8 percent, and the rest is clear crystalline calcite groundmass (see table).

DETRITAL LIMESTONES

The limestones here referred to as detrital contain appreciable amounts of rounded particles of reworked older limestones or previously deposited and partially lithified sediments. The particles may range from small sand grains to well-rounded pebbles, 3 or 4 centimeters across. Commonly these occur in a groundmass of finely macerated organic debris or of calcareous paste. Coarse particles of organic debris and even unworn tests of Foraminifera may occur between the detrital limestone fragments. There probably was very little difference in age between the detrital material and the groundmass in most of the Saipan limestones that are designated as detrital.

Relatively pure detrital limestones are found in the various facies of the Eocene, Miocene, and Pleistocene, but are most abundant in the Pleistocene and Miocene.

BIOCLASTIC LIMESTONES

Although nearly all the limestones of Saipan are clastic limestones, those referred to as bioclastic limestones are composed of fragments or whole tests of Foraminifera, pieces of coral, and pieces of other types of fossils, rather than pieces of older rocks. The majority of them are surprisingly free of terriginous sediments and many of them are very pure chemically. For convenience in discussion, they are divided in groups on the basis of the predominant rock-building organism present.

FORAMINIFERAL LIMESTONES

Foraminifera are present in all of the limestones of Saipan. The calcareous algae and the Foraminifera together are the most important limestone-building organisms present. The percentage of Foraminifera measured in the sections of rock studied ranges from 5 to 85 percent. Where the Foraminifera are present in quantities over 50 percent, the rock may be referred to as a foraminiferal limestone. Examples were observed in the inequigranular facies (pl. 35, fig. 2) of the Miocene Tagpochau limestone; in the tuffaceous facies of the same formation; and in the white facies in the Eocene Matansa limestone, the last at places containing 60 to 75 percent Foraminifera (pl. 35, fig. 1).

ALGAL-FORAMINIFERAL LIMESTONES

In the majority of the Saipan limestones, the Foraminifera and the algae together make up over 50 percent of the recognizable organic debris (see table). In some samples, the amount of the two organisms present is about equal. In others, there is slightly more of one than the other. These are collectively classed as algal-foraminiferal limestones (pl. 32, fig. 3; pl. 34; pl. 35). As they occur in rocks of all ages on Saipan and in almost all of the facies represented, it is not surprising that the algal-foraminiferal limestones show considerable variety. The Foraminifera included may be large or small. The algae may be crustose corallines, articulate corallines, *Halimeda*, or some mixture of these three types.

The Foraminifera commonly stand out clearly in the specimens, slides, or photographs. The algae may include crusts in position of growth, fragments of various crustose types, numerous pieces of articulated algae, or *Halimeda* segments.

CORAL-ALGAL LIMESTONES

In laboratory studies of specimens and thin sections it is difficult to evaluate the importance of corals in rock building because in collecting the specimens in the field one more or less consciously avoids taking hand specimens that are made up entirely of coral or which contain very large pieces of coral. Similarly, in preparing slices for thin sections one avoids pieces that would be entirely coral. In the field, large heads of coral or large rounded fragments of them are frequently observed in the rocks. It is safe to say that corals are more important than the study of the hand specimens and sections would indicate. Certainly coral-rich rocks are important in the Pleistocene and Recent limestones, and a number of specimens indicate that coralline algae and Foraminifera are abundantly associated with them. The term coral-algal limestone is generally employed for this group (pl. 31, fig. 2).

Laboratory studies of specimens of these limestones indicate two quite different types. The first, made up entirely of worn pieces of coral which may range in size from more than a foot across to relatively coarse sand, is a bioclastic limestone (pl. 33, fig. 4). The second, containing either essentially whole colonies of corals and algae which occur more or less in position of growth or large relatively unworn fragments, is a constructional limestone.

ALGAL LIMESTONES

The algal limestones may be divided into three groups on the basis of the type of algae present in the largest amounts: crustose coralline limestones, articulate coralline limestones, and *Halimeda* limestones.

The crustose coralline limestones (pl. 32, fig. 2; pl. 35, figs. 1, 2) are formed of or contain considerable quantities of the crustose corallines, including *Archaeolithothamniom, Lithothamniom, Lithophyllum, Mesophyllum, Lithoporella, and Dermatolithon.* The limestones may contain entire crusts in position of growth, or they may consist of fragments of the plants, commonly worn and abraded.

The articulate coralline limestones (pl. 35, fig. 4) include all limestones which contain an abundance of fragments of the articulated coralline algae—*Corallina, Amphiroa, Jania*, and others. Algae of this type are especially abundant in the Pleistocene Mariana limestone and in certain beds of Miocene limestones, although they do occur occasionally in some of the Eocene limestones, but only in the Miocene and Pleistocene do they occur in sufficient quantities to be of outstanding importance. Even where the pieces are so abundant as to cover a large area of the slide, the actual bulk percentage is commonly smaller than it would appear, because typical segments of these algae are so tiny.

Halimeda limestones (pl. 34) are the last type of bioclastic algal limestone to be considered. As will be noted in the table, *Halimeda* occur in limestones of all ages present on Saipan, and beds may be found which contain them in such quantities that the limestones may correctly be called *Halimeda* limestones. These are abundant and widespread in the *Halimeda*-rich facies of the Pleistocene Mariana limestone, and they are locally abundant in both the inequigranular and the marly facies of the Miocene Tagpochau limestone. *Halimeda* is also fairly abundant at a few localities at places within the white facies of the Eocene Matansa limestone.

The *Halimeda* limestones may be filled with joint fragments which, on weathered surfaces, strongly suggest some of the large platy Foraminifera (pl. 34, fig. 2) but are easily recognized by the differences of structure in thin sections. In other specimens the *Halimeda* segments have been dissolved and the rock appears porous and vuggy on account of the numerous molds of *Halimeda* (pl. 34, fig. 4). In still other samples the joints have been replaced by iron or phosphate.

CONSTRUCTIONAL LIMESTONES

These limestones represent reefy limestone masses formed largely of corals, calcareous algae, or other organisms, enough of which are in the position of growth to indicate constructional origin. Such deposits normally are massive and poorly bedded. Most can be easily recognized in the field, but in hand specimens or slides they cannot readily be separated from bioclastic limestones, as they are built by the same organisms. Many of the coral-algal limestones of Saipan belong in this group.

SUMMARY

Most of the Saipan limestones consist of organic material in an organic or finely crystalline matrix or, rarely, are detrital and derived from earlier formed organic limestones. The results of the study of a series of specimens are tabulated in the following table.

Organic constituents of Saipan limestones

[A plus sign (+) indicates presence, without estimate of percentage]

Age	Formation	Facies	Slide no.	Organisms (percent): Foraminifera	Corals	Molluscan shells	Echinoid spines or plates	*Halimeda*	Crustose coralline algae	Articulated coralline algae	Other algae	Undetermined	Groundmass (percent): Fine organic debris	Fine dark calcareous precipitate	Coarse crystalline calcite
Recent		Beach rock	C66	5	11	7	+	11	10						
Pleistocene	Tanapag limestone	No facies subdivision.	C50	4				20	5				+	+	
			C50	15				18	10				50	+	
	Mariana limestone	Massive	C67 (2)	5	7	4	+	5	7				+	+	
		Massive (pink)	C65	8	8				15	+			60		
			C68	5	11	+			5	10			+		
		Halimeda-rich	C36	6			+	8	5				+		+
			C49	8	13	+		8	5						+
			C52	3	18			8	5						
			C52	4	12			14					+	+	+
			C54	18	55			10	12				+	+	
Miocene	Tagpochau limestone	Inequigranular		21	4	1	2	16	1			11	+		
			B260	22		2			5			30	+	+	
			B261	35		+	+		25				+	+	
			B281	27	4			15	6				+	+	
			B284	27	2			2	27			5	+	+	
			B295	15				2	44			7	+	+	
			B295	11		2			50				+	+	
			C4	50					24				+	+	+
			C16	18	5		+	12	15				+		+
			C16a	11	10	+	+		8				+	+	
			C21	18	4	+	+	3	11	6			+		+
			C55	15			+		12	4			+		
			C62	8	8				6	9			+	+	
			C62	10	30		+		9	5			+	+	
			C73	25	17				5	7			+	+	+
			C73	20	40				8	11			+		+
			C76	35					10	14					+
			S257	12	1			1	20	2			+	+	
			S243	8	9			11	7	1			+	+	
		Marly	C27	5	15	+		5	8				+	+	
			S62	9	7				8	5			+	+	
			C130	9		+	+		4			20	+	+	
		Transitional	C56	16	5		+		15	8			+		+
			C56	21	9		4		22	5			+		+
		Tuffaceous	C14	12		0			10				+		
			C14	65		3			5				+		
			C132	24		+	2		23				+		
		Rubbly	C23	9	+				8	7			+		+
			C23	13	11		+		5	10			+		
			C127	6	15	1	1		21	2		8	+		
Eocene	Matansa limestone	White	B67(1)	5	1		4	8	21				+	+	
			B67(2)	7	16		8	2	16			5	+	+	
			B67(3)	6	7	1	11	3	18				+		
			B75	7	11	+			34			4	+	+	
			B80	8	7	3	+		5				+		
			C13(1)		85	2	+		7					+	
			C13(2)		50	3	+		10					+	
	Hagman	Pink	S262	14	12		2	3	10			6	+		
		Conglomerate-sandstone.	C64	5	15				5	4	30			+	

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INDEX

PLATES 31–35

PLATE 31

[X 40 unless otherwise indicated]

FIGURE 1. Fragments of coral, molluscan shell, calcareous algae (black), and Foraminifera in Recent beach rock (X 15). Field locality C66. USNM 109233.

2. Coral (left half) coated with a thin layer of encrusting Foraminifera, a thin algal crust, and a thick layer of encrusting Foraminifera. Eocene, Matansa limestone, pink facies. Field locality S604. Specimen on USGS type-algae slide a112–1 from paleobotanical locality D173.

3. Section of an echinoid plate. Eocene, Matansa limestone, transitional facies. Field locality S349. Specimen on USGS type-algae slide a88–1 from paleobotanical locality D226.

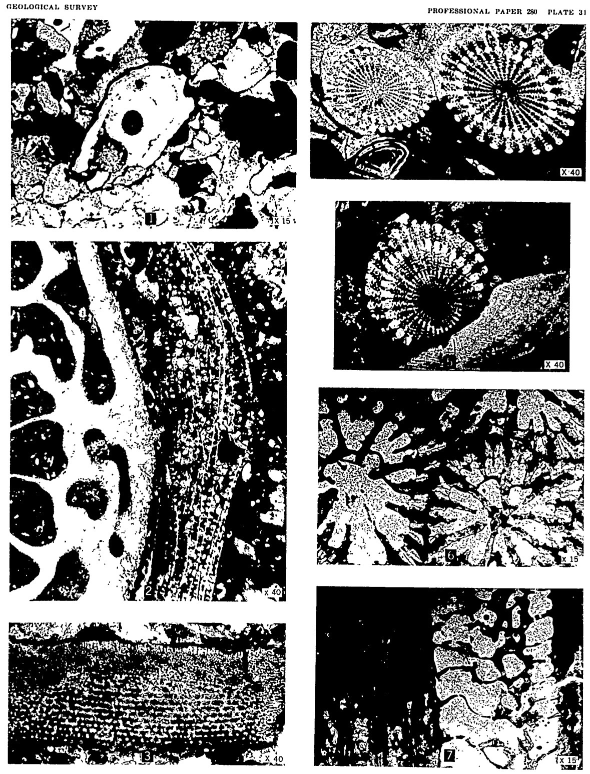
4. Section through two echinoid spines. A foraminifer at lower left. Pleistocene, *Halimeda*-rich facies of Mariana limestone. Field locality S691. USNM 109241.

5. Echinoid spine above fragment of molluscan shell. Recent beach rock. Field locality C66. USNM 109233.

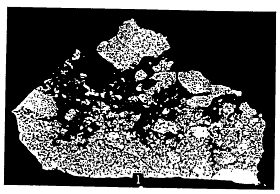
6–7. Coral (X 15). Pleistocene, Tanapag limestone. Field locality C35 (with carbon-14 age 20,000 years). USNM 109229.

6. A perpendicular section.

7. A parallel section.



ROCK-BUILDING ORGANISMS



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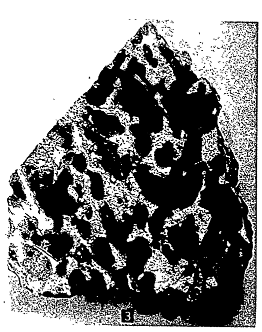

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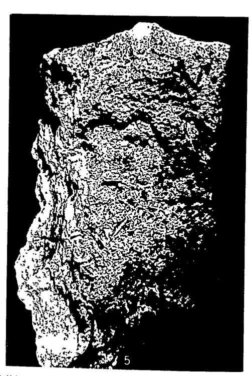


5

SAIPAN LIMESTONES

PLATE 32

[Natural size]

FIGURE 1. Coral-foraminiferal limestone. Eocene, Matansa limestone, white facies. Field locality B69. USNM 109225.

2. Tuffaceous Miocene Tagpochau limestone containing coarse debris of coral, coralline algae, molluscan shells, and some Foraminifera. Field locality B375. USNM 109228.

3. Algal limestone, reworked fragment containing large pieces of coralline algae. Miocene, Donni sandstone member of Tagpochau limestone. Field locality S129. USNM 109236.

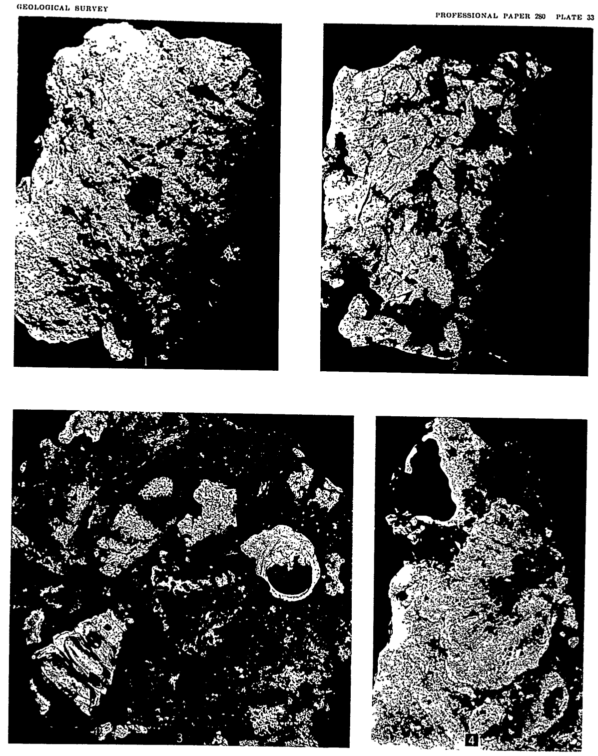
4. Foraminiferal limestone. Weathered surface shows numerous larger Foraminifera. Miocene, Tagpochau limestone, inequigranular facies. Field locality S536. USNM 109240.

5. Coral limestone, reworked fragment. Weathered surface shows large pieces of coral. Miocene, Donni sandstone member of Tagpochau limestone. Field locality S127. USNM 109235.

PLATE 33

[Natural size]

FIGURE 1. Eocene Matansa limestone, pink facies, composed largely of medium-grained to fine organic debris and Foraminifera. Field locality S341. USNM 109238.
2. Typical Miocene Tagpochau limestone, inequigranular facies. Field locality C78. USNM 109234.
3. Coral-foraminiferal limestone with gastropods. Pleistocene, Tanapag limestone. Field locality C50. USNM 109231.
4. Coral-foraminiferal limestone somewhat recrystallized. Pleistocene, Mariana limestone, massive facies. Field locality B226. USNM 109226.



SAIPAN LIMESTONES

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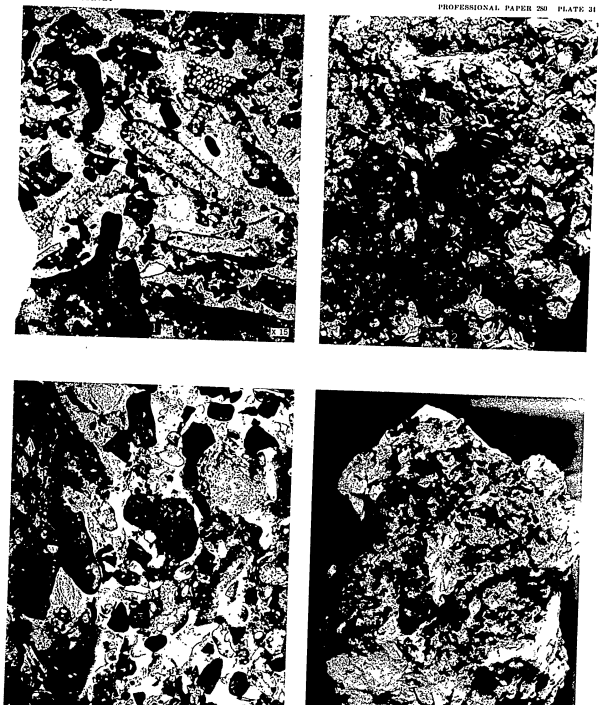


HALIMEDA LIMESTONES

PLATE 34

[Natural size unless otherwise indicated

FIGURE 1. *Halimeda*-rich Miocene Tagpochau limestone, inequigranular facies. Section (X 15), showing sections of *Halimeda* segments, pieces of coral, and shreds of large Foraminifera. Field locality B281. USNM 109227.

2. *Halimeda*-rich Miocene Tagpochau limestone, inequigranular facies. Weathered surface of hand specimen showing *Halimeda* segments, an echinoid spine, and pieces of coral. Field locality C16. USNM 109230.

3–4. *Halimeda*-rich Pleistocene Mariana limestone from Naftan Peninsula, southeast Saipan. USNM 109224.

3. Slide (X 15). *Halimeda* segments, Foraminifera, and fragments of coral.

4. Hand specimen showing pits left by *Halimeda* segments removed by weathering.

PLATE 35

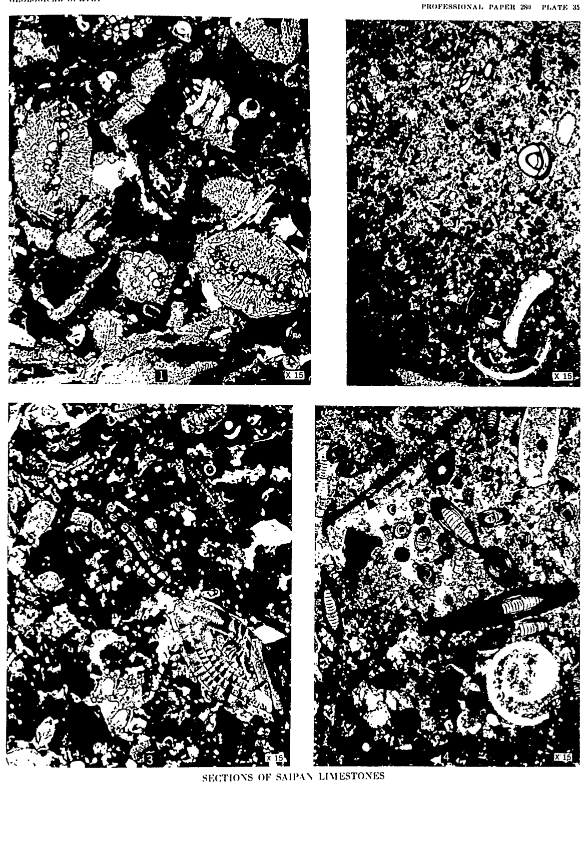
[X 15]

FIGURE 1. Foraminiferal-algal limestone. Eocene, Matansa limestone, pink facies. The black particles are pieces of crustose coralline algae. Field locality B251. USNM Foraminifera type number 624471.

2. Foraminiferal limestone. Miocene, Tagpochau limestone, inequigranular facies. Both larger and smaller Foraminifera present. Much of the groundmass consists of foraminiferal debris. The large light-colored pieces at the base of the photograph are fragments of shells of mollusks. Field locality S257. USNM 109237.

3. Foraminiferal-algal limestone. Eocene, Matansa limestone, pink facies. The black particles are pieces of crustose coralline algae. Most of the rest of the slide consists of tests and fragments of larger Foraminifera. Field locality S345. USNM 109239.

4. Algal limestone. Pleistocene, Mariana limestone, massive facies. Numerous segments of articulated coralline algae (*Amphiroa*) and a gastropod in a groundmass of fine organic debris. Field locality C65. USNM 109232.



SECTIONS OF SAIPAN LIMESTONES

Soils

By RALPH J. McCRACKEN

GEOLOGICAL SURVEY PROFESSIONAL PAPER 280-D

A classification of the soils of Saipan, their distribution, extent, genesis, and morphology

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ILLUSTRATIONS

[Plates in pocket]

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CHART

GEOLOGY OF SAIPAN, MARIANA ISLANDS

SOILS

By Ralph J. McCracken *

ABSTRACT

This report describes factors affecting soil formation and the morphology and distribution of the various soils on the tropical island of Saipan. The annual rainfall of about 80–90 inches is fairly uniformly distributed throughout the year, with a slight decrease in March and April. Mean monthly temperatures are 80°–85° F.

A lithosol (shallow stony soil) underlain by limestone and the miscellaneous land unit of rough stony land on limestone are the two most extensively mapped soil units. Two soils that are moderately deep or deep (3–6 feet or more) over limestone and of intermediate depth (18–36 inches) are of limited areal extent.

Volcanic rocks underlie a little less than one-third of the island. With the exception of two small areas of dacite outcrops that total less than a square mile, the volcanic rocks are andesitic in composition. The dacites give rise to little or no soil owing to the rugged topography of their area of outcrop and their extremely siliceous composition. Two soil series with complete *A–B–C* profiles have developed in the areas of volcanic-rock outcrop. A shallow lithosolic soil type and a miscellaneous land unit, rough broken land, are also recognized.

Less extensive types of parent material are the limesands of the western coastal plain and the colluvial and alluvial materials.

The soils of the uplands with complete *A–B–C* profiles do not possess some of the diagnostic characteristics of latosols, a fact which might be considered anomalous because of the prevailing climate, nature of underlying rocks, and duration of development. These soils do not have low silica-sesquioxide ratios of the clay fraction, do not have low cation-exchange capacities, lack intense iron and aluminum accumulation, and do not have the high degree of aggregate stability common in latosols. They also contain relatively high amounts of 2:1-layer silicate minerals such as vermiculite, hydrous-mica mixed-layer materials, and montmorillonite. However, they are strongly weathered, as indicated by the high content of clay and the low content of most primary minerals and soluble constituents. Their commonly red color indicates intense oxidation.

INTRODUCTION AND ACKNOWLEDGMENTS

This report deals with the soils of Saipan (pl. 36), located at latitude 15° N. in the Mariana Islands of the western Pacific Ocean. The area is tropical—about the same distance north of the Equator as northern Honduras and southern Guatemala—and is a few hundred miles closer to the Equator than the Hawaiian Islands or Puerto Rico.

Field studies and mapping of the soils were in conjunction with geologic studies of the island as a part of the Pacific islands geologic-mapping program of the U. S. Geological Survey, carried out in cooperation with the Corps of Engineers, U. S. Army. The soil-survey party was attached to the geologic field party which was under the direction of Preston E. Cloud, Jr.

The purpose of this investigation was to classify the soils, to determine their distribution and extent, and to learn as much as possible about their genesis and morphology. The study included establishing map units defined largely in terms of soil series and types, and collecting samples of profiles of the major soil series for future laboratory analysis. Mapping was on aerial photographs at a scale of 1:20,000, a level of cartographic generalization comparable to that commonly used in soil surveys in agricultural regions of America and Europe.

Particle-size distribution was determined by the pipette method (Kilmer and Alexander, 1949). The pH was determined on a 1:1 soil suspension using a glass electrode. Neutral normal ammonium acetate was used to extract the exchangeable bases, and barium chloride-triethanolamine was used to determine exchangeable hydrogen (Peech and others, 1947). Organic carbon was determined by dry combustion. Free iron oxides were determined by the V. J. Kilmer modification (written communication) of the Deb method.

For description and definition of soil-group names used, see U. S. Department of Agriculture Yearbook for 1938, and Thorp and Smith (1949).

The field party was fortunate in having access to the report of earlier investigations of Saipan soils by Japanese soil scientists (Kawamura, Tanaka, and Inagaki,

* Tennessee Agricultural Experiment Station; formerly with U. S. Department of Agriculture.

1940). Reports on detailed soil surveys of other near-tropical island groups (the Hawaiian Islands, Cline, and others, 1955; Puerto Rico, R. C. Roberts and others, 1942), as well as reconnaissances of somewhat similar tropical areas elsewhere (the East Indies, Mohr, 1944; the Belgian Congo, Kellogg and Davol, 1949; East Africa, Milne, 1936) were useful as background information. Experience gained from similar soil surveys of Palau Islands and Okinawa, initiated shortly before the work on Saipan, was made available by personal communication from soil-survey men working in those areas, as well as from the work of the writer in the Palau group. In addition, the soil-survey men were fortunate in being able to consult with the members of the geologic field party about the parent rocks and other parent material as the geologic and soil mapping progressed.

The mapping and the collecting of samples were accomplished during the early part of 1949 by Ray E. Zarza (U. S. Geological Survey) and Ralph J. McCracken (U. S. Department of Agriculture). The mapping was reviewed by E. H. Templin (U. S. Department of Agriculture), who was technical consultant on soils investigations for the Pacific islands mapping program at that time.

Laboratory determinations reported and discussed herein were performed in the U. S. Department of Agriculture soil-survey laboratories of which L. T. Alexander is in charge. Differential thermal and X-ray analyses were made by R. S. Dyal; exchangeable-cation determinations by E. M. Roller and R. S. Clarke, Jr., and mechanical analyses, pH, and organic-carbon determinations by B. J. Epstein and C. J. Scott. Determinations of free iron oxide were made by V. J. Kilmer.

In addition to those already mentioned, it is a pleasure to acknowledge the many helpful suggestions of geologists Robert G. Schmidt and Harold W. Burke, both of the Geological Survey, during and after completion of field work. Suggestions by Prof. Marlin G. Cline of Cornell University and by Roy W. Simonson and Guy D. Smith, of the Soil Survey, U. S. Department of Agriculture, during preparation of the manuscript are also gratefully acknowledged. Acknowledgment is also made to Prof. R. T. Endo for translation of a number of journal articles from the original Japanese.

FACTORS INFLUENCING SOIL FORMATION

CLIMATE

Mean annual rainfall, its monthly distribution, and whether it comes as heavy, sustained rain or frequent showers are of particular interest to the student of tropical soils. Mean monthly temperatures and the range of diurnal variations are also of great interest. Rain-

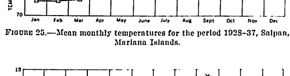

FIGURE 25.—Mean monthly temperatures for the period 1928–37, Saipan, Mariana Islands.

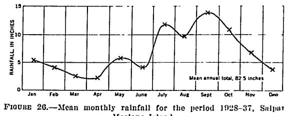

FIGURE 26.—Mean monthly rainfall for the period 1928–37, Saipan Mariana Islands.

shadow effects are not significant in soil development on Saipan. The highest peak on the island reaches an elevation of only a little more than 1,500 feet, and, as the axial ridge is oriented in a north-northeast direction and storms and winds in the rainier season often come from the south or southwest, no differences in soils were observed on the western (lee) slopes as compared with the eastern slopes.

The climate of Saipan is discussed in Chapter A (General Geology), but the importance of climate in soil development makes advisable the graphic summation of the essential data here (figs. 25, 26).
scriptions including chemical analyses and the stratigraphic relationships of the parent rocks are given in discussed below.

In Puerto Rico seven rainfall belts (due to rain-shadow effects) have been found to coincide with rather distinct soil regions (Roberts and others, 1942, p. 57–58, 426–484). Latosolic soils with some red-yellow podzolic soils were found to dominate in those regions which received an average of more than about 75 inches of rainfall per year and were generally not found in regions receiving less than this amount of annual rainfall.

Distribution of soils in the Hawaiian Islands (Cline and others, 1955) is a striking example of the influence of amount and distribution of rainfall on soil development over mainly basaltic parent rocks in the tropics. Those belts of the islands receiving 45–150 inches of rain per year have brown forestlike soils or humic latosols, if the rainfall is seasonally distributed. Soils designated as hydrol humic latosols are found in those regions receiving more than 150 inches of rain per year.

Descriptions of these soil groups and the changes in morphological properties are discussed in detail.

Significant changes in chemical properties and mineralogical content of the Hawaiian soils with change in annual rainfall have been demonstrated in the work of Tamura, Jackson, and Sherman (1953) and Tanada (1951). These investigators postulate that with increasing annual rainfall the content of bases and of silica decreases, whereas gibbsite, iron oxides, and organic matter increase. However, the soils receiving very high (more than 150 inches) annual rainfall are an exception to this generalization since reducing conditions resulting from this high rainfall cause a decrease in iron oxide content. According to the above-mentioned investigators, under the conditions in Hawaii the content of 2:1-layer clays (such as vermiculite, hydrous-mica mixed-layer materials, and montmorillonite) and of potassium in the soils increases with increasing annual rainfall and reaches a maximum at about 80 inches per year. Tamura, Jackson, and Sherman (1953) postulate that the increase of 2:1-layer silicates (such as illite and hydrous mica) can be explained by the nature of the rainfall, which, as it increases in amount, comes as frequent showers. These showers probably maintain the soil moisture at near field capacity. Under this condition, it is postulated that silica is not completely lost by leaching and is available for combination with alumina to form silicate clay. The importance of these observations to the present study lies in the fact that annual rainfall of Saipan is about 82 inches, and other soil-forming factors on the island are roughly similar to those prevailing in the Hawaiian Islands.

That distribution of annual rainfall is an important factor in soil development in warm regions has been postulated by Mohr (1944, p. 55–67), Humbert (1948), and Sherman (1949). In Mohr's classification of tropical climates according to the number and distribution of wet and dry months, dry months have an average of less than 2.4 inches (60 mm) of rain, wet months 4–8 inches, and very wet months more than 8 inches.

Sherman (1949) has presented data for Hawaiian soils which indicate that the proportion of dry, wet, and very wet months, as defined by Mohr (1944), is important in determining the nature of free oxides which become stabilized and accumulate in the soil solum (*A* and *B* horizons). He generalizes that in warm climates with alternating wet and dry seasons (2 or more consecutive months receiving less than 2.4 inches of rainfall), soils exhibit a different course of development than those developing without a definite dry season. The iron and titanium oxide content of those which are intermittently dry is postulated to be increasing, with an iron-rich laterite crust as an end product. The iron oxide content of the continually moist warm soils, on the other hand, is postulated as decreasing as the annual rainfall increases, with a bauxite laterite as an end product. The observations of Humbert (1948) in British New Guinea tend to confirm these generalizations.

Saipan can be classed as having no dry months according to Mohr's criteria and therefore no significant dry season. However, a drier season does occur during March and April, as can be seen in figure 26, although actually more than 2.4 inches of rain falls during these months.

PARENT MATERIALS

Parent material is perhaps best simply defined as partly weathered and unconsolidated rock from which soil is developing. Soil parent material, according to a definition by Jenny (1941, p. 52–53), is the initial state of the system at the inception of soil formation.

The nature of the parent rocks, which when weathered act as soil parent material, influences soil genesis and soil distribution. The mineralogy, age, and special weathering features of the parent material are of special importance. Characteristics of each of the main types of parent material are discussed in the following paragraphs in so far as they are relevant to soil genesis (see also pl. 2; chart). Complete mineralogical descriptions including chemical analyses and the stratigraphic relationships of the parent rocks are given in other chapters of this report.

Primary volcanic rocks and sediments derived largely through marine reworking of volcanic source materials underlie a little less than one-third of the soils. These volcanic rocks, which are the oldest rocks exposed, make up the central core of the island and comprise dacite and andesite.

The andesitic rocks are assigned to the Hagman and Densinyama formations of late Eocene age and to the Fina-sisu formation of late Oligocene age. They crop out chiefly in the east-central and northeast parts of the island, above the dacites. The Hagman formation consists of andesitic breccias, tuffs, conglomerates, tuffaceous sandstones, and minor andesite flows. The Fina-sisu formation is made up of andesite flows and marine andesite tuffs. The Donni sandstone and Machegit conglomerate members, and much of the tuffaceous facies, of the Miocene Tagpochau limestone are also andesitic rocks, which give rise to essentially similar soils. The andesitic rocks have a relatively high content of alumina and calcium oxide and a low content of potash compared to average andesite. They are broadly similar, as parent rocks for soils, to the

Hawaiian basalts. They give rise to a weathered zone 50 feet or more thick below the soil solum, where erosion has not been severe. This thick weathered zone is referred to by some authors as the saprolite or zersatz zone.

The dacites, classified as the Sankakuyama formation, are also believed to be of Eocene age although older than the overlying andesites. They crop out in two small areas in northern Saipan. These rocks have an unusually high silica content and low alumina, iron and alkalis, and alkaline-earths contents (see Chapter A). Soils are shallow or entirely lacking in these areas due to the rugged topography, rapid erosion, and slow rate of parent-material formation.

Limestones underlie a little more than two-thirds of the soils of the island. The most extensive of these are the Tagpochau limestone of early Miocene age and the Mariana limestone of Pleistocene age. The other limestones of Saipan do not significantly contribute to soil parent materials.

Four soil conditions are found in the areas underlain by limestone (and all are characterized by an abrupt contact between the soil and underlying limestone): deep, firm, plastic, clayey soils of reddish hue with more or less complete profiles that are more than 3 and commonly less than 6 feet deep; rather friable brown soils 18–42 inches deep; friable alkaline brown shallow stony soils about 6–18 inches deep; and very shallow soil mixed with stone and less than 6 inches deep, with numerous small areas of limestone outcrops. The last condition is a land type—rough stony land on limestone—rather than a soil unit. The third and fourth conditions are the most extensive map units on the island.

The soils underlain by limestone have, in general, developed from residuum remaining after solution of the limestone. They therefore tend to differ from the soils underlain by volcanic rocks in the following ways: The contact between soil and unaltered limestone is abrupt, although irregular, whereas the soils underlain by volcanic rocks are commonly underlain by a saprolite or zersatz zone of a few to many tens of feet in thickness; soils underlain by limestone are influenced to a great extent by the nature of the soil parent material remaining after the limestone dissolution; and soils underlain by limestone are generally free of the variegated mottling and ghost crystals which characterize the soils derived from andesitic materials.

A fourth soil parent material is the limesand of the western coastal plain. This material consists of beach and shallow lagoonal deposits lying a few feet above sea level. Sufficient organic matter has accumulated to darken the upper foot or so of this material, and it increases in amount between the coast and the inland edge of the coastal plain. The soils are moderately to strongly calcareous.

Alluvium and slope wash (local alluvium) constitute a fifth parent material, which is of limited areal extent. Soils beginning to develop on the alluvium have little or no profile differentiation. They are found in small valleys cut in limestone, in sinks, and on the coastal lowlands. Some of the slope-wash material has given rise to soils with recognizable profile development. This is especially true on low inland slopes of southwestern Saipan.

SLOPE AND DRAINAGE

Topography has influenced the course of soil development in two ways. The steep slopes of the dissected landscape, as well as the convex moderate slopes that are being actively eroded, undergo such rapid erosion that the development of complete soil profiles is inhibited; the acreage of this rough broken land exceeds that of deep soils. Also, moisture relations in the nearly level land underlain by limestone differ from those in the sloping land underlain by limestone to such an extent that properties of soils developing in the two situations differ. The level soils are more nearly saturated during wet periods and remain moist longer. As a consequence, they are less well oxidized and exhibit yellowish rather than reddish hues as in the sloping soils. According to current American soil-survey terminology, the former would be considered as somewhat poorly drained, the latter moderately well to well drained.

However, toposequences, or groups of soils developing from similar parent materials but differing in properties due to natural drainage, were not found on Saipan, with the above-described exception of deep soils underlain by limestone. The rolling to hilly dissected terrain, the porous limestones with good drainage, and the lack of a water table near the soil surface probably all help to explain the absence of this drainage relationship which is commonly found in continental areas.

Poorly drained soils are found in several marshy areas on the western coastal plain. These areas are continually wet and are often covered with water, so that they are mapped as marsh rather than as a distinct soil type. Some of the inextensive soils included with the association of alluvial clays are also poorly drained and unoxidized.

TIME

Time in soil studies means the elapsed time of soil development. Time zero is the time at which the parent material is introduced into a zone where it can be acted upon by climatic factors and influenced by vegetation and other organisms to start soil development.

Geologic evidence suggests that weathering in the uplands has been proceeding without interruption (except for such as caused by changes in rate of erosion due to uplift or eustatic changes in sea level) since at least late Pleistocene time. Terrain above an elevation of about 500 feet may have been emergent since Pliocene time.

This does not mean that the upland soils with complete *A–B–C* profiles are indicative of the degree of soil development attained under action of soil-development factors for the indicated elapsed time of tens of thousands to a million years or more. Where soils are underlain by limestone, soil material has continually been moving across the limestone bench and platform surfaces by slope wash and colluviation. Some soil has accumulated in pockets, where there has not been opportunity for complete development due to continual addition of fresh soil material. Despite unequal periods of weathering on the various bench surfaces cut in the Miocene and Pleistocene limestones, no appreciable soil differences were observed on them. Where soils develop in residuum from volcanic rocks and tuffaceous sediments, rate of removal of soil material by erosion has almost exceeded the soil-development rate.

The upland soils of Saipan cannot be considered as representative of old soils, since fresh soil parent material is continually being exposed by erosion. Observations of soils under similar weathering conditions elsewhere (Sherman, 1949; Tamura, Jackson, and Sherman, 1953) as well as generalizations on mineralogical changes in soils with time of weathering (Jackson, Tyler, and others, 1948) indicate that relatively high concentrations of aluminum or iron and titanium minerals occur in more mature soils weathered under tropical climates. Since concentrations of these minerals are lacking in Saipan soils (table 2), their lack of maturity seems to be confirmed.

VEGETATION

Extensive clearing for sugarcane during the period of Japanese control (1914–44) and earlier clearing for copra production, as well as introduction of exotic plant species, makes it difficult to infer what the original composition of the vegetative cover on Saipan was. As deduced from scattered primary-forest remnants, secondary forests, and disturbed areas, the vegetation before cultivation seems to have consisted of fairly dense forests and some small savannalike areas. To what extent the savannas are manmade is unknown; on many tropical islands of the Pacific where vegetation has been relatively undisturbed, the presence of savanna coincides with areas of laterized volcanic rocks, generally highly eroded. This is true on Saipan, although some areas of savanna growing on rough stony land on limestone were observed on the southern slopes of the central ridge.

Among the tree species present in the primary forests were daog, *Calophyllum inophyllum* Linné; the legume ifil, *Intsia bijuge* (Colebrooke) O. Kuntze; breadfruit, *Artocarpus* sp.; and several species of *Pandanus*. The secondary forests and areas on to which trees are readvancing appear to be dominated by the legume *Leucaena glauca* (Linné) Bentham and the Formosan koa *Acacia confusa* Merrill.

That there are no significant differences in influence of vegetation on different soils (exclusive of savanna areas, where no samples were taken because of extreme erosion or shallowness) seems indicated by the fact that the surface horizons of 7 of the 8 profile samples collected contained 3½–5½ percent organic carbon. The eighth profile contained about 7 percent organic carbon in the surface horizon, which can probably be explained by the more favorable physical properties of this soil. This conclusion also seems to be confirmed by the fact that ratios of carbon to nitrogen, as determined by Kawamura, Tanaka, and Inagaki (1940), do not differ significantly among soils.

Some of the earlier investigators reasoned that the organic-matter content of latosolic soils must necessarily be low (for example, less than 2 percent in the surface horizon) due to increased rates of oxidation and of bacterial decomposition under year-round high temperatures (Mohr, 1922; Corbet, 1935). Recent studies indicate, however, that the content of organic matter and nitrogen within many latosolic profiles is relatively high—significant amounts have been found at depths of 2 or 3 feet—although there may be little or no surface litter. This has been reported for Puerto Rican soils by Smith, Samuels, and Cernuda (1951); for Hawaiian soils by Cline and others (1955) and by Dean (1937); for Colombia by Jenny (1950); and for certain soils of the Belgian Congo by Kellogg and Davol (1949). The Hawaii and Puerto Rico investigators suggest that the luxuriant vegetation formed by year-round high temperatures favors accumulation of organic matter and nitrogen at a greater rate than oxidation and bacterial decomposition. Jenny (1941) suggested that in Colombia the relatively high incidence of leguminous species in the flora with correlative nitrogen fixation may be the main causative agent of the relatively high content of nitrogen and organic matter observed in the soils.

The organic-matter content of the deep and moderately deep Saipan soils, 3½–5½ percent in the upper 6 inches, is relatively high. These soils do not contain as much organic matter below the surface 6 inches as the humic latosols of Hawaii or many of the latosolic soils of Puerto Rico and the Belgian Congo. A Saipan flora recorded by Kawagre (1915) and discussed in a U. S. Navy civil-affairs handbook (1944), but not seen by the author, lists 10 species of legumes; how many are arborescent is not specified. Although the incidence of legumes may be relatively high in the Saipan flora, symbiotoc nitrogen fixation does not necessarily follow. The discussion of Smith, Samuels, and Cernuda (1951) seems applicable to Saipan; that is, the frost-free year-round growing season encourages luxuriant vegetation which causes organic matter and nitrogen accumulation in the soil profile.

SOIL SERIES AND TYPES

The map units were established as phases of soil series and types wherever possible (see pl. 36).

The soil series is defined (U. S. Dept. of Agriculture, 1951) as "a group of soils having soil horizons similar in differentiating characteristics and arrangement in the soil profile, except for the texture of the surface soil, and developed from a particular type of parent material." The soil type is defined as "a subdivision of the soil series based on the texture of the surface soil," and the soil phase refers to subdivisions of the series and type according to degree of slope (certain ranges of slope constitute a slope phase) or the degree to which erosion has truncated the profile.

However, owing to the limited number of phases established and the relatively minor differences among phases of a given series and type, for brevity the written descriptions are in terms of soil series and types, rather than the phases.

Differing soils in some small areas form intricate patterns. It was not possible to differentiate a landscape unit as homogeneous as the soil series in these places, and soil complexes (intricate geographic associations of different soils) were established.

The description of each of the soil series includes an outline of the more important properties and the range of those properties within the series, how they are differentiated from related series, the parent rock from which they were derived, and the position in the landscape which they occupy. (The clay loam and clay types of the Akina series are separately described, but all other series are monotypes.) This is followed by a detailed description of a profile which is near the central concept of the series.

Numerical notations in parentheses in the soil profiles describe the moist-soil colors according to the Munsell color system (see Soil Survey Staff, 1951, p. 194–203), and color names generally conform to those listed and described in that publication.

The percentages of clay (<2μ in diameter), of organic carbon, and of base saturation and the cation-exchange capacity of the various horizons of the important soils are shown graphically in figures 28–35 and listed in table 1. Amounts of exchangeable cations,

FIGURE 27.—Percentage distribution of Saipan soil groups and land types.

the pH, free iron oxide, and the particle-size distribution analyses, are listed in table 1. On the accompanying soil map (pl. 36) it has been necessary to show the distribution of the soils as soil associations, or groups of soil series which are geographically associated on certain landscapes, in order to reduce the scale. The proportionate areas of the soils of Saipan are shown in figure 27.

SOIL PROFILES AND DESCRIPTIONS

SOILS OF THE UPLANDS WITH COMPLETE A-B-C PROFILES

AKINA SERIES

The Akina series includes Akina clay and Akina clay loam. This is the only series which has more than one type. These are soils with plastic yellowish-red, reddish-brown, and yellowish-brown acid clay *B* horizons. The lower part of the *B* horizons and especially the *C* horizons are commonly variegated and contain ghosts of altered primary silicates. The *A* horizons are ordinarily dark brown. Weathered andesitic breccias, conglomerates, and sandstones of moderately mafic (basic) composition are the chief parent materials except in the clay-loam type where the upper solum is developing in a quartz-rich surficial deposit 6–30 inches thick. Presumably this is a terrace deposit formed during a period of Pleistocene submergence.

The Akina soils occupy somewhat convex ridge crests and gentle slopes in the dissected areas of volcanic outcrop. These soils are well to moderately well drained. They are differentiated from the Dago soils (to which they are closely related) by less red subsoil colors and slightly less acid reactions. Also, the Dago soils have developed from weathered andesitic flow rocks and tuffs.

AKINA CLAY

Akina clay, which is much more extensive than the Akina clay loam, has the following characteristics.

Soil profile, Akina clay

[See fig. 28; table 1]

Horizon	Depth (inches)	Description
A_1	0–5	Clay, dark-brown (7.5*YR* 3/2) to very dark grayish-brown (10*YR* 3/2); moderately well-developed medium granular structure; moderately firm and plastic; a few quartz grains, 1–2 mm in diameter.
B_{21}	5–12	Clay, reddish-brown (5*YR* 4/4) and yellowish-red (5*YR* 5/6); massive to weakly blocky structure; plastic and firm.
B_{22}	12–22	Clay, yellowish-red (5*YR* 4/6), with a few coarse mottles of red (2.5*YR* 5/6); massive to weakly developed coarse blocky structure; very plastic and firm; cracks and vertical cleavages pronounced when dry; broad transition to B_3 horizon.
B_3	22–42	Clay, mottled yellowish-red (5*YR* 5/6), red (2.5*YR* 5/6), and yellowish-brown (10*YR* 5/6), with mottles of light gray and yellow common; moderately plastic and firm; massive structure; relict texture of the parent rock, with phantom crystals of weathered minerals that become more numerous in the lower part of the horizon; broad transition to C_1 horizon.
C_1	42–60	Clay, mottled yellowish-red (5*YR* 5/6), brown (7.5*YR* 4/4), light-gray, and yellow, with large spots of less weathered green-gray parent material, ranges from friable to firm.

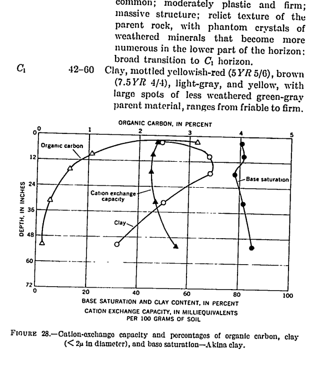

FIGURE 28.—Cation-exchange capacity and percentages of organic carbon, clay (< 2μ in diameter), and base saturation—Akina clay.

AKINA CLAY LOAM

The clay loam of the Akina series is very limited in extent. The upper 6–30 inches of the solum is a coarse quartz-rich nonconformable surficial deposit. In the profile described, the clay loam is about 7 inches thick.

Soil profile, Akina clay loam

[See fig. 29; table 1]

Horizon	Depth (inches)	Description
A_1	0–7	Clay loam, dark-brown (7.5*YR* 3/2); moderately developed medium granular structure; slightly plastic.
B_2	7–28	Clay, yellowish-red (5*YR* 5/6); weakly developed blocky structure; very firm and plastic; slight local effervescence with 10 percent hydrogen peroxide is interpreted as indicating concentrations of manganiferous material; gradual transition to B_3 horizon.
B_3	28–40	Clay, yellowish-red (5*YR* 5/6) and strong-brown (7.5*YR* 5/6), massive, very firm and plastic; occasional dark streaks effervesce with hydrogen peroxide; gradual and irregular transition to *C* horizon.
C	40–60	Clay, strong-brown (7.5*YR* 5/8), red (2.5*YR* 4/6), and light-gray, mottled, massive, slightly firm and plastic; relict parent-rock texture and phantom crystals common; depth to unaltered conglomerate estimated to be 25–30 feet at this site.

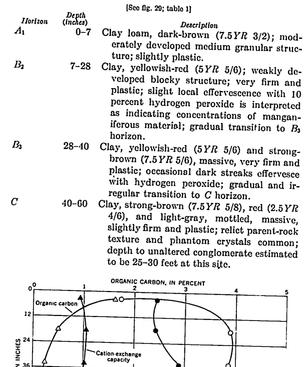

FIGURE 29.—Cation-exchange capacity and percentages of organic carbon, clay (<2μ in diameter), and base saturation—Akina clay loam.

DAGO CLAY

Dago clay includes soils with dark-red to red plastic clay *B* horizons and reddish-brown to dark-reddish-brown clay surface soils, developing chiefly from weathered andesitic flow rocks and tuffs. They are differentiated from the closely related Akina soils by the latter's yellowish-red to yellowish-brown *B* horizons and dark-brown to grayish-brown *A* horizon. Dago soils are slightly more acid than the Akina soils.

These soils occur on slightly convex ridge tops and on moderate slopes as small areas at scattered localities. They are well to moderately well drained.

Soil profile, Dago clay

[See fig. 30; table 1]

Horizon	*Depth (inches)*	*Description*
A_1	0–6	Clay, dark-reddish-brown, (5*YR* 3/4); moderately developed fine granular structure; moderately plastic and firm.
B_2	6–30	Clay, dark-red (10*R* 3/6), massive, very plastic and firm; gradual transition to B_3 horizon.
B_3	30–50	Clay, dusky-red (10*R* 3/4) and yellowish-red (5*YR* 5/6), with light-yellow and white spots a few millimeters in diameter common; spots are plantom crystals of weathered minerals; massive; plastic, firm, with some locally friable spots; gradual transition to C_1 horizon.
C_1	50–72	Clay, highly mottled dark-red (2.5*YR* 3/6) and dusky-red (10*R* 3/4), with numerous small white and yellow spots that become more pronounced in lower part of the horizon; weathered parent rock of variable texture and consistency.

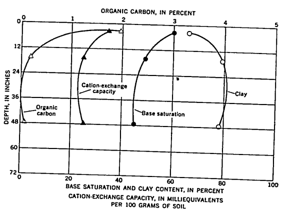

FIGURE 30.—Cation-exchange capacity and percentages of organic carbon, clay ($<2\mu$ in diameter), and base saturation—Dago clay.

CHACHA CLAY

The Chacha soils have yellowish-brown and strong-brown very firm clay *B* horizons (containing numerous ferromanganese concretions) and dark-brown clay *A* horizons. They are developing over limestones on level, nearly level, and gently sloping landscapes. The dull-yellow manganiferous *B* horizons of these soils classify them as somewhat poorly drained; that is, they are somewhat restricted in oxidation. Due to these properties they contrast with the red well-oxidized Saipan clay, which appears to be developing from similar parent materials. Depth to underlying limestone ranges from 3 to 8 feet, average depth is 5 or 6 feet.

Soil profile, Chacha clay

[See fig. 31; table 1]

Horizon	*Depth (inches)*	*Description*
A_1	0–7	Clay, dark-brown (7.5*YR* 3/2 to 10*YR* 4/3); moderately developed medium granular structure; moderately firm and plastic; dark spherical nodules (ferromanganese concretions) averaging 1/8–1/4 inch in diameter are common; effervesces with hydrogen peroxide.
B_2	7–24	Clay, yellowish-brown (10*YR* 5/6), with mottles of strong brown (7.5*YR* 5/6); massive to weakly granular; dark streaks and nodules which effervesce with peroxide are common.
B_3	24–72	Clay, strong-brown (7.5*YR* 5/6), mottled with yellowish brown (10*YR* 5/6), brownish yellow (10*YR* 5/8), and occasional spots of light gray or white; very firm and plastic; massive; dark streaks which effervesce with peroxide are numerous; irregular and abrupt contact with underlying Mariana limestone.

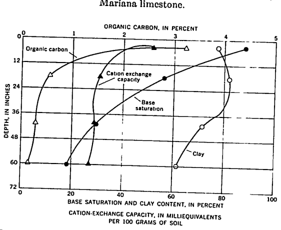

FIGURE 31.—Cation-exchange capacity and percentages of organic carbon, clay ($<2\mu$ in diameter), and base saturation—Chacha clay.

SAIPAN CLAY

Included in the Saipan clay are soils with red and yellowish-red firm and plastic clay *B* horizons, which are neutral to slightly acid, and dark-brown to dark-reddish-brown granular clay *A* horizons. These soils are developing over limestone, which is generally at a depth of 3½–6 or 8 feet. Occasional small pockets of soil are 12–15 feet in depth. The reddish *B* horizons differentiate them from the yellowish Chacha soils. The Dago soils, which are of similar color, are underlain by weathered andesitic flow rocks and tuffs.

These soils are developing on gently to moderately sloping topography and are well to moderately well drained; that is, they are well oxidized. Large continuous areas are found on the gently sloping limestone benches. On the more sloping sites, these soils occur as small patches in association with the shallower Chinen soils.

Soil profile, Saipan clay

[See fig. 32; table 1]

Horizon	*Depth (inches)*	*Description*
A_1	0–4	Clay, dark-reddish-brown (5*YR* 3/3); moderately developed medium granular structure; slightly plastic, friable.
A_3, B_1	4–15	Clay, reddish-brown (5*YR* 4/4); weakly developed medium granular structure; firm and plastic.
B_2	15–36	Clay, red (2.5*YR* 4/6), with some very coarse yellowish-red (5*YR* 4/6) mottles; massive; very firm and plastic; a very few spots effervesce with hydrogen peroxide.
B_3	36–80	Clay, red (2.5*YR* 4/6); massive; very firm and plastic; very abrupt and irregular contact with underlying Tagpochau limestone (Miocene) at this site.
D	80+	Limestone.

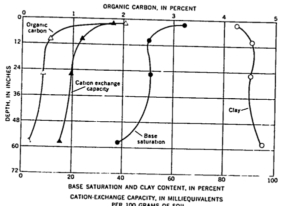

FIGURE 32.—Cation-exchange capacity and percentages of organic carbon, clay ($<2\mu$ in diameter), and base saturation—Saipan clay.

SHALLOW SOILS OF THE UPLANDS

Shallow soils of the uplands cover slightly more than one-third of the area of Saipan. Three soil units are recognized—the Chinen and the Dandan series developing over limestone and the Teo soils (a complex) developing over volcanic sediments and tuffaceous limestones.

CHINEN CLAY LOAM

The Chinen clay loam includes very shallow (3 to about 18 inches of soil material) stony dark-brown and brown granular soils, about neutral in reaction, developing over limestone. They are differentiated from the associated Dandan and Saipan series by their thinner and stonier profiles and by lack of horizon differentiation. The land type—rough stony land on limestone—contains less soil material and more stone in the surface layer.

This stony soil is developing on a wide range of limestones, from the Pleistocene limestones of the lower bench to the Miocene limestones of the central ridge, and is found on gently sloping to steep slopes.

The texture (particle-size distribution) ranges from loam or silty loam to heavy clay loams; the clay-loam texture described here is dominant.

Soil profile, Chinen clay loam

Horizon	*Depth (inches)*	*Description*
A_1	0–9	Clay loam, dark-brown (10*YR* 4/3); moderately developed medium to coarse granular structure; friable and nonplastic; alkaline in reaction.
D	9+	Limestone. The soil material may extend to depths of several feet in crevices and fissures in the limestone. The contact of the soil and limestone is abrupt but extremely irregular, with many small pockets of deep soil and many small pinnacles of limestone exposed at the surface.

No laboratory data are available for this soil series.

DANDAN CLAY

The Dandan clay includes soils with friable to firm clay *B* horizons, and granular and friable dark-brown clay *A* horizons. The limestone is at an intermediate depth (18–42 inches). The associated Chinen soils are shallower over limestone and lack *B* horizons. The occurrence of Dandan soils is largely confined to the areas of younger Pleistocene limestones. They are developing on nearly level to gently sloping surfaces. However, their relatively high permeability and the high porosity of the underlying limestone allows rapid internal drainage, so that they are well drained.

Dandan soils are differentiated from those of the Saipan and Chacha series, which are also developing over limestone, by lower plasticity, browner color, shallowness, and apparent confinement to the areas of the younger limestones of the western, northern, and eastern platforms.

Soil profile, Dandan clay

[See fig. 33; table 1]

Horizon	Depth (inches)	Description
A_1	0–6	Clay, dark-brown (7.5*YR* 3/2); feels like silty loam when rubbed between fingers; strongly developed medium granular structure; friable but slightly plastic.
B_2	6–21	Clay, brown (7.5*YR* 4/4); feels like silty loam; moderately developed medium granular structure; friable and slightly plastic.
B_3	21–36	Clay, strong-brown (7.5*YR* 4/6); weak granular structure; friable and slightly plastic.
D	36+	Limestone. The soil and limestone contact is an abrupt but highly irregular surface.

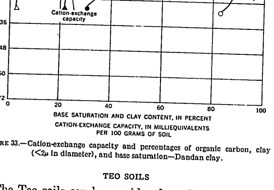

FIGURE 33.—Cation-exchange capacity and percentages of organic carbon, clay (<2μ in diameter), and base saturation—Dandan clay.

TEO SOILS

The Teo soils can be considered a soil family or an association of two or more related series. They comprise acid firm and plastic red, yellowish-red, and yellowish-brown clays of intermediate and shallow depth underlain by weathered siltstones and sandstones (derived from andesitic volcanic rocks) and weathered tuffaceous limestones.

These soils are developing on moderately sloping to hilly, steep dissected terrain. The thickness of the solum (*A* and *B* horizons) ranges from about 12 to 24 inches; a thickness of 10–18 inches is modal.

The Teo soils are differentiated from the Chinen and the Dandan series by redder colors, higher plasticity, more acid reaction, and occurrence on reworked volcanic rocks and highly impure limestone (compared with the relatively pure limestones underlying the Chinen and the Dandan soils). Soils of this map unit which have thin reddish *B* horizons are described below. Soils without *B* horizons and soils with thin yellowish less firm *B* horizons are intimately associated with soils like that described below to constitute the map unit of Teo soils.

Soil profile, Teo clay

[See fig. 34, table 1]

Horizon	Depth (inches)	Description
A_1	0–4	Clay, dark-reddish-brown (5*YR* 3/3); moderately developed medium and coarse granular structure; firm and plastic.
B_2	4–12	Clay, red (2.5*YR* 5/6), massive; very firm and plastic; irregular and gradual transition to next lower horizon; moderate acid reaction.
B_3–C_1	12–32	Clay, dark-red (2.5*YR* 3/6) and light-yellowish-brown (10*YR* 6/4), massive; varies from firm to friable; relict texture of parent rock readily discernible; gradual transition to C_2 horizon.
C_2	32–60+	Limestone, highly tuffaceous, altered, soft, mottled pale-brown (10*YR* 6/4) and dark red (2.5*YR* 3/6).

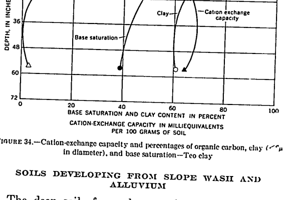

FIGURE 34.—Cation-exchange capacity and percentages of organic carbon, clay (<2μ in diameter), and base saturation—Teo clay

SOILS DEVELOPING FROM SLOPE WASH AND ALLUVIUM

The deep soils from slope wash and alluvium are developing entirely from transported material derived from the soils and weathered rocks of the uplands. Two map units were established for these soils—the Lito series, the soils of which have *B* horizons, and the alluvial clays, a generalized unit equivalent to a soil family or an aggregation of two or more series. These units cover only a total of a few hundred acres.

LITO CLAY

Included in the Lito clay are soils with firm and plastic slightly acid red clay *B* horizons mottled with brown and dark-brown granular clay *A* horizons. They are developing from acid mottled slope-wash clays and bedded clays. These soils are ordinarily found on gentle concave slopes at the foot of more strongly sloping uplands. The largest areas are along the western

and northwestern coasts in the west coastal-plain and low inland-slopes geomorphic subdivision.

Transported residuum from volcanic rocks and from limestones has been the parent material for these soils. The observation that their parent material is moderately acid suggests the dominance of volcanic residuum as source material.

Natural drainage, which governs the state of oxidation, ranges from moderate to somewhat poor. The profiles of these soils range from those with very thin *B* horizons to profiles with more strongly expressed and thicker *B* horizons than the modal profile described here.

On the generalized map (pl. 36) these soils have been included with alluvial clays on the northwestern coast and the Akina-Dago association on the western coast.

Soil profile, Lito clay

[See fig. 35; table 1]

Horizon	Depth (inches)	Description
A_1	0–7	Clay, dark-brown (10*YR* 4/3); moderately developed coarse granular structure; very firm and plastic.
B_2	7–24	Clay, red (2.5*YR* 5/6), with coarse, highly contrasting mottles of strong brown (7.5*YR* 5/6); massive; very firm and plastic.
B_3-C_1	24–48	Clay, red (2.5*YR* 5/6), reticulately mottled with very pale brown (10*YR* 7/3), strong brown (7.5*YR* 5/6), and white (10*YR* 8/1); massive; very firm and plastic; local effervescence with hydrogen peroxide indicates the presence of manganiferous compounds.
C_2	48–66	Clay, strong-brown (7 5*YR* 5/6), pale-brown (10*YR* 7/3), and red (2.5*YR* 4/6), mottled with spots and streaks of white (10*YR* 8/1); massive; very firm and plastic; observed to extend to a depth of at least 8 feet in a nearby manmade ditch.

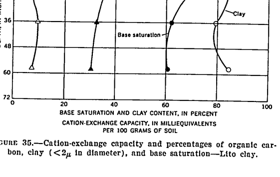

FIGURE 35.—Cation-exchange capacity and percentages of organic carbon, clay (<2μ in diameter), and base saturation—Lito clay.

ALLUVIAL CLAYS

The alluvial-clay unit is an association of dominantly brown and yellow, firm and plastic, neutral clays. They accumulate by slope wash, solifluction, and alluviation and are found in limestone sinks, small valleys cut in limestone, and on coastal lowlands. The soil material is derived chiefly from residuum of limestones.

Included in this unit are somewhat poorly drained soils (described in the profile below) and poorly drained soils (not described here). Most of the alluvial clays show little or no evidence of soil development.

Soil profile, alluvial clay

Depth (inches)	Description
0–15	Clay, brown (10*YR* 5/3); weakly developed medium granular structure; firm and plastic; neutral in reaction.
15–30	Clay, brown (10*YR* 5/3), yellowish-brown (10*YR* 5/4), mottled; massive; very firm and plastic; neutral in reaction.
30–42	Clay, strong-brown (7.5*YR* 5/6) and very dark brown (10*YR* 2/2), mottled; massive; very firm and plastic; some local effervescence with hydrogen peroxide indicating presence of manganiferous compounds; neutral in reaction.

No laboratory data are available for this unit.

SOILS OF THE WESTERN COASTAL PLAIN

Only one soil series, the Shioya, was mapped on the elevated limesands of the west coastal plain. Marsh is a land type found in this region.

SHIOYA LOAMY SAND

This series includes light-colored limesands (calcareous sands composed almost entirely of calcium carbonate) in which the surface foot or two is slightly darkened with organic matter. This series is developing on slightly elevated beaches and lagoon floors; the parent material is detrital and waterworn fragments of corals, Foraminifera, and shells of marine invertebrates. These soils are only a few feet above sea level and grade into light-colored beach sand on the seaward margin. Thickness of the A_1 horizon and darkening by organic matter increases toward the landward side of the soil area. Some local areas of sandy loam texture are included.

Soil profile, Shioya loamy sand

Horizon	Depth (inches)	Description
A_1	0–18	Sand, loamy, grayish-brown (10*YR* 5/2); single-grain structure; loose; calcareous.
C	18–42	Sand, loamy, light-gray (10*YR* 7/1), single-grain structure; loose; calcareous.

No laboratory data are available for this unit.

MISCELLANEOUS LAND TYPES

The term "miscellaneous land type" designates a map unit in which landforms or land conditions are more important than the soil characteristics (see Soil Survey Staff, 1951, p. 306). Four miscellaneous land units are recognized on Saipan—marsh, rough stony land on dacite, rough stony land on limestone, and rough broken land.

MARSH

Marsh comprises about a square mile on the western coastal plain and a few small areas on the northwestern coastal plain. The water table is at or near the surface throughout the year, and hydrophytic plants grow profusely in water-saturated silts and clays. The soil material is dark, plastic, and highly mottled. In a few places it contains nearly enough organic matter to be classed as muck.

ROUGH STONY LAND ON DACITE

Rough stony land on dacite is confined to 2 small areas of about 250 acres each in northern Saipan in which the slopes are steep and precipitous and the ravines deep. Approximately two-thirds of the area has a mantle of grayish-brown and pale-brown acid stony clay or clay loam less than 6 inches thick. The balance of the area is bare dacite rock. Vegetation consists of the fern *Gleichenia* and scattered small shrubs.

ROUGH STONY LAND ON LIMESTONE

Rough stony land on limestone is the most extensive map unit, covering about one-third of the island area. It includes those areas of limestone mantled with a very thin (less than 3 or 4 inches) layer of brown stony loam soil material. Locally bare limestone crops out, as in escarpments and cliff faces. Except for the outcrops, there is sufficient soil material on the surface and in fissures and joints (to depths of several feet) to support a fairly dense vegetative cover of secondary forest. An exception, however, is a savanna area on the southern slope of Mount Tagpochau, the central peak, where the limestone contains a high proportion of volcanic impurities. The topography is hilly and steep to moderately sloping in the areas of this land type.

ROUGH BROKEN LAND

Rough broken land is characterized by newly formed gullies, erosion scars, sharp ridges, and ravines in areas of weathered volcanic rocks. Altered, rotten rock or saprolite is everywhere exposed at the surface, with the exception of scattered areas mantled with a thin layer of red or reddish-brown acid clay.

This is the condition in several areas in the east-central and northern parts of the island, especially in the geomorphic subdivision "central volcanic ridge and slopes."

MORPHOLOGY AND GENESIS

The following discussion summarizes the outstanding morphological and chemical properties of the soils and generalizes their genetic processes. The foregoing descriptions of profiles and data shown graphically in figures 28–35 and tabulated in the tables are used.

The outstanding gross morphological features of the soils are the warm red and yellow colors, the relatively high content of organic matter in the surface horizon (considering the year-round high temperatures), the plasticity and firmness of the *B* horizons, the thickness of saprolitic material below the *B* horizon and above the parent rock where the soils are developing from residuum from volcanic rocks, and the sharp contact between soil and limestone in those soils underlain by limestone.

Perhaps the most interesting of the series of depth versus soil-property plots of figures 28–35 are those illustrating variation in concentration of clay with depth. Many of these show a bulge, indicating maximum clay content, at depths of 18–24 inches, although the increase may not be significant in soils containing such high amounts of clay. Also, the *B* horizon of every soil consists of more than 50 percent clay less than 2 microns in diameter, with a high of 95 percent in the B_3 horizon of Saipan clay.

The dissimilar pattern of the Teo-clay curve can perhaps be explained by the fact that the horizons below 12 inches contain partly altered parent rocks which have not broken down to clay as completely as have more weathered horizons. These soils are developing under relatively rapid erosion, causing the continual presentation of fresh material to be weathered due to the constant removal of soil. The fact that the clay versus depth curve for the Lito soils tends to rise after decreasing from the clay maximum can probably best be explained by stratification of parent material.

The lower content of clay in the *A* and upper *B* horizons is accompanied by an increase in the percentage of silt, especially that 2–20 microns in diameter. That this tendency towards a clay maximum independent of differences in the exchange capacity and percentage of base-saturation curves occurs in all the deeper soils (as seen by comparison of the curves for the Akina soils with the others) suggests that the lower clay content and higher fine-silt content of the upper portions of the profile is due to a concentration effect. The more resistant minerals in the fine silt may be concentrated near the surface (silicate minerals in the fine silt might be expected to be more resistant to weathering because of larger particle size and decreased specific surface).

TABLE 1.—*Physical and chemical characteristics of Saipan soils* [1]

Horizon	Depth of horizon (inches)	Exchangeable cations (milliequivalents per 100 g of whole soil): Ca	Mg	K	Na	H[2]	Cation-exchange capacity[3]	Base saturation (percent)	Free Fe_2O_3 (percent)	Particle-size distribution (percent): Coarse and medium-grained sand (2.0–0.2 mm)	Fine and very fine sand (0.25–0.05 mm)	Coarse silt (0.05–0.02 mm)	Fine silt (0.02–0.002 mm)	Clay (<0.002 mm)	pH	Organic carbon (percent)
Akina clay																
A_1	0–5	27.7	9.4	1.6	1.0	9.1	48.8	81	4.2	24.0	7.6	4.1	15.0	49.3	6.1	3.18
B_1	5–12	25.4	11.4	.9	.8	8.1	40.6	83	......	18.6	4.9	2.0	8.0	66.5	6.3	1.03
B_2	12–22	21.9	12.9	.7	.8	9.7	46.0	79	4.7	14.0	7.0	2.3	8.0	68.7	5.3	.69
B_3	22–42	23.1	14.6	.6	.9	8.5	47.7	82	......	10.2	13.0	3.7	12.9	51.2	5.6	.29
C_1	42–60	28.5	18.4	.8	1.1	7.9	56.7	86	2.7	17.9	23.9	5.5	19.9	32.8	6.0	.14
Akina clay loam																
A_1	0–7	5.5	3.2	0.2	0.2	9.5	18.6	49	......	32.0	14.6	7.0	12.0	34.4	6.2	1.64
B_2	7–28	4.3	5.2	.3	.3	11.0	21.1	48	12.3	6.2	3.4	3.1	9.6	77.7	4.5	.49
B_3	28–40	5.7	5.5	.2	.3	8.5	20.2	58	......	3.6	5.0	2.5	11.4	77.5	5.0	.22
C_1	40–60	5.5	4.5	<.1	.2	8.1	18.3	56	......	2.6	5.0	3.2	14.5	74.7	5.1	.16
Dago clay																
A_1	0–6	36.6	6.4	0.6	1.0	6.4	51.0	88	......	0.7	2.8	3.8	15.1	77.6	7.7	3.23
B_2	6–30	10.6	5.5	.2	.6	13.4	30.3	56	11.8	.1	1.0	2.8	14.0	82.1	5.3	.54
B_3	30–50	4.8	2.9	.2	.4	20.7	29.0	29	......	.1	2.0	5.1	21.0	71.8	4.7	.30
C_1	50–72	2.0	2.2	.3	.4	22.2	27.1	18	......	.5	5.6	8.8	23.5	61.6	4.6	.18
Chacha clay																
A_1	0–7	14.9	4.9	0.4	0.7	13.8	31.7	60	10.1	6.1	5.1	5.0	17.5	66.3	6.1	1.98
B_2	7–24	7.3	4.2	<.1	.7	12.6	24.8	49	12.2	3.3	3.6	2.6	11.1	79.4	5.7	.17
B_3	24–72	6.4	4.3	.1	.6	13.8	25.2	45	10.9	3.8	4.6	2.7	10.5	78.4	5.3	.08
Saipan clay																
A_1	0–4	18.9	2.9	0.3	0.6	12.8	35.5	64	......	0.6	2.5	2.3	9.2	85.4	6.7	2.05
A_3–B_1	4–15	9.6	1.8	.2	.3	11.9	23.8	50	10.1	.5	1.9	.6	5.2	91.8	6.9	.56
B_2	15–36	8.2	1.4	.2	.3	9.6	19.7	51	......	.3	1.3	.4	6.7	91.3	7.0	.44
B_3	36–80	3.8	1.7	.2	.1	9.5	15.3	38	11.4	.7	.7	.8	3.7	95.1	6.6	.15
Dandan clay																
A_1	0–6	29.1	6.8	0.4	0.7	12.0	49.0	76	......	1.7	5.4	5.5	20.0	67.4	6.7	3.98
B_2	6–21	8.0	2.8	.2	.9	14.4	26.3	45	9.7	.3	1.9	.6	8.9	88.3	5.8	.43
B_3	21–36	3.5	2.5	.2	.6	15.0	21.8	31	......	.7	5.7	2.0	7.5	83.1	6.0	.14
Teo clay																
A_1	0–4	24.5	18.5	0.3	0.9	11.0	55.1	80	......	1.3	2.1	2.6	10.3	83.7	6.3	2.73
B_2	4–12	16.5	15.6	.2	.7	13.8	46.8	71	10.0	.4	1.3	1.8	14.0	82.5	5.4	1.28
B_3–C_1	12–32	10.5	19.8	.3	1.1	34.5	66.2	48	......	.4	3.9	5.7	25.0	65.0	4.6	.25
C_2	32–60	6.7	16.9	.2	1.3	39.8	64.9	39	6.0	1.0	5.9	6.3	26.0	60.8	4.4	.11
Lito clay																
A_1	0–7	44.4	14.4	0.4	0.4	4.7	64.3	93	......	1.3	2.1	2.5	14.0	79.7	7.4	2.45
B_2	7–24	14.2	13.9	.2	.6	9.1	38.0	76	10.2	.4	1.3	2.1	7.6	84.2	6.2	.51
B_3–C_1	24–48	8.3	10.9	.2	.7	12.4	32.5	62	......	.4	3.9	2.7	7.1	79.6	5.6	.48
C_2	48–60	7.3	10.4	.2	.8	12.0	30.7	61	11.9	1.0	5.9	2.1	6.4	81.8	5.0	.38

[1] Average values for each horizon.
[2] Determined by the barium chloride-triethanolamine method (Peech and others, 1947), which may be responsible for somewhat higher values than those that would be determined by other methods.
[3] The sum of the exchangeable cations is taken as an estimate of the cation-exchange capacity.

The organic-carbon versus depth curves show a relatively high organic-matter content (3½–6 percent for soils of comparable texture) in the surface horizons which correlates with the dark colors and granular structure observed in the field. The content of organic matter decreases rapidly with depth, more so than reported for soils developed under similar conditions in Hawaii (Cline and others, 1955; Dean, 1937) and in Puerto Rico (Smith, Samuels, and Cernuda, 1951), but still remains at a higher level in the *B* horizon than for many well-drained soils of the United States Midwest. Data from an earlier study by Kawamura, Tanaka, and Inagaki (1940) indicate a stabilization of C: N at 11–12 (see table 2). This indicates a relatively high nitrogen content and also indicates that the organic matter is stable.

TABLE 2.—*Some constants of representative Saipan soils*

[After Kawanura, Tanaka, and Inagaki, 1940]

Depth of sample (inches)	Humus: C (percent)	Humus: C (percent) × 1.724	Humus: N (percent)	Humus: C:N	Cation-exchange capacity (milliequivalents per 100 g whole soil)
Saipan clay [1]					
0–6	5.95	10.26	0.52	11.4	7.2
6–45					7 2
Chacha clay [2]					
0–8	2.48	4.28	0.24	10.3	6.6
8–22					
Dandan clay [3]					
0–10	3.98	6.86	0.34	11.7	
10–33					9.0
Dago clay [4]					
0–12	2.9	5.0	0.23	12.6	
12–50					12.1
Akina clay [5]					
0–8			0.28		
8–24					35.2

[1] "Red-colored limestone soil," idem.
[2] "Yellow-colored limestone soil," idem.
[3] "Brown-colored limestone soil," idem
[4] "Red andesitic soil," idem.
[5] "Red tuffaceous soil," idem.

Cation-exchange capacities diminish fairly rapidly with depth in all profiles except the Akina clay and clay loam and the Teo clay. Further, this decrease of exchange capacity seems to correlate with the drop in organic-carbon content. It can then be postulated that the organic matter in the *A* horizons is contributing appreciably to the exchange capacity—perhaps as much as 10 milliequivalents per 100 grams of soil. The increase in exchange capacity with increasing depth of the Akina soils and the Teo soil is accompanied by increases in exchangeable Mg with depth (see table 1). This increase in exchange capacity with depth also correlates with the field observations that these soils have a higher content of less altered material in the horizons studied than the other soils. The Akina clay between the depths of 22–42 inches (B_3 horizon) shows the relict texture of the parent rock, and the Teo clay between depths of 12–32 inches (B_3–C_1 horizons) is composed of partly altered parent rock. It therefore seems logical to postulate that the lower horizons of these particular soils contain a greater amount of clay minerals of high exchange capacity. The estimates of mineralogical composition (table 3) tend to support this hypothesis. The lower horizons of the Akina clay are estimated to contain 35 percent kaolin and a vermiculite hydrous-mica mixed-layer material. The Teo clay between depths of 32–60 inches (C_2 horizon) is estimated to contain 20 percent kaolin and considerable montmorillonite, perhaps as much as 70 percent. Both vermiculite and montmorillonite have a high exchange capacity as compared with kaolin. Two factors may be responsible for their presence: a rapid rate of erosion which continually exposes fresh material to weathering, accompanied by constant removal of the more weathered material which contains clay minerals of low exchange capacity (this would be especially true for the shallow Teo soil). The Akina soils are developing from weathered volcanic sediments (andesitic conglomerates and sandstone; see Chapter A), some of which are known to contain a high percentage of 2: 1-layer clays. The Teo soils are developing from siltstones and sandstones of andesitic composition, as well as tuffaceous limestones, parts of which are altered to a plastic bentonitic (montmorillonitic) material.

TABLE 3.—*Estimated mineralogical composition of clay ($<2\mu$ in diameter) from selected horizons of some Saipan soils*

[Estimates by R. S. Dyal from differential thermal analyses and X-ray diffraction patterns]

Soil	Horizon	Depth (inches)	Mineralogy
Akina clay	A_1	0–5	30 percent kaolin and a vermiculite and hydrous-mica mixed-layer material.
Do	B_2	12–22	35 percent kaolin and a vermiculite and hydrous-mica mixed-layer material.
Do	C_1	42–60	Do.
Chacha clay	A_1	0–7	50 percent kaolin.
Teo clay	C_2	32–60	20 percent kaolin and considerable montmorillonite, perhaps as much as 70 percent, with the remainder free oxides.

The average exchange capacities of the majority of Saipan soils are relatively high. An exception is the Akina clay loam, which might be expected to have a lower exchange capacity because of its relatively high sand and silt content and low organic-matter content. In general, the soils developing over limestone are lower in exchange capacity than those developing in residuum from primary volcanic rocks and sediments derived from volcanic source materials. This is associated with lower contents of exchangeable Mg. Probably related to these features are the lower silica-sesquioxide ratios (for the clay $<2\mu$ in diameter) of the soils underlain by limestone (see table 4). Also of interest is the estimate of 50 percent kaolin in the Chacha surface soil as compared to the 30 percent kaolin estimated for the Akina-clay *A* horizon (see table 2). These observations tend to indicate a somewhat different clay mineralogy for the soils underlain by limestone—that they are higher in kaolin and hence somewhat further along in the weathering sequence. This conclusion seems to be confirmed by the data of Kawamura, Tanaka, and Inagaki (1940), which show that silica-sesquioxide ratios of the clay fraction are lower in the soils underlain by limestone than in the soils underlain by volcanic rocks (see table 4). This may be related to the nature of the residuum which serves as parent material.

TABLE 4.—*Chemical composition of the clay ($<2\mu$ in diameter) fraction of representative Saipan soils*

[After Kawamura, Tanaka, and Inagaki, 1940]

Depth of sample (inches)	SiO_2 (wt percent)	Al_2O_3 (wt percent)	Fe_2O_3 (wt percent)	SiO_2:Fe_2O_3 (mol. ratio)	SiO_2:R_2O_3 (mol. ratio)
Saipan clay] [1]					
0–6	23.53	34.79	15.77	1.15	0.89
6–45	25.91	40.56	10.35	1.08	.93
Chacha clay [2]					
0–8	33.99	43.21	15.36	1.33	1.09
8–22	37.50	36.37	8.77	1.74	1 51
22+	40.70	38.78	6.52	1.78	1.58
Dandan clay [3]					
0–10	15.09	40.05	10.81	0.64	0.54
10–33	12.25	43.30	13.91	.48	.40
Dago clay [4]					
0–12	33.90	33.24	11.32	1.73	1.42
12–50	36.32	33.39	13.27	1 84	1.47
Akina clay [5]					
0–8	49.37	25.96	11.15	3.20	2.51
8–24	45.98	27.92	7.96	2.66	2.25
24+	42.50	28.06	11.34	2.58	2.05

[1] "Red-colored limestone soil," idem.
[2] "Yellow-colored limestone soil," idem.
[3] "Brown-colored limestone soil," idem.
[4] "Red andesitic soil," idem.
[5] "Red tuffaceous soil," idem.

The percentage of base saturation decreases with depth (sometimes rapidly) in all soils studied, with the exception of the two Akina soils. One might reason that the return of bases to the soil by the vegetation residues is responsible for the relatively high base saturation of the surface soils. In the Akina soils, both exchangeable Ca and Mg increase with depth; therefore, saturation remains high. The increase in exchangeable Mg seems best attributed to the presence of Mg-bearing 2: 1-layer clay minerals, but it is difficult to explain the increase in exchangeable Ca in this soil, inasmuch as it decreases rapidly in the other soils. A complementary-ion effect may be a contributing factor; that is, it is known that exchangeable Ca is more tightly held when associated with exchangeable Mg than with exchangeable H.

The content of free Fe_2O_3 may be taken as a measure of iron oxide accumulation in the profiles. The range of 9–12 percent (with the exception of 2–4 percent in the Akina clay) is relatively low for latosolic soils. For example, 37 percent free Fe_2O_3 has been reported for a Hawaiian humic latosol (Tamura, Jackson, and Sherman, 1953) developing under similar conditions. (The basaltic parent rocks of the Hawaiian latosols contain more iron that the andesitic rocks of Saipan. This may be partly responsible for the differences in free F_2O_3 in the soils.) The relatively low iron oxide contents are correlated with the field observations of plasticity and lack of aggregation of the *B* horizons of the Saipan soils (iron and aluminum oxides in latosolic soils are believed responsible for the aggregation which gives them the friability and permeability so often reported in the literature). However, the warm red and yellow colors of the deep Saipan soils do attest some iron oxide accumulation.

To summarize and speculate on the genesis of the soils: They have developed under climatic conditions characterized by uniformly high year-round temperatures (80°–85° F.) and an approximate mean annual rainfall between 80 and 90 inches. This rainfall is somewhat unevenly distributed, but on the average the soils are moist the year round. In areas of shallow soils, the rate of erosion has been so rapid that soil-forming factors have not had an opportunity to be effective.

The parent material is apparently broken down to dominantly clay sizes in the initial stages of weathering and soil formation in all soils (as especially evidenced in the "young" Teo soil, fig 31), with the exception of the shallow and stony Chinen soil. With soil-profile formation, the clay may tend to be redistributed, as indicated by the bulges in the clay versus depth curves.

The summation of effects of all genetic factors on soils underlain by primary volcanic rocks and volcanic sediments has apparently resulted in the clay of the soils being dominated by 2:1-layer clay minerals. They contain approximately 30 percent kaolin and 4–10 percent free iron oxides (table 3). The deeper soils underlain by limestone apparently contain a higher percentage of 1:1-layer clay minerals, although there does not appear to be any significant difference in free iron oxide accumulation between these soils and those derived from volcanic parent materials. Evidence for this observation is somewhat scanty, but the trends can be deduced from the plasticity, firmness, and swelling properties of these soils as observed in the field (although Tamura, Jackson, and Sherman, 1953, state that 10–15 percent of 2:1-layer silicates in the clay fraction is sufficient to give soils these plastic properties). These generalizations tend to be confirmed by the relatively high exchange capacities and the contents of exchangeable Mg (assumed to be related to Mg-bearing 2:1-layer silicates), as determined in the laboratory.

If these hypotheses as to clay mineralogy are correct, the soils from volcanic residuum can be placed at about stages 8 and 9 in the weathering sequence of clay-size minerals in soils and sediments as described by Jackson, Tyler, and others (1948).[1] The soils underlain by limestone can be placed at stages 9 and 10.

Upland soils of Saipan with complete *A–B–C* profiles do not appear to be as far along in the weathering sequence and laterization as the humic latosols of Hawaii (Cline and others, 1951; Tamura, Jackson, and Sherman, 1953) or those latosols of the Belgian Congo (Kellogg and Davol, 1949) developing under similar soil-forming factors. That they are not entirely unique can be seen by comparison with certain Puerto Rican soils developed under similar conditions (for example, the Cialitos soils described by Roberts and others, 1942), or descriptions of "non-laterized red earths" described by Milne (1936) in British East Africa.

The lack of intense weathering and laterization which might be expected under the prevailing climatic conditions can perhaps be attributed to one or more of the following factors.

1. The 80–90 inch approximate annual rainfall, without a marked dry season and in the form of frequent showers, favors accumulation of 2:1-layer silicates. The evidence at hand tends to confirm the postulations by Tamura, Jackson, and Sherman (1953) that 2:1-layer silicates tend to reach a maximum in Hawaiian humic latosols under conditions of 80 inches of annual rainfall in the form of frequent showers which keep the soil saturated, making silica available for recombination in 2:1-layer clays due to this soaking effect.

2. A large part of the parent materials are bentonitic (here used to mean weathered volcanic tuffs and sandstones consisting largely of montmorillonite-type clay minerals). This may be due both to the weathering characteristics of the andesitic rocks and to reversion of clay minerals to 2:1-layer silicates in the marine sediments and tuffaceous limestones when these materials were under sea water.

3. The relative youth of even the thick soil profiles, due to continual truncation by erosion, has prevented the full influence of the climatic factors. However, the relatively high content of organic matter in the surface soils does tend to rule this out to a certain extent.

[1] A weathering sequence of clay-size particles has been postulated by Jackson, Tyler, and others, and later expanded by Jackson, Hseung, and others (1952); related to latosolic soil by Tamura, Jackson, and Sherman (1953); and summarized by Jackson and Sherman (1953). In the part of this sequence which pertains to latosolic soils, the clay fraction of stage 7 is postulated to be dominated by illite, 8 by hydrous-mica intermediates, 8.5 by vermiculite, 9 by the montmorillonite group, 10 by kaolinite, 11 by gibbsite, 12 by hematite, and 13 by anatase and rutile. The sequence is considered reversible, as in diagenetic processes.

CLASSIFICATION

Most of the Saipan soils have been grouped into soil series. These are narrowly defined groups delimited by differences in certain properties of the various soil horizons. The following discussion is an attempt to classify these soils into still broader groups convenient for regional studies and interarea comparisons. The level of the classification scheme in the United States which is appropriate for this discussion is the category "great soil group."

Kellog (1948; Kellog and Davol, 1949) proposed that the term "latosol" be adopted to embrace all the zonal soils in tropical regions that have as their dominating characteristics low silica-sesquioxide ratios, low physical and chemical activity of the clay fraction, a high degree of aggregate stability, and some red color. Kellogg further proposed that the term be introduced into the classification scheme at the second highest level of generalization—the category of the suborder. Names of great soil groups, the third highest level of generalization, would then be derived by using modifiers with latosol.

The shallow soils of Saipan that lack *B* horizons can rather easily be placed in great soil groups. The Shioya series and the Teo soils are classed as regosols, since their parent material is unconsolidated. The Chinen series is classed as a lithosol, since it is stony and shallow over consolidated limestone.

However, the placement of the soils of the uplands with more or less complete *A–B–C* profiles is more difficult, since they lack some characteristics of latosols as described by Kellogg (1948), yet do not fit in any presently described great soil group. It can be argued that since erosion has been rapid enough to prevent full expression of the active soil-forming factors, these soils should not be classed as true latosols, but with some group of relatively immature soils which are progressing towards latosols in development. Also, if the bentonitic composition of the parent material is chiefly responsible for the incomplete development of latosolic characteristics in these soils, then they should be classed with those soils in which effects of a certain parent material or topographic position overbalance the effects of the active formational factors as climate and vegetation (such soils have been called intrazonal soils). On the other hand, if the amount of rainfall and its distribution are the prime causes for the somewhat anomalous lack of latosolic characteristics of these soils and if their horizons are considered to be fairly well expressed, they can be considered as normal or zonal. They then might be considered as a unique great soil group of the broader group of latosols, although admittedly lacking in certain latosolic characteristics.

Great soil groups of latosols have not been completely defined. Not enough information is available to define accurately and to classify all latosolic soils, of which there are a great many. It is also not yet clearly established, at least in the author's opinion, which properties should be selected as differentiating characteristics for latosolic great soil groups. Although color has been tentatively used, it seems of doubtful significance unless it can be demonstrated that a number of other latosolic soil properties covary with color, and if so, the manner in which they vary. Gross morphological properties coupled with the clay mineralogy and position in the weathering sequence as determined in the laboratory seem the best differentiating characteristics for latosolic soils, but sufficient information is not available concerning many tropical soils, as in the present study.

Uplands soils with complete *A–B–C* profiles possess some of the features of the red-yellow podzolic soils, although they lack other features which are common in these soils in the southeastern United States. They do show some evidence of silicate-clay illuviation and iron accumulation, and they have firm and plastic *B* horizons with apparently as much or more 1:1-layer clay minerals in the *B* horizon as in the *C* horizon. The Saipan soils lack the bleached A_2 horizons and very thin A_1 horizons of low organic content and the pronounced, definite evidence of silicate clay illuviation common in the red-yellow podzolic soils.

Therefore, it does not seem appropriate to fit these Saipan soils into any presently defined group. They may be considered as intergrades between latosols and some group such as the red-yellow podzolic soils. It is of some importance to note that similar soils have been described as occurring under somewhat similar conditions elsewhere (in Puerto Rico by Roberts and others, 1952, and in East Africa by Milne, 1936). If the present definition of red-yellow podzolic soils were changed to put less emphasis on the occurrence of bleached A_2 horizons, these soils would seem to fit best in such a group.

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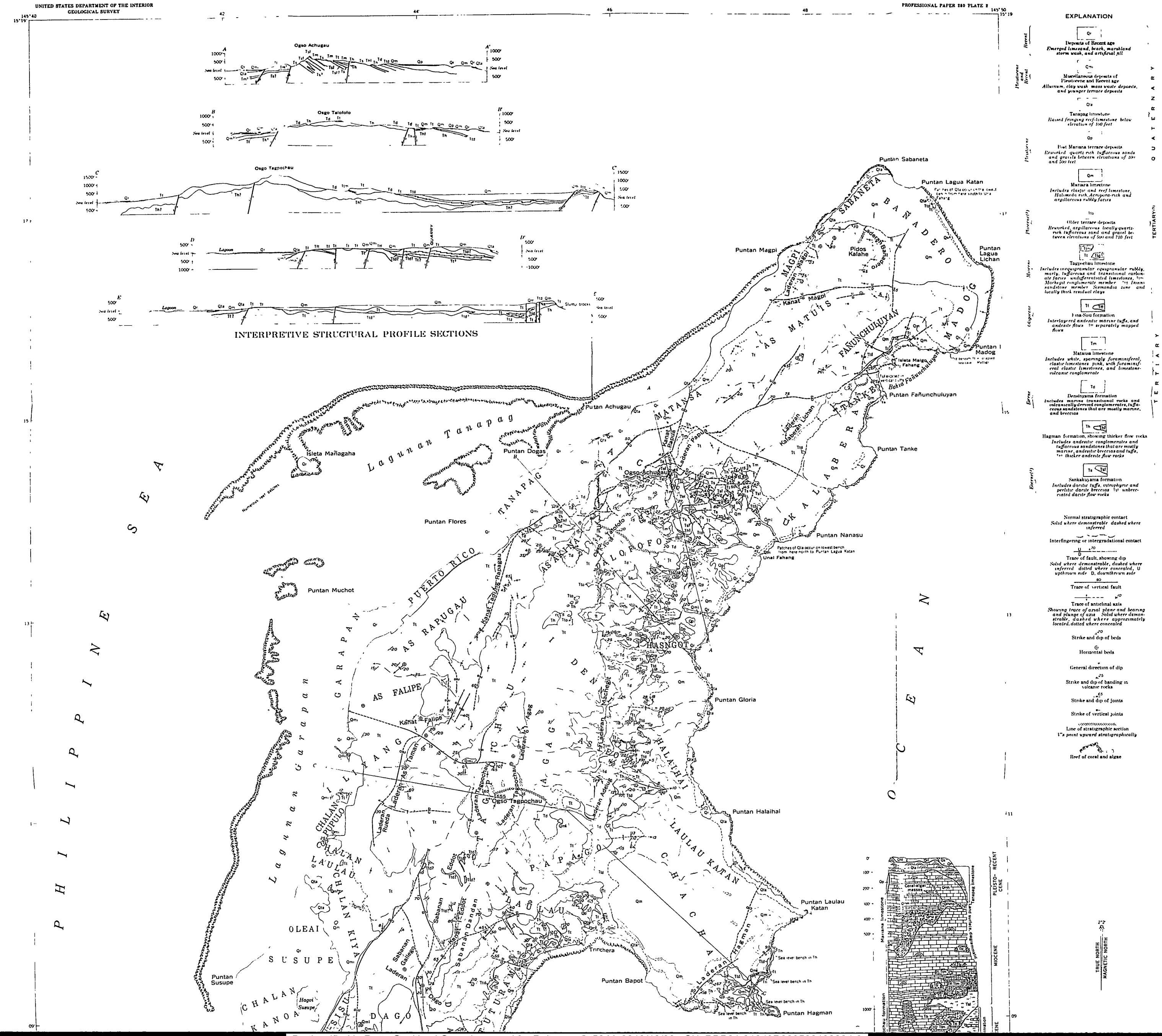
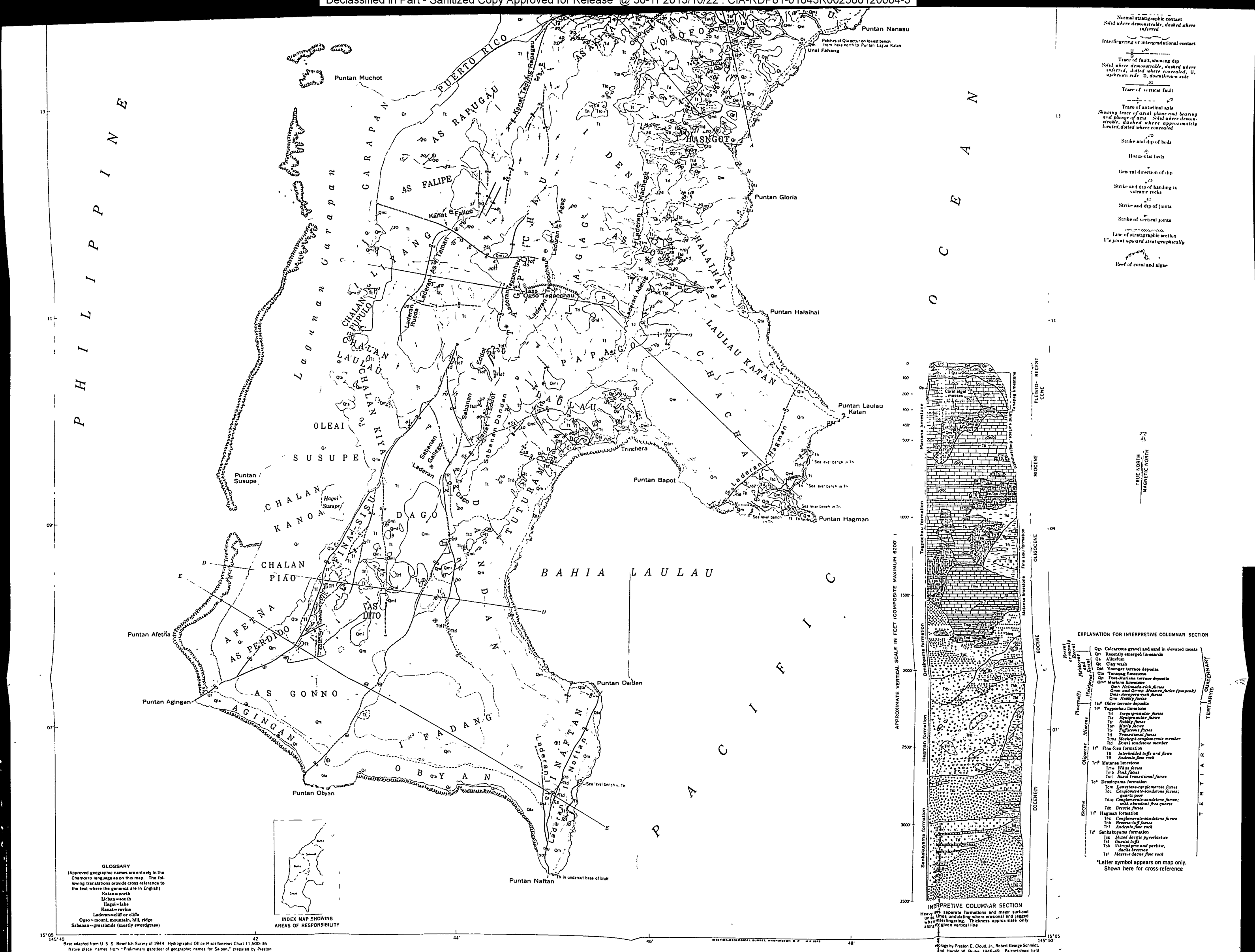
Age		Unit	Distinctive features	Areal distribution and approximate acreage	Thickness (feet) Total range	Thickness (feet) Common range or average	Weathering characteristics	Terrain and vegetation	Conspicuous fossils	Inferred origin
Quaternary, Recent		Present reef and beach deposits	Fringing and barrier reefs, terraced ramps, and pedestals. Beach sand and gravel (mostly calcium carbonate), beach rock, and minor slightly emerged reef limestone.	Shoreline and offshore	A veneer					
Quaternary, Recent		Gravel and sand on emerged fringing reef surfaces.	Poorly sorted gravel and sand, consisting of organically derived calcareous fragments	Linear patches parallel to and just inshore from east and north coasts. 67 acres.	A veneer			Linear shallow trenches parallel to and bordering coast. Ordinarily supports thick growths of low, tangled brush.	Recent types of Foraminifera, corals, and mollusks.	Largely(?) debris washed up by great storms. May in part include primary moat deposits.
Quaternary, Recent		Marsh deposits	Soft, sticky blue-gray to grayish-brown muck in and around several permanent ponds and sloughs.	Depressions in west Saipan, south from Matansa. Largest area surrounds Lake Susupe. 600 acres.	A veneer			Marshland. Vines, ferns, and thickly tangled, tall, tough grasses. About 11 acres of mangrove near Tanapag.		
Quaternary, Recent		Recently emerged limesands	Loose, unbonded limesands, coarse and gravelly at places; contains numerous mollusk shells and Foraminifera.	Strip along west coast, south from northern Matansa, widening toward south and interrupted by areas of fill. 1,650 acres, half filled over	0-30 ?	8-12	Not noticeably affected by weathering	Gently sloping to flat coastal plain area. Supports low leguminous brushes, tangled grasses, scattered trees.	Recent marine shells and pottery shards to 6-ft. depth locally.	Complex shoreline and nearshore processes
Quaternary, Pleistocene and Recent		Alluvium and clay wash	Includes the primarily clay deposits of closed or nearly closed depressions and the linear clay and gravel or clay deposits of out-draining valleys.	Localized in depressions and valleys in many parts of island. 900 acres.	0-30 ?	5±	Locally gullied by rill wash at margins of larger deposits.	Occurs in broad or narrowly linear depressions. Commonly cultivated, or with vegetation of grasses or vines.		
Quaternary, Pleistocene and Recent		Deposits formed by mass wasting	Chaotically mixed blocks of limestone naturally transported to or nearly residual on present sites.	Two small patches at bluff top and on hillslope above Hagman beach. Coarse slump rubble of steep coasts. 11 acres.	- - -	- - -				Landslide, creep, and slump
Quaternary, Pleistocene and Recent		Younger terrace deposits	Mostly gravels and gravelly and sandy clays of reworked volcanic materials. Locally includes ferruginous quartz sands, and grades laterally into material mapped as clay wash.	Strip along and a little inshore from north part of west coast. Mostly from 20 to 80 feet above sea level. 420± acres.	0-20 ?	8±	Nonsiliceous components are largely weathered to clay minerals and the deposit is mainly a gravelly clay.	A gently rolling surface incised by small intermittent washes and gullies. Cultivated, or with abandoned cane, grasses, or brush.		Fluviatile outwash deposits from contiguous sources to the east.
Quaternary		Tanapag limestone	Coral and algal-rich emerged reef limestone, highly porous and open in texture. Shell material of mollusks and coral skeletons generally well preserved, serving to distinguish from Mariana limestone.	Generally linear patches, parallel to and mostly adjacent to coast, and extending from sea level to 100 ft above. 1,050 acres.	<50	10-20?	Natural weathered surface very rough, with many pinnacles and irregular ridges of 1 to 6 ft amplitude.	Mantles lowest raised marine bench or occurs as isolated patches. Surface mostly rough, with little soil, bare or with low brush.	Mostly living species. Carbon-14 determinations and position indicate late Pleistocene age.	An emerged tropical fringing reef only slightly modified by chemical erosion.
Quaternary		Post-Mariana terrace deposits	Iron-stained, locally quartz-rich, clay sands and minor gravels of volcanic source materials, at elevations between 100 and 500 ft.	Scattered irregular occurrences on seaward slopes of east-central Saipan and north shore of Laulau bay 136 acres.	0-10	3-4	Some alteration to thin clay soil	Mostly gently sloping surfaces planted to sugar-cane; small patches north of Laulau bay are steep, gullied, and swordgrass covered.		Fluviatile outwash deposits on marine benches
Quaternary, Pleistocene	Mariana limestone	Summary of formation	Generally coarsely porous, nonbedded to indistinctly bedded, dirty white to brownish, bioclastic to constructional limestones. Mollusk shells are ordinarily dissolved away and coral skeletons noticeably altered. Corals more abundant than in older rocks, and fossils of different sorts.	Along south, east, north and northwest coasts, with largest areas of outcrop in south, in east peninsula, and in north. Small outcrops elsewhere below altitudes of 500 ft. 7,430 acres.	0-500±	400±	Mantled by generally thin clay soil through which project irregular residual rock pinnacles as high as 6 ft. Rock is porous; caves and crevasses are common.	Wave-cut scarp and bench topography; mostly planted to cane, with small trees along property lines. Jungle on and near scarps and locally on beaches.	Foraminifera, corals, mollusks, echinoids, and algae mostly of living species.	Bank, lagoonal, and reef-complex limestones formed in shallow tropical waters.
Quaternary, Pleistocene	Mariana limestone	*Halimeda*-rich facies	Bioclastic limestone distinctive in its rich concentration of the calcified, small, fan-shaped joints of the green alga *Halimeda*.	Southeast peninsula (I Naftan) and northeast part of east peninsula (Chacha). 1,130 acres.	0-400 ?	?	Mantled by thin, brownish to black, somewhat powdery, clay soil through which project limestone pinnacles.	Wave-cut scarp and bench topography. Vegetation of low thick brush, sparse swordgrass, cane, or jungle growth.	As above	Concentrations of light-weight but large-grained calcareous debris, grading shoreward to varied bioclastic and constructional deposits.
Quaternary, Pleistocene	Mariana limestone	Massive facies	Generally massive to obscurely bedded, dirty white to brownish; coarsely porous to cavernous, well-indurated, bioclastic to constructional limestone, with coral and algal remains common and at places abundant A pink subfacies occurs locally	Essentially as Mariana limestone in general, includes considerably more than one-half of total outcrop of Mariana limestone. 4,480 acres.	0-300±	200-300?	Same as second box above	Same as second box above	Same as second box above	Bank, lagoonal, and reef-complex deposits. Probably similar to bulk of deposits presently forming west of Saipan
Quaternary, Pleistocene	Mariana limestone	*Acropora*-rich facies	Rich in broken fragments of the staghorn coral *Acropora*, mostly clay bonded, but in part fairly pure calcium carbonate with occasional *Acropora* colonies in position of growth.	A narrow northeast to southwest belt near central part of south Saipan, and small occurrences nearby 200 acres	0-100	50?	Leaching of calcareous material leaves a thick, yellowish to red-brown, mottled clay cover	Gently sloping to flat Mostly cultivated, but partly in old cane, tangled grass, or leguminous brush.	Staghorn *Acropora* the dominant fossil. Associated rocks indicate post-Miocene age.	Mainly locally derived though fragmentary staghorn coral mixed with clay from adjacent gently sloping volcanic shores.
Quaternary, Pleistocene	Mariana limestone	Rubbly facies	Conspicuously and coarsely fragmental limestones, generally rich in broken and randomly oriented coral and algal fragments, poorly indurated and with a generally large amount of clay contamination.	Outcrops as a broad belt along east coast from southern Kalabera at north to Chacha at south. 1,300 acres.	0-400	200-300?	Where terrace deposits absent, it is generally weathered to brownish clay soils 1-5 ft thick, around scattered limestone pinnacles.	Gently rolling cane-covered benches, with rare tree-clusters, cut by shallow valleys and narrow ravines with jungle vegetation.	Foraminifera, corals, mollusks, echinoids, and algae mostly of living species.	Displaced coral and calcareous sediments, mixed with clay from adjacent volcanic terrain along a relatively steep coast.
Quaternary, Pleistocene	Mariana limestone	Clays over rubbly facies	Yellowish to brown and gray, mottled, kaolinitic clay	Western margin of eastern peninsula (Chacha). 320 acres.	0-40	5-10	The unit is the product of weathering	Flat or very gently sloping clay-covered surfaces, with rows of small trees growing along property lines.		Product of weathering of rubbly facies of Mariana limestone.
Tertiary, Pliocene		Older terrace deposits	Generally quartz-rich, iron-stained, clay sands and minor gravels of volcanic source materials, occurring in two sets between altitudes of 500 and 710 feet.	A few small patches in central and north-central Saipan to southern slope of Mt Achugau. 21 acres.	0-10	3-5	Locally yields thin clay soil which, with washing out of finer sediments, leaves surface film of quartz and magnetite.	Gently sloping to level surfaces, with growth of swordgrass or scrubby leguminous trees.		Fluviatile outwash deposits on marine benches
Tertiary, Miocene	Tagpochau limestone	Summary of formation	Mainly a complex of varied calcareous facies that intergrade with one another and are distinguished from other limestones on Saipan by their contained fossils. Commonest and most distinctive facies is pure inequigranular limestone. Also includes impure limestone, as well as sandstone and conglomerate of volcanic source materials.	Widespread. Underlies nearly half of Saipan, and forms most of axial ridge. 13,170 acres.	0-1,000?	300-600?	Solution produces clay soils around residual limestone pinnacles, gradational contacts where impure. Caves, crevasses, and sinkholes abundant.	Characterized by scarp and bench topography with general north-northeast orientation. Scarps as high as 600 ft. Benches with irregular surfaces. Dense jungle when not cleared for cane.	Foraminifera, corals, echinoids, mollusks, decapods, and algae of early Miocene (Tertiary e) age.	Clastic deposits of shallow to moderately deep, tropical, marine waters.
Tertiary, Miocene	Tagpochau limestone	Tagpochau limestone undifferentiated.	Mostly somewhat impure limestones not conveniently placed in any named facies of Tagpochau limestone because of intermediate or mixed nature.	Mainly in south-central Saipan in large, irregular patches extending south from Mt. Tagpochau 600 acres.	0-500?	200-300?	Mostly weathers to clay soil with outcropping ledges but few or no residual pinnacles.	Whaleback ridges and steep slopes interrupted by abrupt scarplets. Vegetation thick swordgrass, with local scrub trees and patches of jungle vegetation.	Essentially as above	Accumulated in marine waters of shallow to moderate depth within reach of clay contamination from land.
Tertiary, Miocene	Tagpochau limestone	Inequigranular facies	Generally massive to obscurely bedded, pure, compact and well-indurated, pink to white, inequigranular limestone.	Widespread, especially in and adjacent to Mt. Tagpochau and axial ridge north of Mt. Achugau 9,720 acres.	0-900±	200-500?	Weathers to red clay soil, around many smooth-surfaced residual pinnacles. Underground are caves, sinkholes, and crevasses.	Steep to vertical jungle-covered scarps separated by gently sloping benches, with cane and woodlots. Minor brush and swordgrass locally.	Same as above.	Accumulation of mainly bioclastic calcareous sediments on open sea banks (or in lagoons?) of moderate to shallow depth.
Tertiary, Miocene	Tagpochau limestone	Equigranular facies	Well-bedded to massive, well-indurated to moderately indurated, mostly rather pure, generally white, fine- to coarse-grained but dominantly equigranular limestone.	West-central and northern Saipan. Especially in lowest terrace east from Muchot point, in As Matuis; and Fanunchuluyan bay. 770 acres.	0-220±	100-200?	Generally as above, except residual pinnacles sparse in outcrop area of west-central Saipan	As above, except area east from Muchot point is low, and tends to overgrowth of vines, grasses, and brush.	Same as above	Same as above
Tertiary, Miocene	Tagpochau limestone	Rubbly facies	Unevenly indurated, fairly pure, generally white limestone that characteristically consists of aggregated angular fragments without obvious bedding. At places thinly bedded and locally with argillaceous impurities.	Mainly in eastern and southern part of east-central Saipan in north-south belt along base of Tagpochau and I Agag cliffs. 350 acres.	0-120±	100±	Weathers to clayey soil in sharp contact with underlying limestone.	Cliff bases and valley floors have 10°-20° slope angles. Vegetation is old cane, a few trees, and minor jungle growth.	Same as above	Intermediate between above and below
Tertiary, Miocene	Tagpochau limestone	Marly facies	Well-bedded, thinly to thickly bedded, marly limestone of generally yellowish color and moderate degree of induration.	Mostly in central Saipan, in irregular patches submarginal to mass of inequigranular facies 1,280 acres.	0-500±	100-150?	Weathers to alkaline clayey soil around scattered residual limestone pinnacles Transition generally sharp.	Slopes as much as 20°, with occasional projecting ledges and subdued scarplets. Vegetation is swordgrass, with scattered brush, jungle growth, and cane.	Larger Foraminifera, mollusks, echinoids, and algae of early Miocene age.	Accumulated in marine waters of shallow to moderate depth within reach of clay contamination from land.
Tertiary, Miocene	Tagpochau limestone	Tuffaceous facies	Poorly indurated, mostly thin-bedded, somber colored, calcareous rocks that include varying and generally large proportions of reworked andesitic materials.	Mainly in west and south-central Saipan, west, south, and southeast of Mt. Talofofo. Few small patches in north. 390 acres.	0-170±	100-150?	Dependent on proportion of andesitic contaminants. More impure phases form clay soil over rotted rock. Deep and extensive residual clays described below	Moderate slopes that locally pitch into sharp valleys or border low scarps of purer limestones. Vegetation varied	Foraminifera, staghorn coral (*Acropora*), occasional mollusks, and echinoid fragments of early Miocene age	Accumulated in tropical marine waters of shallow to moderate depths adjacent to residual volcanic highs.
Tertiary, Miocene	Tagpochau limestone	Clays over tuffaceous and marly facies.	Mottled and banded reddish-brown, yellowish-brown, red, gray, and white clays, plastic when wet Banding subparallel, at all attitudes between horizontal and vertical.	Central and southern part of east-central Saipan, southern end of Mt Talofofo and lower east slopes of Mt Tagpochau. 130 acres.	0-30?	10-20?	The unit is the product of weathering	Gently sloping to nearly flat, with tangled grasses and occasional copses of small leguminous trees		Product of weathering of tuffaceous and, in part, of marly facies of Tagpochau limestone.
Tertiary, Miocene	Tagpochau limestone	Transitional facies	Calcareous tuffaceous sandstone, marl, and calcareous andesitic conglomerate, at places with larger Foraminifera comprising a large volume of the rock.	Mainly linear outcrops in east, just east of Machegit and Adelug cliffs, and at Hagman and I Naftan. 90 acres.	0-40+	40?	Produces thin clay soil	Gentle slopes or parts of cliff faces; supports jungle, swordgrass, and sugarcane	Foraminifera, corals, echinoids, and algae of early Miocene age.	Clastic marine deposits, gradational between relatively pure and relatively impure calcareous facies or to volcanic rocks.
Tertiary, Miocene	Tagpochau limestone	Machegit conglomerate member	Andesitic conglomerate, with same quartz-rich rocks Resembles conglomerates of Densinyama formation, but associated with and overlying beds rich in lower Miocene Foraminifera.	East-central Saipan, narrow band at base of (east of) Machegit cliff. 40 acres.	0-40	20-40	Forms clay soils with rock-weathering effects extending downward tens of feet Relict textures preserved in boulders.	Low and discontinuous, sloping terrace, with cane, tangled grasses, and low brush	No fossils found, but larger Foraminifera of associated rocks are Miocene.	Reworked conglomerates of the Densinyama formation.
Tertiary, Miocene	Tagpochau limestone	Donni sandstone member	Tuffaceous and calcareous and well-bedded and generally thinly bedded, poorly indurated sandstones, rich in smaller Foraminifera.	Outcrop belt on east slope of Saipan from Achugau at north to Laulau at south Also at Fanunchuluyan, Hagman, I Naftan, and elsewhere. 800 acres.	0-200	100+	Weathers to expanding (bentonitic?) clays that yield only a thin soil layer and are easily removed by rill wash.	Intricate pattern of narrow ravines separated by short, rounded spurs. Swordgrass is typical cover, but jungle, Formosan koa, and cane grow locally.	*Globigerina*, *Orbulina*, and many other smaller Foraminifera. Early Miocene age indicated by rare larger Foraminifera and stratigraphic associations	Moderately deep marine environment adjacent to source area of reworked volcanic sediments.
Tertiary, Oligocene	Fina-sisu formation	Summary of formation	Well-stratified, andesitic marine tuffs and interlayered andesitic flows that are mostly less than 10 to 20 ft thick but range to 80 to 100 feet thick	South Saipan in Fina-sisu and As Lito districts. 500 including tuffs and all flows	0-400+ (inclusive)	?	Deeply weathered, clay soils as deep as 20 feet; few natural outcrops.	Area of outcrop gently rolling and mostly cultivated, but locally with tangled grasses and copses of Formosan koa	Smaller Foraminifera of the late Oligocene (Tertiary d?) *Globigerinatella insueta* zone. Rare discoasters and Radiolaria.	Marine tuffs and interbedded lava flows, probably deposited in moderately deep tropical waters.
Tertiary, Oligocene	Fina-sisu formation	Thicker flow rocks	Greenish-gray, vesicular, aphanitic to finely porphyritic, augite andesite. Locally with columnar jointing.	South end of Fina-sisu ridge and in northwestern As Lito. 70 acres.	80-100?	90	Clay at surface, grading down to rotten rock. Joint blocks weather spheroidally	Eastern dip slopes gentle, with thick clay soil and tangled grasses Faceted wooded spurs and short valleys face up dip along west margin.	Smaller Foraminifera of associated tuffs are of late Oligocene age.	Presumably submarine lava flows
Tertiary, Eocene	Matansa limestone	Summary of formation	Pure to impure, inequigranular, white to pink or dark-red clastic limestone containing a distinctive upper Eocene foraminiferal assemblage.	North-central Saipan, patches between Fanunchuluyan and Talofofo 310 acres.	0-500+	200-500?	Mostly similar to inequigranular facies of Tagpochau limestone. See above.	Mostly similar to inequigranular facies of Tagpochau limestone See above	Larger Foraminifera of late Eocene (Tertiary b age). Also calcareous algae and rare corals	Clastic bank deposits of tropical marine waters of shallow to moderate depth.
Tertiary, Eocene	Matansa limestone	White facies	White to locally pinkish white, sparingly foraminiferal, inequigranular, generally pure, clastic limestones.	North-central Saipan, mostly on east slopes, patches between Fanunchuluyan and Talofofo 195 acres.	0-300+	300?	Same as above	Same as above	Same as above	Same as above
Tertiary, Eocene	Matansa limestone	Pink facies	Pink to dull-red, richly foraminiferal, inequigranular, slightly to moderately impure, clastic limestone.	North-central Saipan, on both east and west slopes adjacent to Mt Achugau. 85 acres.	0-150	100?	Weathers to red clay soil on rough limestone surface.	Jungle-covered scarps and sloping benches covered with cane, brush, some jungle growth and patches of swordgrass.	Same as above	Same as above
Tertiary, Eocene	Matansa limestone	Transitional facies	Dull-white, tan or reddish-brown, tuffaceous to marly limestone and conglomerate, with locally abundant larger Foraminifera. Overlies or grades laterally to upper beds of the Densinyama formation and resembles limestone-conglomerate facies of Densinyama.	North-central Saipan, along and near Talofofo Road, on both east and west slopes of Talofofo ridge. 30 acres.	0-140+	100?	Weathers to a thin, stony, red, neutral to slightly acid soil.	Steep slopes cut by short, narrow, steep-walled ravines. Swordgrass abundant, and casuarina forms thick stands locally	Same as above	Same as above, but nearer to source of contamination with reworked volcanic debris.
Tertiary, Eocene	Densinyama formation	Summary of formation	Volcanic breccia, tuffaceous sandstone, calcareous sandstone, tuffaceous limestone, and conglomerate. Rock types in fragments varied; with andesite the most abundant and quartz or quartzose rocks the most distinctive.	North-central Saipan and extending south through east-central Saipan in generally linear belt 1,200 acres.	0-800±	200-600?	Forms clay soils, with rock-weathering effects extending downward tens of feet Relict textures preserved in boulders.	Rough and cut by closely spaced, steep-walled ravines at north. Less dissected to south. Swordgrass abundant, casuarina common on ridge crests.	Foraminifera of late Eocene (Tertiary b) age. Also echinoid spines and coral and algal fragments.	Mainly by reworking of preexisting volcanic and penecontemporaneous calcareous source materials in and adjacent to a tropical sea.
Tertiary, Eocene	Densinyama formation	Limestone-conglomerate facies	Impure limestone and calcareous conglomerate, with abundant reworked volcanic constituents and larger Foraminifera. Very similar to parts of transitional facies of Matansa limestone, but associated with rocks characteristic of Densinyama formation.	Central Saipan, on east and west slopes of Mt Talofofo. 30 acres.	0-50±	10-20	Weathers to a thin, stony, red, neutral to slightly acid soil	Spurs and gentle to steep slopes that break to ravine heads or low bluffs. Swordgrass thick, with copses of casuarina locally	Same as above.	Reworking of preexisting volcanic and penecontemporaneous calcareous source materials in a nearshore tropical environment.
Tertiary, Eocene	Densinyama formation	Conglomerate-sandstone facies	Intergrading, well-stratified beds of tuffaceous sandstone and volcanic conglomerate, with interstitial calcium carbonate and marine fossils locally. Predominantly andesitic and in part with abundant free-quartz.	Same as second box above. 955 acres.	0-500±	100?	Same as second box above	Same as second box above	A few upper Eocene Foraminifera locally	Formed by reworking of preexisting volcanic source materials in a nearshore but in part moderately deep marine environment.
Tertiary, Eocene	Densinyama formation	Breccia facies	Unsorted deposits of angular fragments of andesite and less abundant dacitic volcanic rocks and chert.	North-central Saipan, on east and west flanks of central and northern parts of Talofofo ridge 215 acres.	0-250±	60-100?	Weathers to sticky clays on the surface of which are pebbles and cobbles of siliceous rock or spheroidally weathered andesite.	Intricately dissected, exposures common, swordgrass thrives where clay mantle present.	No fossils found, but Foraminifera from associated rocks are late Eocene.	Subaerial pyroclastic deposits
Tertiary, Eocene	Hagman formation	Summary of formation	Andesitic rocks of both subaerial and marine detrital facies, as well as massive andesite flow rock. Essentially quartz-free throughout.	Mainly in east- and west-central Saipan, in As Akina and Talofofo Also in southeast-central, south, and north-central parts. 800 acres.	0-1,100±	?	Forms thick clays at surface, grading downward to rotted rock with relict textures.	Intricately dissected, with dense swordgrass, occasional casuarina, and local Formosan koa copses. Relief subdued in south.	Foraminifera of late Eocene (Tertiary b) age; other fossils locally.	Mafic pyroclastic rocks and lava, in part reworked in a moderately deep to shallow tropical marine environment.
Tertiary, Eocene	Hagman formation	Conglomerate-sandstone facies	Well-stratified to poorly stratified conglomerates and sandstones, locally containing interstitial calcium carbonate and marine fossils.	East from mid-width of Saipan in central, south-east central, and south parts. Also in sea bluffs at Hagman and I Naftan. 270 acres.	0-400+	?	Most outcrops in bluff faces; surface weathering yields acidic clay soils.	Precipitous swordgrass-covered slopes and bare cliffs at Hagman and I Naftan Elsewhere not distinctive.	Foraminifera of late Eocene age. Also calcareous algae, discoasters, and Radiolaria.	Reworked pyroclastic deposits which came to rest nearshore in shallow to moderately deep marine water.
Tertiary, Eocene	Hagman formation	Breccia-tuff facies	Poorly consolidated, largely unstratified and andesitic breccias and tuffs that lack fossils and interstitial calcium carbonate.	Central and southeast Saipan. In south Talofofo, north As Akina and Mt. Laulau. 520 acres.	0-600+	?	Forms iron-stained clays with rock alteration extending tens of feet downward. Matrix more weathered than included fragments.	In general is intricately dissected, with swordgrass cover, scattered casuarina, and local copses of Formosan koa.	No fossils found, but Foraminifera from associated rocks are late Eocene.	Subaerial pyroclastic deposits
Tertiary, Eocene	Hagman formation	Flow rock facies	Massive, gray to greenish-gray, coarsely porphyritic, augite-hypersthene andesite in tabular bodies that range from 30 to 80 ft. thick Also olive-gray, finely porphyritic, vesicular, augite andesite.	Small patches in east- and west-central Saipan. 10 acres.	0-100	60-80?	Clay at surface grades down to rotten rock	Outcrop areas too small to develop distinctive characteristics.	Foraminifera from associated rocks are late Eocene.	Andesitic lava flows
Tertiary, Eocene (?)	Sankakuyama formation	Summary of formation	Dacitic rocks, mainly breccias and massive flow rocks. Glassy, in part conspicuously laminated and locally vesicular	North-central Saipan; at Mt. Achugau and to about 1 mile east and south from it. 455 acres.	?-1,800+	?	Only locally altered to clay where vesicular or tuffaceous.	Steep, rough, and rocky; with swordgrass or xerophytic ferns, and local copses of casuarina.	No fossils. Inferred to be Tertiary because of abundance of tridymite and cristobalite in the rocks.	Mostly or wholly subaerial pyroclastic debris and lava flows.
Tertiary, Eocene (?)	Sankakuyama formation	Mixed pyroclastic facies	Well-bedded silicic tuffs and breccias, commonly cross bedded, and with unusual "brick-work" sedimentary structure.	Islet of Maigo Fahang and sea cliffs at south Fanunchuluyan beach. 5 acres.	?-160+	?	Unweathered	Bare sea-facing bluffs and sea level bench, capped by resistant rocks.	Same as above	Water-laid(?) pyroclastic debris
Tertiary, Eocene (?)	Sankakuyama formation	Tuff facies	Thinly bedded, glassy tuffs and lapilli tuffs comprised of angular particles of dacite vitrophyre, quartz, dacite and glass shards and small grains of quartz, oligoclase, and magnetite.	Minor occurrences in north-central Saipan, at upper Nanasu and north Fahang ravines, and at Mt. Achugau. 10 acres.	?-400+	?	Weathers at surface to 1 to 5 ft of acidic reddish-brown clay soil.	Gentle swordgrass-covered slopes breaking to 150-ft cliffs in upper Nanasu ravine.	Same as above	Subaerial volcanic ash and lapilli
Tertiary, Eocene (?)	Sankakuyama formation	Breccia facies	Mostly banded and laminated, gray to white breccias and flow breccias of angular to subrounded fragments of dacite vitrophyre and perlite in a glassy tuffaceous matrix. Most of facies is vitrophyric, some is also perlitic	Patches occur through outcrop area of formation in north-central Saipan. 240 acres.	?-400+	?	Locally altered to clay where vesicular or tuffaceous. Mainly of fresh appearance.	Steep to gentle, rocky slopes cut by steep-walled ravines. Supports swordgrass, xerophytic ferns, and local casuarina.	Same as above	Subaerial pyroclastic debris and autoclastic flow breccias.
Tertiary, Eocene (?)	Sankakuyama formation	Flow rock facies	Tabular or lens-shaped bodies of massive, glassy quartz dacite of chocolate, reddish, or pinkish color. Observed areal dimensions of individual bodies not exceeding ¼ mile.	Patches occur through outcrop area of formation in north-central Saipan. 200 acres.	0-500? (individual flows to 60 ft.)	?	Essentially unweathered except for partial devitrification of dacite glass.	Generally caps prominent rocky ridges and hills. Vegetation sparse swordgrass or xerophytic fern.	Same as above	Viscous lava flows and domal protrusions

SUMMARY OF GEOLOGIC UNITS OF SAIPAN

388406 O - 1956 (In Pocket)


EXPLANATION
INTERPRETIVE STRUCTURAL PROFILE SECTIONS
Ogso Achugau
Ogso Talofofo
Ogso Tagpochau
Sea level
Lagoon
PHILIPPINE SEA
OCEAN
Lagunan Tanapag
Lagunan Garapan
Isleta Mañagaha
Puntan Sabaneta
Puntan Lagua Katan
Puntan Lagua Lichan
Puntan Magpi
Puntan Achugau
Puntan Dogas
Puntan Flores
Puntan Muchot
Puntan Fañunchuluyan
Puntan Tanke
Puntan Nanasu
Unai Fahang
Puntan Gloria
Puntan Halaihai
Puntan Laulau Katan
Puntan Bapot
Puntan Hagman
Puntan Susupe
SABANETA
BAÑADERO
MAGPI
AS MATUIS
FAÑUNCHULUYAN
MADOG
MATANSA
TANAPAG
KALABERA
TANKE
ALOLOFO
PUERTO RICO
AS RAPUGAU
GARAPAN
AS FALIPE
HASNGOT
HALAIHAI
LAULAU KATAN
PAPAGO
CHACHA
LAULAU
OLEAI
SUSUPE
CHALAN KANOA
Trinchera
Kanat Falipe
Isleta Maigo Fahang
Bahia Fañunchuluyan
Pidos Kalahe
Sea level bench in Th
Deposits of Recent age
Miscellaneous deposits of Pleistocene and Recent age
Tanapag limestone
Post Mariana terrace deposits
Mariana limestone
Older terrace deposits
Tagpochau limestone
Fina-Sisu formation
Matansa limestone
Densinyama formation
Hagman formation, showing thicker flow rocks
Sankakuyama formation
Normal stratigraphic contact
Interfingering or intergradational contact
Trace of fault, showing dip
Trace of vertical fault
Trace of anticlinal axis
Strike and dip of beds
Horizontal beds
General direction of dip
Strike and dip of banding in volcanic rocks
Strike and dip of joints
Strike of vertical joints
Line of stratigraphic section
Reef of coral and algae
QUATERNARY
TERTIARY
MIOCENE
TRUE NORTH
MAGNETIC NORTH



GENERALIZED GEOLOGIC MAP AND SECTIONS OF SAIPAN, MARIANA ISLANDS

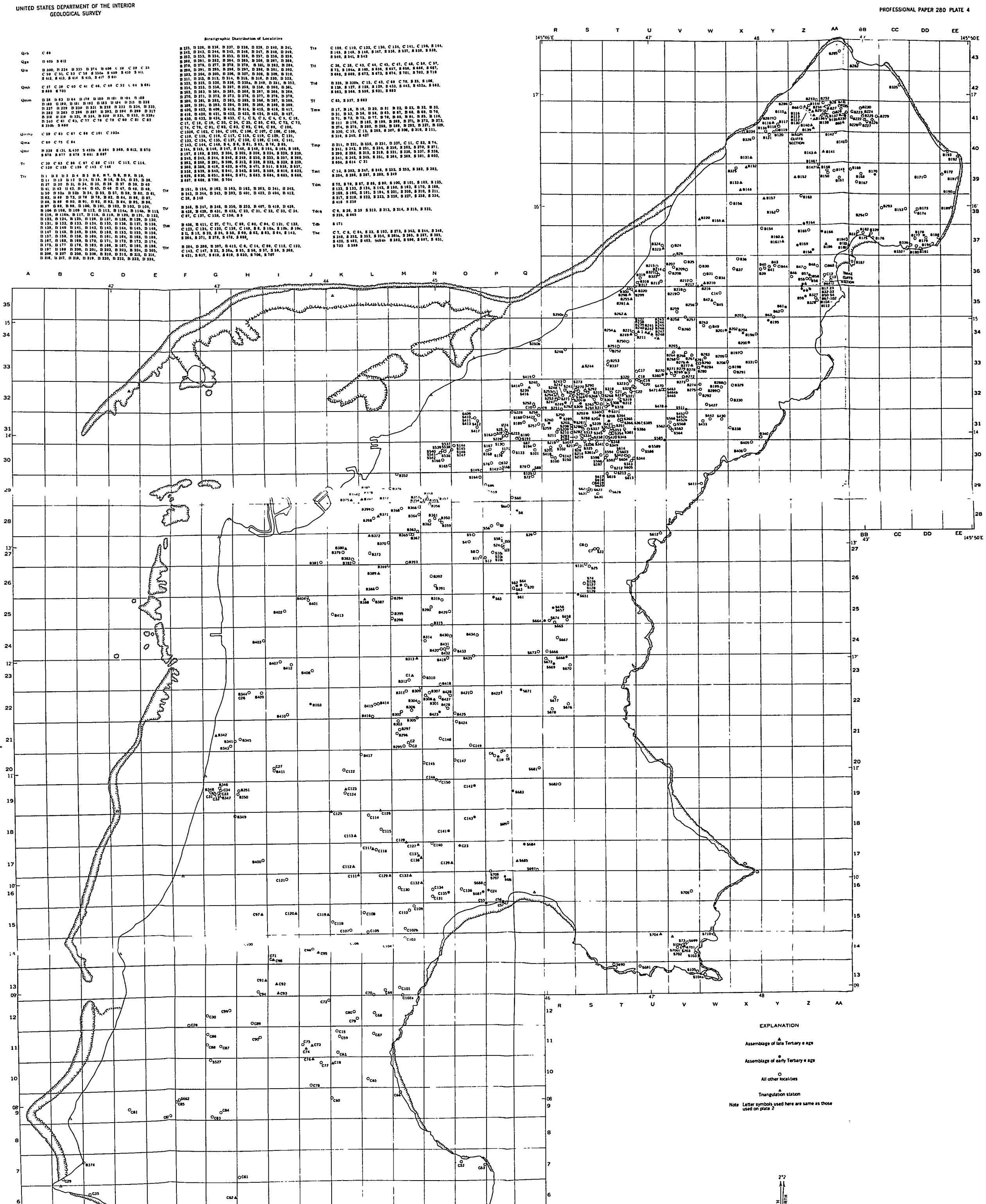
Contour interval 100 feet
Datum is mean sea level

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

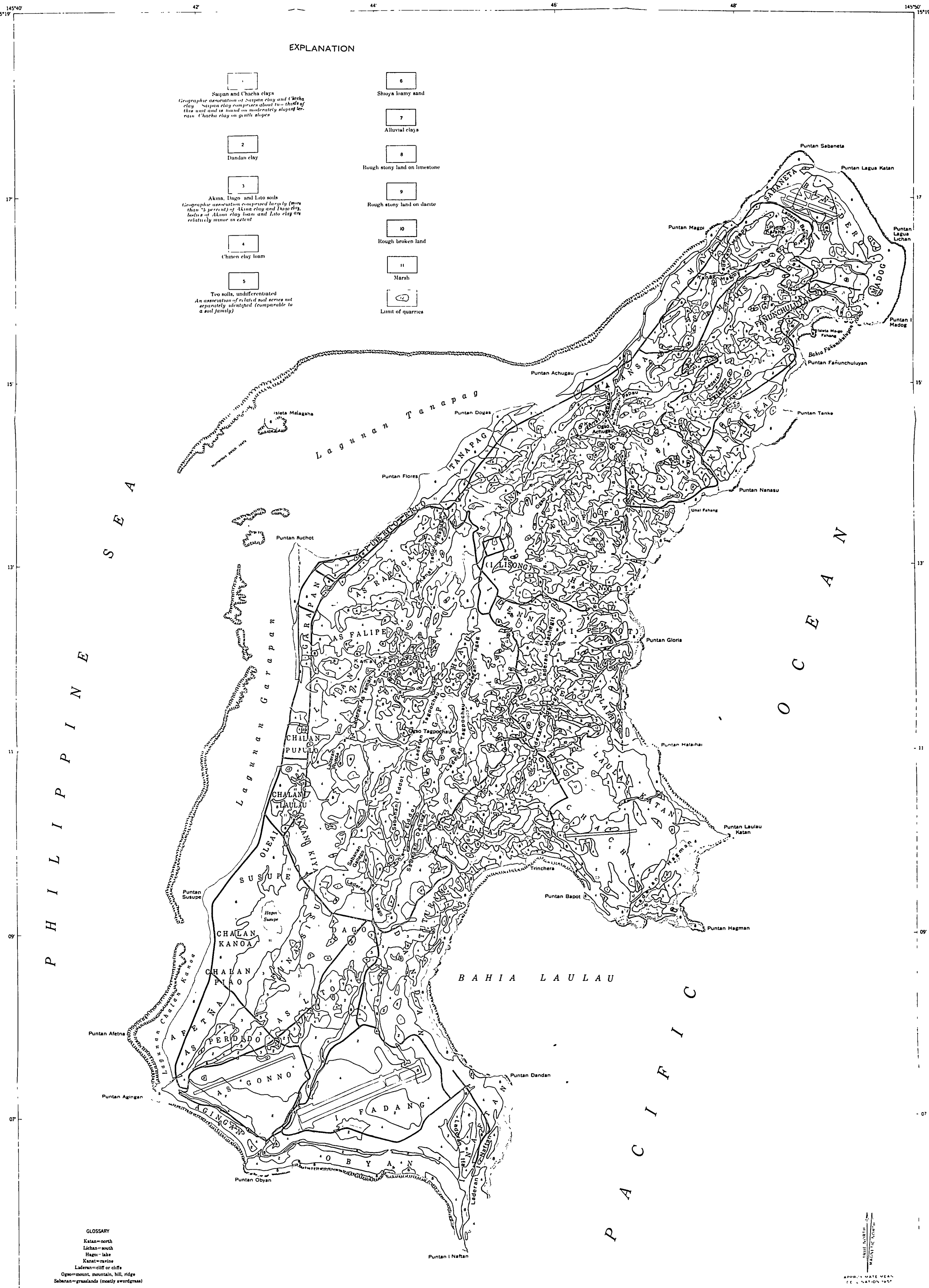
PROFESSIONAL PAPER 280 PLATE 4

Stratigraphic Distribution of Localities

LOCALITY LIST



FOSSIL LOCALITY FINDING MAP FOR SAIPAN, MARIANA ISLANDS



GENERALIZED SOIL MAP OF SAIPAN, MARIANA ISLANDS

Scale 1:36,000

Contour interval 100 feet
Datum is mean sea level