Petrology of the Volcanic Rocks of Guam

GEOLOGICAL SURVEY PROFESSIONAL PAPER 403-C

U.S. DEPARTMENT OF THE INTERIOR

March 3, 1849

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By JOHN T. STARK

With a section on

TRACE ELEMENTS IN THE VOLCANIC ROCKS OF GUAM

By JOSHUA I. TRACEY, JR., *and* JOHN T. STARK

GEOLOGY AND HYDROLOGY OF GUAM, MARIANA ISLANDS

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A study of the basaltic and andesitic volcanic rocks of Guam and their relations to similar rocks of Saipan and Japan

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By John T. Stark

ABSTRACT

The volcanic rocks of Guam consist of basaltic and andesitic lava flows and dikes and pyroclastic deposits of similar composition. They are predominantly continental and belong to the circumpacific province; they show close affinities to the volcanic rocks of the nearby island of Saipan and to the Izu Peninsula of Japan. A classification after Kuno, according to color index of the groundmass, shows the Guam lavas to be about 45 percent mafic andesite, 10 percent medium andesite, and 45 percent basalt and olivine basalt. Both andesite and basalt have hypersthene-bearing varieties.

Chemical compositions and norms of major rock types are given and are plotted in variation diagrams to show the close affinity of the rocks of Guam with those of Saipan and the Izu Peninsula of Japan; they are also compared with those of the Hawaiian Islands and with Daly's average rock types. On a triangular MgO-FeO-alkali diagram, the variation trend for the rocks of Guam follows closely the variation trend for Kuno's hypersthenic rock series of Japan.

The Eocene and Oligocene, and the Miocene volcanic rocks of Guam originate from separate volcanic vents west and southwest of the island. Variations in the trace elements in these rocks suggest two differentiation series, one of Eocene and Oligocene age, and the other of Miocene age.

INTRODUCTION

This report on the petrology of the volcanic rocks of Guam is based on fieldwork which began in June 1952 and concluded in October 1954, as a part of the Pacific Geological Mapping Program of the U.S. Geological Survey and Corps of Engineers of the U.S. Army.

The island of Guam is the southernmost of the Mariana Islands, which extend from lat 13° to about 21° N. and between long 145° and 146° E. (fig. 1). Guam is 31 miles long and has an area of approximately 212 square miles.

ACKNOWLEDGMENTS

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OUTLINE OF GEOLOGY

The volcanic rocks of Guam (pl. 1, Tracey and others, 1963) are extensively exposed in the southern half of the island, where there are only subordinate outcrops of limestone. The volcanic rocks consist of Eocene, Oligocene, and Miocene flows, dikes, and pyroclastic deposits. The northern half of Guam is a plateau of Miocene to Recent limestone through which volcanic rocks are exposed in three small inliers—Mount Santa Rosa, Mataguac Hill, and Palia Hill. No subaerial volcanic rocks have been recognized anywhere on the island; the flows and pyroclastic rocks appear to be wholly of submarine origin. The breccias and the tuffaceous shales and sandstones are generally well stratified, and blocks in some beds are rounded to cobbles and boulders by water action. Foraminifera and Radiolaria are common in the tuffaceous shales and sandstones and in the fine-grained matrix of the pyroclastic breccias and conglomerates.

The stratigraphic sequence of the volcanic rocks on Guam is as follows:

- Tertiary *e* (Miocene).
  - Umatac Formation:
    - Dandan Flow Member
    - Bolanos Pyroclastic Member
    - Maemong Limestone Member
    - Facpi Volcanic Member
  - Unconformity.
- Tertiary *b* and *c* (Eocene and Oligocene).
  - Alutom Formation:
    - Mahlac Member

The Alutom Formation is dominantly tuffaceous shales and sandstones interbedded with mafic lava flows and many lensing conglomerate and breccia beds composed of cobbles and blocks of basalt and andesite. The Mahlac Member is a calcareous foraminiferal shale that has a maximum known thickness of 200 feet. The outcrop thickness of the Alutom Formation is estimated to be 2,000 to 3,000 feet.

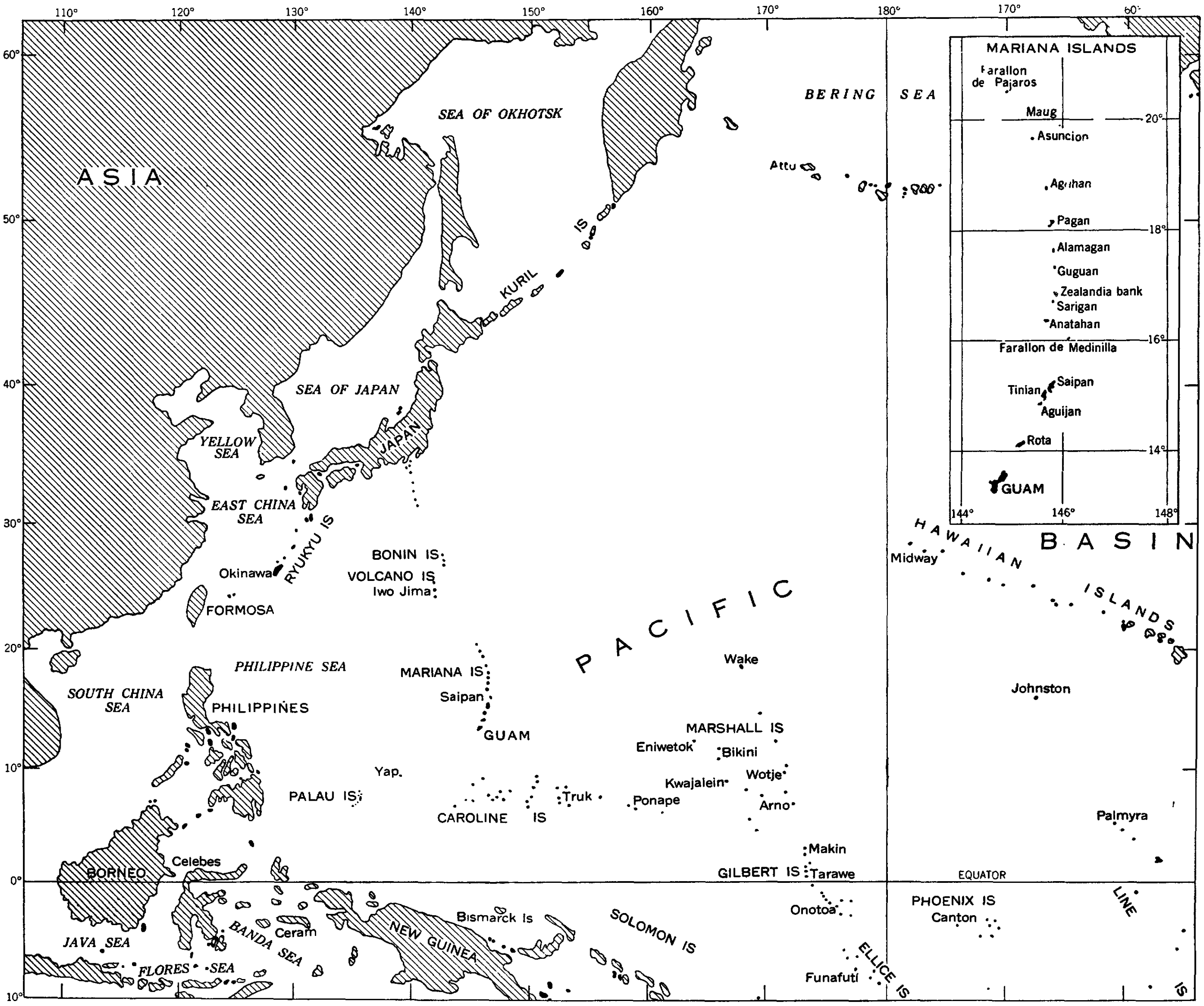


FIGURE 1.—Index map of western north Pacific Islands.

The Umatac Formation consists of four distinct members. At the base is the Facpi Volcanic Member of pillow lavas, which are interbedded with increasing amounts of pyroclastics near the top. The Maemong Limestone Member, which is gradational into tuffaceous shales and sandstone, forms tongues within the Facpi. The Bolanos Pyroclastic Member is a water-laid deposit of tuff breccia and conglomerate interbedded with a few lava flows. It is overlain by the Dandan Flow Member, composed of basalt and andesite flows, and beds of coarse water-laid pyroclastics. The Umatac Formation is about 2,200 feet thick.

A profound unconformity separates the Alutom Formation of Eocene and Oligocene age from the overlying volcanic rocks of Miocene age. Both series have been affected by gentle tilting and numerous faults. The Eocene volcanic rocks have been locally intensively distorted by slumping and gravitational sliding. Some outcrops, ranging from a few yards to several acres in extent, are such a confused jumble of segments of pyroclastic beds and blocks of lava rock that subsidiary centers of explosive and extrusive volcanism are suggested.

CLASSIFICATION OF THE VOLCANIC ROCKS

Guam lies just west of the Andesite Line, which marks the transition zone, structural and physiographic, between the andesite-rhyolite kindred of the Pacific Margin (the circumpacific province) and the olivine basalt-trachyte association of the island groups within the Pacific Basin (the intrapacific province); (Turner and Verhoogen, 1951, p. 124). The volcanic rocks of Guam show some affinities with the rocks of both provinces, but they are predominantly continental and closely resemble the rocks of the Hakone Volcano and adjacent areas of Japan described by Kuno (1950).

A classification of the igneous rocks on the basis of the average composition of the modal feldspar, as used by Macdonald (1949, p. 154) for the rocks of the Hawaiian Islands would restrict all but a small percentage of the dikes and lava flows on Guam to basalt and olivine basalt. Less than 15 percent of the rocks now exposed have a sufficient amount of andesine to be called andesites. These few rocks would be called basaltic andesites, following Macdonald, because of their resemblance in habit and mafic minerals to the basalts. In none of the basaltic rocks is the percentage of feldspar low enough to be equivalent to the picrite basalts of the Hawaiian petrographic province. Typical trachytes and feldspathoid-bearing rocks have not been found on Guam.

A classification after Kuno (1950, p. 958) according to the color of the groundmass, "namely the sum of the normative femic minerals Wo+En+Il+Hm as calculated from the groundmass composition," would include many of the rocks of Guam in mafic and medium andesite and fewer in basalt. About 45 percent of the specimens studied under this classification are mafic andesites, 10 percent are medium andesites, and 45 percent are basalts and olivine basalts. Silicic or sodic andesites are represented by only a few blocks in volcanic breccia.

Schmidt classified the igneous rocks of Saipan (1957, p. 131–132) "primarily on the basis of the sum of their modal and (or) normative femic minerals (pyroxene, hornblende, magnetite, ilmenite, and hematite)"; and secondarily on the average composition of the modal feldspar. Where the modal composition was not available 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). In the absence of chemical analyses, the rocks were classified on the basis of comparison to analyzed rocks. This, in general, accords with Kuno's classification. As the mafic rocks of Saipan appear to be closely related to the andesites and basalts of Guam, this classification has been generally followed. The Guam rocks are almost wholly mafic or calcic andesites, basalts, and olivine basalts.

The only rocks on Guam which approach the dacitic rocks of Saipan in modal composition are quartz-bearing blocks from a volcanic conglomerate that crops out on the southeast slope of Mount Santa Rosa. Similar quartz-bearing rocks were described by Risaburo Tayama (1941) as occurring in gravels along the Fena River in southern Guam. This area is now flooded, owing to impounding of river water by the Fena dam. That such dacitic rocks did form a part of the volcanic pile on Guam and are now largely eroded is suggested by the quartz-bearing blocks in the conglomerate on Mount Santa Rosa. Kuno called them andesites with quartz xenocrysts (oral communication, 1954), but even though the quartz-bearing blocks are the result of contamination, the quartz xenocrysts must have been derived from a rock containing primary quartz.

In connection with the classification of the volcanic rocks of Guam, the chemical analyses (table 1) show an interesting contrast between the silica content of bedrock outcrops of flows and dikes and the silica content of residual boulders in highly weathered pyroclastic beds presumably derived from the same magmas as the mafic flows. (Locations of samples are shown in figure 2.) The bedrock outcrops average 51.19 percent, and the boulders average 60.56 percent silica. The number of analyses may be too few for this difference to have any significance. However, the question is raised as to whether there has been secondary addition of silica to the mafic boulders of the pyroclastic beds.

Veins of chalcedony and quartz are conspicuous in many areas, and open spaces are commonly lined with quartz crystals. The fine-grained volcanic tuffs in the Mount Tenjo and Mount Alutom areas have hardened in many places by silicification following brecciation, and in other outcrops hardening by silica occurs where no brecciation is evident. Analyses of the boulders were from hand specimens of seemingly fresh rock taken well below the altered periphery. Thin sections of the boulders show evidence of secondary silicification, and pore spaces are lined with chalcedony and quartz. In a classification of rocks based partly on their normative composition this possible contamination by secondary quartz is of considerable importance.

Macdonald (oral communication, 1957) suggests that the pyroclastics in general may represent the early, more explosive parts of eruptions, derived from the upper gas-rich and silica-rich portion of the magma column, whereas the flows probably came in large part from a lower portion of the magma column that was poorer in silica. This decrease in silica through the course of eruption is known in several instances—for example, the 1948 eruption of Hekla and the 1955 eruption of Kilauea.

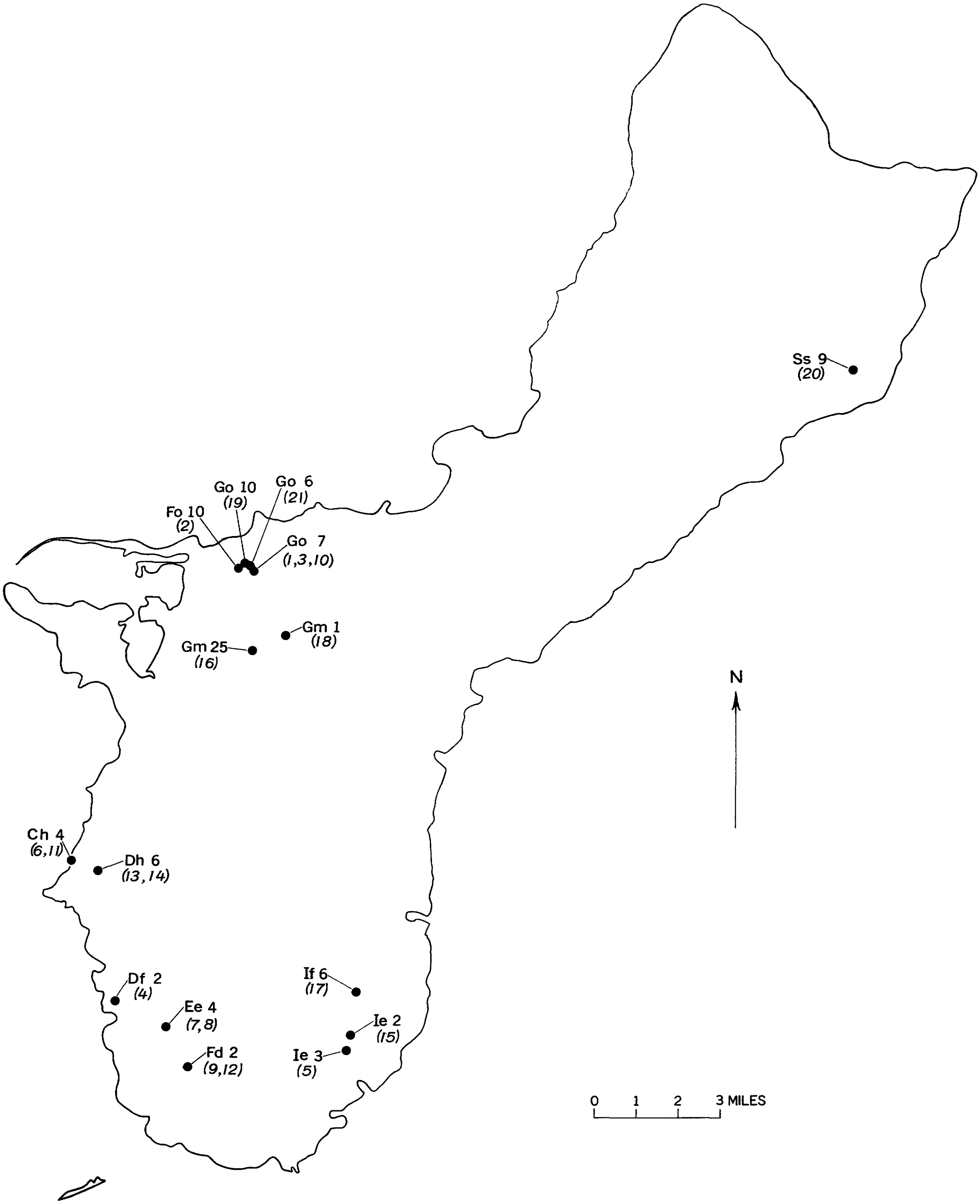


FIGURE 2.—Location of analyzed specimens. Vertical letters and numbers refer to field locality numbers; inclined numbers refer to analyses (tables 2–4).

MINERALOGY

The essential minerals of the volcanic rocks of Guam are relatively few: plagioclase, pyroxene, olivine, and quartz. Primary accessory minerals are magnetite, hematite(?), hornblende, biotite, and an alkali feldspar. Silica minerals—quartz, chalcedony, tridymite, cristobalite, and opal—are conspicuous in cavities and interstitial in the fine-grain groundmass as late crystallizations and replacements. Secondary and alteration minerals are chlorite, serpentine, calcite, pyroxene, zeolites, quartz, chalcedony, iron oxides, and clay minerals.

PLAGIOCLASE FELDSPAR

The plagioclase feldspars are present in all the volcanic rocks as phenocrysts and as small grains in the groundmass. The proportion of phenocrysts ranges from a few widely scattered crystals to 50 percent of the rock. The total plagioclase averages between 50 and 60 percent. Phenocrysts are less numerous in the very fine grained rocks. Most of the plagioclase is labradorite, averaging around An_{55}, but there is a range from bytownite (An_{75}) in the youngest (Dandan) flows to andesine and oligoclase (An_{20}) in the sodic andesite. Broad twinning bands, zoning, and dust inclusions are characteristic of both the phenocrysts and small grains of the groundmass. Zoning is especially well developed in the Dandan Flow Member of Miocene age, and in blocks of lava in volcanic water-laid breccias of the Alutom Formation of Eocene and Oligocene age. Centers of the zoned crystals are generally slightly more calcic than the peripheral zones. However, reversals were noted in which the composition changed outward from calcic labradorite to slightly more sodic labradorite, to an outer rim of calcic labradorite. In only a few crystals does bytownite form the central core.

Zones of small dustlike inclusions of pyroxene and iron ore parallel borders of the phenocrysts, forming clouded areas between clear centers and clear outer rims. In other crystals the centers are filled with small inclusions surrounded by clear labradorite. Some phenocrysts are clouded throughout by small dustlike inclusions. These inclusions appear similar in every way to inclusions in the plagioclase phenocrysts of the volcanic rocks of the Hakone Volcano (Kuno, 1950, p. 967–968).

Kuno explains these finely divided particles of pyroxene and iron ore, with or without glass, as having

> **formed in plagioclase enclosed by a magma in equilibrium with more calcic plagioclase. The dust originated by partial crystallization of liquid particles formed by incipient melting of xenocrystic plagioclase along its cleavages. A part of the liquid particles was introduced from magma outside by diffusion.**

The extreme fracturing and fragmentation of many of the large dust-filled plagioclase crystals would appear to support the interpretation that they may be xenocrysts rather than phenocrysts. Such fracturing is strikingly well developed in the basalt boulders and blocks in the volcanic breccia of the Dandan Flow Member of the Umatac Formation. It should be noted, however, that the occurrence of inclusion-filled and "moth-eaten" feldspar is so common as to be characteristic of calc-alkaline andesite provinces (Macdonald, written communication, 1957).

The plagioclase crystals in the rocks of Guam show all degrees of alteration. Completely euhedral crystals are rare. The outer edges of many plagioclase grains are extremely irregular from resorption embayments and fracturing. Glomeroporphyritic clusters and fragments of crystals are extremely common. Calcite is conspicuous in the saussuritization of the plagioclase.

ALKALI FELDSPAR

The presence of alkali feldspar, probably anorthoclase, is suggested by the occurrence in the fine-grained groundmass of very small areas of clear to clouded feldspar with an index of refraction distinctly lower than that of adjacent plagioclase. The material is interstitial, irregular, or shows faint rectangular outlines. In a few slides examined by Kuno (oral communication, 1954) these were identified as probable anorthoclase. The amount is not large and it occurs more commonly in the andesites of medium to sodic composition, but it is present also in some basalts. A check on the presence of alkali feldspar was made on a number of the Guam rocks by staining thin sections and rock chips after the method described by Chayes (1952). Corroboration of alkali feldspar in some of the andesites was obtained, but the amount is extremely low, probably less than 0.01 percent.

PYROXENE

Monoclinic pyroxene is second only to plagioclase as a primary constituent of the volcanic rocks of Guam. It occurs abundantly as phenocrysts and small crystals interstitial to plagioclase in the fine-grained groundmass. It is generally present in all the igneous rocks and averages from 25 to 35 percent of all thin sections. The pyroxene is predominantly augite, occurs in euhedral crystals, and ranges from very fine grains in the groundmass to phenocrysts as large as 8 mm, although more commonly they are less than 2 mm. Elongation parallel to the *c* axis is general, although all variations occur from slender prisms to stout crystals. Glomeroporphyritic clusters of small phenocrysts and clusters of fragments of larger crystals that are especially prominent in many specimens perhaps suggest shattering of the large augite crystals when the lava was extruded and the floating together of the fragments before solidification. Twinning on the 100 plane and polysynthetic twinning on the 001 plane are fairly common. Some phenocrysts show a wavy extinction, and others have an hourglass structure. Maximum extinction angles are generally low, averaging around 40°.

Hypersthene is associated with augite, and in places they are intergrown. The orthorhombic pyroxene is prominent in basalt lava flows of the Alutom Formation at Mount Santa Rosa and near Mount Alutom at Sasa, and is present in the basaltic flows of the Umatac Formation near Facpi Point. In a few flows of the Dandan Member it forms as much as 10 percent of the rock. The hypersthene occurs both as large platy phenocrysts and as small grains in the groundmass. Pleochroism is generally very faint in pale tints of pink and green. The negative optic sign and parallel extinction readily distinguish it from augite. Hypersthene also occurs as small crystals in reaction coronas surrounding fibrous pseudomorphs of serpentine and chlorite after olivine and monoclinic pyroxene. These small crystals are prismatic in habit, optically negative, and show parallel extinction.

OLIVINE

Fresh euhedral olivine occurs in only a few of the volcanic rocks of Guam, but its former presence is indicated in many of the basalts by fibrous pseudomorphs of serpentine which retain the outlines of original olivine crystals. In some thin sections small relict centers of fresh olivine are surrounded by fibrous areas of serpentine and associated chlorite, pyroxene, calcite, and magnetite, which fill in euhedral outlines of the original olivine phenocrysts. The serpentine is largely antigorite and is by far the most abundant alteration product. Calcite is rarely absent from the alteration areas. Other pseudomorphs after olivine consist of cores of serpentine and calcite and have peripheral zones of granular and vermicular magnetite surrounded by an outer zone of small randomly oriented crystals of augite and hypersthene. Films of chlorite and yellowish-green serpentine, due to reaction or weathering, fill joint fractures and form zones around the pseudomorphs. In many rocks the olivine crystals are stained by dark brownish-red iron oxide, and the crystal borders are altered to iddingsite.

Beach sands which border cliffs of basaltic lava in southwest Guam contain numerous fresh olivine grains that apparently are residual from weathering of the lava flows. However, specimens from nearby flows show only extremely small amounts of fresh olivine.

Olivine is most common in the olivine basalt of the Facpi Volcanic Member of the Umatac Formation, but it is represented by serpentine pseudomorphs in both the earlier Alutom Formation and the later flows of the Dandan Member.

SILICA MINERALS

Quartz grains, resembling phenocrysts in hand specimens, occur in andesitic blocks and boulders of water-laid pyroclastic conglomerate and breccia of the Alutom Formation on the southeast slopes of Mount Santa Rosa and in the Nimitz Hill area. The quartz crystals range in diameter from a fraction of a millimeter to 3 mm. Under the microscope they show rounded resorption edges and embayments. They are associated with highly shattered dust-filled fragments of plagioclase. Professor Kuno examined thin sections of the quartz-bearing rocks and interpreted the quartz grains as xenocrysts in a groundmass of andesite. The total pyroxene content was too high for the rock to be called dacite under his classification (Kuno, 1950, p. 958).

The quartz grains are more abundant in the vicinity of Mount Santa Rosa than at Nimitz Hill, but at both places they occur in sodic andesite boulders. Near Mount Santa Rosa a few small doubly terminated quartz prisms, from 2 to 3 mm long, were found in a sandy tuffaceous bed. Similar crystals were collected from tuffaceous sandstone talus about 1 mile east of Nimitz Hill. Under the microscope the quartz prisms are relatively free from inclusions and appear to be erosion relicts from a rock containing true phenocrysts of primary quartz. It is possible that they originated from dustfalls or represent erosion relicts from a dacite porphyry similar to those on Saipan described by Schmidt (1957, p. 139–141). The quartz-bearing blocks and boulders of Mount Santa Rosa and Nimitz Hill may have been contaminated by such relict quartz crystals.

Chalcedony, tridymite, and cristobalite occur in the groundmass of many of the basalts and andesites. Only chalcedony is abundant, and much of it is clearly late fillings of small pores, vesicles, and fractures. Cristobalite, commonly as slender rods, and tridymite, rudely wedge-shaped in outline, occur interstitially in the fine-grained groundmass and probably were formed during a late stage of crystallization rather than being introduced by pneumatolytic or hydrothermal processes, as Kuno has suggested for volcanic rocks of the Hakone area (1950, p. 969). Veins of chalcedony and quartz commonly fill fractures and vesicles in flows and dikes and are probably partly of hydrothermal origin. Veins of these silica minerals, ranging in width from a fraction of an inch to 5 inches, transect the pyroclastic tuffs, sandstones, and conglomerates. They commonly withstand erosion and form tabular ridges a few inches high and several yards in length. Chalcedony is particularly abundant in the groundmass of the fine-grained and glassy flows.

Volcanic tuffs near Tenjo and Alutom peaks have been hardened in many places by silicification, following brecciation. Shear zones thus cemented by chalcedony and quartz are easily recognized by the greenish color that commonly accompanies the silicification. Wider areas of light green tuffs where silicification has occurred show no evidence of having been brecciated following deposition. Small amounts of opal are associated with secondary quartz and chalcedony in the weathered zones of these light-green tuffs.

IRON ORES

Magnetite is an accessory mineral in all the volcanic rocks of Guam. The amount ranges from a few extremely small widely scattered grains in the groundmass of sodic andesite blocks of Eocene age on Mount Santa Rosa to as much as 6 percent of the Dandan flows of Miocene age. The magnetite occurs in small irregular grains interstitial in the groundmass, as small octahedra in the groundmass, as poikilitic inclusions in larger crystals of plagioclase and pyroxene, and less commonly as euhedral grains one-half millimeter in diameter in the groundmass. Small grains, associated with other reaction minerals, also occur in peripheral zones around fibrous pseudomorphs after olivine and pyroxene. In a few thin sections, rods and ladderlike growths of magnetite appear to have developed later than the groundmass grains.

Hematite in some basalt specimens appears to be primary, but generally it is an alteration product after other iron-bearing minerals. It commonly forms rims around magnetite. Ilmenite was not recognized as a separate mineral. The presence of titanium in very small amount is shown in the chemical analyses, and it is probably incorporated in the magnetite.

BIOTITE

Rods and flakes of biotite, rarely more than a quarter of a millimeter in length, occur in fine-grained foraminiferal tuffs of the Alutom Formation. The biotite is associated with hornblende in some of the tuffaceous beds, which are now largely altered to clay. The small biotite rods and flakes show pleochroism, parallel extinction, and negative optic sign typical of biotite. Biotite was recognized only in one or two thin sections from the dikes and flows.

HORNBLENDE

A few widely scattered grains of green hornblende are associated with abundant calcite and a few rods of biotite in foraminiferal tuffs of Eocene age in the vicinity of Mount Alutom. The grains are generally fragments of larger crystals and appear to be derived from the explosive brecciation of a rock containing hornblende phenocrysts. A few euhedral basal sections are diamond shaped and show the characteristic intersecting prismatic cleavages. Elongated fragments parallel to c show a faint pleochroism and maximum extinction angles between 12° and 25°.

The only other hornblende observed was in quartz-bearing blocks of sodic andesite in volcanic conglomerate on Mount Santa Rosa. The hornblende there is similar to that in the Alutom Formation. The total amount of hornblende in the specimens studied is extremely small, probably less than 0.01 percent of the rocks now exposed.

APATITE

Apatite occurs in minor amounts as small acicular crystals in olivine basalts.

IDDINGSITE

Iddingsite occurs as alteration rims around the pseudomorphs of serpentine from primary olivine crystals.

SERPENTINE

Few of the volcanic rocks of Guam are free from weathering, and serpentine is generally present as an alteration product of olivine and pyroxene. In many places the original crystals are completely changed to pseudomorphs of fibrous antigorite. In other specimens greenish-yellow serpentine forms alteration borders around olivine and pyroxene grains. Incipient alteration penetrates along fractures, and all degrees of serpentinization occur. Commonly, small centers of original pyroxene and olivine grains are all that remain unaltered in thin sections.

CALCITE

Calcite is present in most of the volcanic rocks of Guam. It occurs as vesicle and fracture fillings, as an alteration product of olivine and pyroxene in association with serpentine, and as a product of the saussuritization of plagioclase. Dark-green extremely fine grained tuffaceous material cemented by calcite commonly fills spaces between ellipsoids in pillow lavas. Many surface outcrops of flows and dikes are intimately traversed by a stockwork of calcite veinlets.

ZEOLITES

Zeolites are abundant as vesicle and fracture fillings and as replacement veinlets in many exposures of flows and dikes. They are especially conspicuous in the Facpi Volcanic Member, which forms the sea cliffs between Umatac and Facpi Point. In places, zeolites constitute about 5 percent of the outcrop. Zeolite amygdules, ranging from extremely small pellets to grains one-half inch in diameter give a white spotted appearance to many exposures. Radiating clusters as large as 2 inches in diameter and intricate stockworks of small veinlets are characteristic. The most abundant zeolites are analcite, natrolite, chabyzite, and heulandite. All are closely associated with calcite.

CLAY MINERALS

Deep weathering and the formation of clay materials characterizes most exposures of the volcanic rocks (Carroll and Hathaway, 1963). Halloysite, montmorillonite, and gibbsite are commonly present and are intimately associated with hematite and goethite.

ROCK TYPES

The volcanic rocks of Guam consist of lava flows, dikes, and pyroclastic beds formed of the following types: olivine basalt, basalt, hypersthene-bearing basalt, sodic to calcic andesite, and hypersthene-bearing andesite. In two small areas, Mount Santa Rosa and Nimitz Hill, blocks in the pyroclastic beds have a silica content which places them within a type between sodic andesite and dacite. However, because the quartz grains in these blocks are believed to be xenocrysts rather than phenocrysts, the rocks are classed as sodic andesites.

Rocks with labradorite and augite as essential minerals are by far the most abundant on the island. The weathering and alteration of the exposed rocks are generally so intense that many flows, now called basalts because no olivine is recognizable, originally may have been olivine basalts. Other flows contained olivine as a primary constitutent, as indicated by small relict grains of fresh olivine and fibrous pseudomorphs of serpentine, chlorite, and calcite which show orthorhombic crystal outlines. Many flows are so completely weathered that no euhedral outlines of olivine (if ever present) are preserved. The abundance of olivine grains in sands bordering cliffs of highly weathered basaltic lavas also suggests that olivine basalts are important on the island.

The ratio of basaltic to andesitic rocks, based on specimens studied, is approximately 45:55. Calcic andesite predominates greatly over sodic andesite. The tuffaceous shales and sandstones and the coarser pyroclastics are of the same general composition as the flows and dikes. A summary of the principal rock types is given in table 1.

OLIVINE BASALT

Olivine basalts are found in both the Alutom and Umatac Formations, especially in the Facpi Volcanic Member of the Umatac. Textures of the olivine basalts are intergranular to intersertal, generally porphyritic, with traces of ophitic and subophitic textures commonly preserved. Glomerporphyritic clusters of crystals and fragments of crystals are conspicuous in many flows. The olivine basalts range in color from black when fresh to shades of gray, brown, and red when weathered. Many flows weathered to soft claylike material show a characteristic light mauve tint. Fresh olivine is rare and is preserved only in relic grains less than 0.02 mm in diameter, surrounded by fibrous serpentine (largely antigorite), chlorite, and calcite. In some flows the relict olivine grains are enclosed in opaque areas of hematite and have thin rims of iddingsite. Pseudomorphs of serpentine and chlorite as much as 5 mm in length have been observed. Phenocrysts of plagioclase (An_{50-70}) are much more abundant than the olivine, form as much as 40 percent of some specimens, and range in length from 0.5 to 2 mm. They are commonly fractured, altered, and show deep resorption embayments. Many show zoning, with cores of slightly more calcic composition than the peripheral rims.

Pyroxene in the olivine basalts is chiefly augite, although small amounts of hypersthene are closely associated with the augite. The pyroxene phenocrysts are subordinate to plagioclase and, like them, show fracture, resorption embayments, and are for the most part altered. They are generally smaller than the plagioclase, and form glomeroporphyritic clusters as well as individual phenocrysts as much as 1.5 mm in length. Magnetite is always present and averages between 2 and 3 percent of the rock. It occurs as small octahedra, elongated rods, and irregular grains, and is commonly oxidized to hematite and limonite. Small amounts of apatite in acicular needles are enclosed in other minerals.

In general, the groundmass is fine grained and contains as much as 20 percent interstitial glass. The intergranular texture of the groundmass gives way in a number of flows to ophitic and subophitic texture. Hyalopilitic texture occurs near edges of dikes and flows. Glassy rims are prominent around ellipsoidal structures of the pillow lavas. The plagioclase of the groundmass is generally labradorite (An_{50-65}), less calcic than the plagioclase phenocrysts. Monoclinic pyroxene forms 25 to 40 percent of the groundmass.

TABLE 1.—*Description of principal volcanic rock types of Guam*

Rock types	Composition	
	Phenocrysts	Groundmass
Olivine basalt	Olivine, 0–15 percent, 1–5 mm long, partly altered to serpentine and chlorite with only small relict grains of fresh olivine. Plagioclase, 0–40 percent, 0.5–2 mm long, zoned An_{50-70}, much fractured and altered, glomeroporphyritic clusters. Augite, 0–25 percent, 0.5–1.5 mm long, partly altered.	Plagioclase (An_{50-65}), 30–55 percent. Olivine, 1–13 percent, partly altered to serpentine and chlorite. Augite, 25–40 percent, altered. Magnetite, 1–4 percent, oxidation rims to hematite and limonite. Apatite, acicular needles enclosed in other minerals. Glass, interstitial as much as 20 percent, selvages around pillows and chilled borders of dikes.
Basalt	Olivine, 0–5 percent, 1–4 mm long, pseudomorphs of serpentine and chlorite show euhedral outlines of primary olivine. Plagioclase, 0–35 percent, 1–5 mm long, partly altered, deep resorption embayments. Augite, 0–20 percent, 1–3 mm long, glomeroporphyritic clusters, partly altered, resorption embayments.	Plagioclase (An_{50-70}) 35–60 percent. Olivine, 0–5 percent, almost completely altered to serpentine and chlorite; Iddingsite rims. Augite, 25–40 percent. Quartz xenocrysts, rare. Biotite and Hornblende, rare. Hypersthene, 0–5 percent. Magnetite, 1–12 percent. Alkali feldspar, small amount. Glass, interstitial as much as 30 percent, chilled contacts.
Hypersthene-bearing basalt.	Olivine, 0–12 percent, partly altered to serpentine and chlorite. Plagioclase, 0–50 percent, 0.5–5 mm long. Augite, 0–20 percent, 1–4 mm long, for the most part altered. Hypersthene, 0–5 percent, 0.5–5 mm long, broken, altered, resorption embayments, glomeroporphyritic clusters.	Plagioclase (An_{50-70}), 35–45 percent. Olivine, 0–3 percent, almost completely altered to serpentine and chlorite. Augite, 10–15 percent, for the most part altered. Hypersthene, 5–20 percent, fresh flakes to altered. Magnetite, 1–9 percent, small octahedra, irregular grains, and elongated rods. Glass, 1–20 percent, interstitial.
Andesite	Olivine, rare, almost completely altered. Plagioclase, 0–20 percent, 1–8 mm long. Augite, 10–20 percent, 1–5 mm long. Hypersthene, scarce. Hornblende, rare <0.1 percent.	Plagioclase (An_{25-50}), 40–60 percent. Olivine, traces. Augite, 15–35 percent. Hypersthene, 0–5 percent, associated with augite and in alteration rims of olivine. Alkali feldspar, small amount. Magnetite, 1–8 percent. Hornblende, rare. Glass, 0–15 percent, interstitial.
Hypersthene-bearing andesite.	Olivine, rare, almost completely altered to serpentine. Plagioclase, 0–40 percent, 1–6 mm long. Augite, 5–20 percent, mostly altered. Hypersthene, 0–5 percent, 1–5 mm long.	Plagioclase (An_{30-55}). Olivine, traces. Alkali feldspar, small amount, interstitial. Augite, 25–30 percent, 1–4 mm long. Hypersthene, 5–10 percent. Magnetite, 2–6 percent.

Pigeonite, common in the olivine basalts of Hawaii (Macdonald, 1949, p. 1545) was looked for, but it could not be identified conclusively, as the optic angles measured were too high. Norms of the rocks of Guam show a range of about En_{59}-to-En_{65} (fig. 15), and with this composition it is doubtful that any of the augite is pigeonite. A few flakes of hypersthene occur in the groundmass.

BASALT

The basalts of Guam differ from the olivine basalts chiefly in having less than 5 percent recognizable olivine. Basalts are found in flows and relict boulders of the Alutom and Umatac Formations. The textures of the basalts range from porphyritic to nonporphyritic and commonly show traces of ophitic and subophitic patterns. Extremely small vesicules characterize many of the fine-grained basalts and extend throughout some of the dikes and flows. Interstitial glass is abundant in most flows and ranges from 0 to 30 percent. The phenocrysts are dominantly of labradorite (An_{50-70}), range from 0 to 35 percent of the rock, and show much fracturing, resorption embayments, and saussuritization. Labradorite forms 35 to 60 percent of the groundmass. The abundance of serpentine and chlorite in the groundmass suggests that olivine may have been present in greater amount, but pseudomorphs with euhedral outlines are missing. Small amounts of interstitial alkali feldspar (anorthoclase?) are present. Monoclinic pyroxene, predominantly augite, forms as much as 20 percent of the phenocrysts and 40 percent of the groundmass. Hypersthene forms 0 to 5 percent of the groundmass and is generally closely associated with augite. Xenocrysts of quartz occur rarely in basalt blocks in the coarser pyroclastics. Both hornblende and biotite are extremely rare. In a few thin sections small flakes and narrow rods of brown biotite were observed. In one thin section small prismatic and basal flakes of green hornblende showed characteristic pleochroism and cleavage. Similar flakes of hornblende occur in some of the tuffaceous shales and sandstones.

HYPERSTHENE-BEARING BASALT

Hypersthene-bearing basalts are found in flows and relict boulders of the Alutom and Umatac Formations. Many of the basalt flows contain more than 5 percent hypersthene. Phenocrysts of the orthorhombic pyroxene range in length from 0.5 to 5 mm long and show faint pleochroism, parallel extinction, and negative optic character of hypersthene. Hypersthene is intimately associated with augite and commonly occurs with it in glomeroporphyritic clusters. Hypersthene ranges from 5 to 20 percent in the groundmass. Augite is always present and is generally more abundant than the hypersthene. Labradorite (An_{50-70}) averages between 35 and 45 percent of the groundmass. Except for the greater amount of hypersthene, these rocks are generally similar in texture and composition to the other basalts of Guam.

ANDESITE

The andesites of Guam, found in flows and relict boulders of the Alutom and Umatac Formations, range from calcic in which plagioclase is close to An_{50}, to sodic andesite in which the plagioclase is close to the oligoclase boundary. The calcic andesites predominate and grade into the basalts. In general, the andesites are less porphyritic than the basalts, although a few flows contain phenocrysts, as much as 8 mm in length, that form as much as 40 percent of the rock. Some flows have subtrachytic textures. The pyroxene is chiefly augite, which forms 10 to 20 percent of the phenocrysts and 15 to 35 percent of the groundmass. Small irregular grains of alkali feldspar are interstitial in the groundmass. Orthorhombic pyroxene is associated with the augite in amounts less than 5 percent of the groundmass. Magnetite is generally more abundant than in the basalts, ranging from 1 to 8 percent of the groundmass and averaging about 5 percent. The presence of olivine is indicated by traces of relict grains in masses of fibrous serpentine and chlorite. Green hornblende is present in extremely small amounts in a few andesite flows.

HYPERSTHENE-BEARING ANDESITE

In some andesite, found in the flows and boulders of the Dandan Flow Member of the Umatac Formation, the amount of orthorhombic pyroxene averages between 5 and 10 percent of the groundmass; but it is never more than the augite, which ranges from 25 to 30 percent of the groundmass, and forms from 5 to 20 percent of the phenocrysts. Except for the increase in orthorhombic pyroxene, hypersthene-bearing andesites are similar in texture and composition to the other andesites.

PYROCLASTICS

The pyroclastic sedimentary rocks of Guam are composed of fragments of rock and minerals and their weathered products that are similar in texture and composition to the flows and dikes. All these volcanic rocks were deposited under subaqueous conditions. Sedimentary structures and marine organisms in most outcrops leave no doubt as to their submarine origins. In some exposures the field evidence is not conclusive, but in no place has clear evidence been found for subaerial deposition.

WATER-LAID TUFFS AND TUFFACEOUS SHALES

The water-laid tuffs are fine-grained friable to well-indurated pyroclastic deposits of dust-sized particles, presumably derived from submarine explosions. They grade horizontally and vertically into tuffaceous shales and sandstones. Tuffs and shales are predominantly light in color in most outcrops and range from dead white through grays to dark gray. The darker colors are due to slightly coarser grain size and to an increasing amount of dark mineral and rock particles. A light-green color characterizes the tuffs where silica, chalcedony, and quartz have been deposited by circulating waters.

Under the microscope the tuffs and shales show sharply angular particles of volcanic glass, crystal, and rock fragments, which average from 0.2 to 0.5 mm in length. In a few sections some rounding of particles is evident, but angularity is the dominant characteristic. The larger particles are embedded in a matrix of extremely fine grained material that is isotropic or weakly birefringent, according to the degree of alteration and weathering.

Most of the fine-grained pyroclastics are vitric tuffs, which average less than 25 percent crystal fragments (Pettijohn, 1943, fig. 73). These grade into vitric crystal tuffs. Rarely is the original glassy material less than 50 percent, and commonly slides show more than 90 percent of isotropic and opaque groundmass. A few beds, composed almost entirely of rock fragments, are lithic tuffs. None of the outcrops are wholly fresh, and nearly all thin sections show white chalky clouding due to secondary development of clay minerals.

The clastic glassy matrix ranges from almost completely isotropic through stages of alteration, where shards and rock fragments are outlined by thin lines of brightly polarizing material, to completely devitrified glass. The devitrified glass has a greenish appearance suggestive of chlorite. Patchy areas of chalcedonic silica and probably opal are abundant, in both granular "pepper and salt" aggregates and radiating fibrous wedges with gradational boundaries. In other sections the chalcedony forms areas of smaller circular rosettes; these are especially abundant in the glass of rock fragments and as vesicle fillings. Amygdules are commonly banded chalcedony. Fragments of glass show varying degrees of alteration to clay minerals, and chloritic stainings are accompanied by an increase of weakly polarizing lines of birefringence. The formation of chlorite appears intimately connected with the alteration to chalcedony and opaline silica. The zones most highly silicified in outcrop are characteristically green to yellowish green and greenish brown.

In general, the tuffs are too fine grained to show recognizable fossils megascopically, but under the microscope abundant Radiolaria, globigerinid Foraminifera, and algae were observed. In some of the finest grained tuffs they make up as much as 50 percent of thin sections, and they are distributed throughout the tuffs in the Tenjo area. Careful examination of sections from most outcrops of any extent reveal organisms which indicate the marine environment in which the tuffs were deposited.

The crystal fragments of the tuffs are, in general, too small for identification, but the coarser grains are predominantly plagioclase, monoclinic pyroxene, and magnetite. Extremely small amounts of green hornblende and biotite were observed in a few thin sections. Clastic quartz grains form a small portion (less than 0.01 percent) of some tuffs. Quartz amygdules are fairly common. Calcite is present in all the tuffs containing organisms, and in a few outcrops it is abundant and forms calcareous tuffs which grade into limestone beds.

TUFFACEOUS SANDSTONES

The tuffaceous sandstones differ chiefly from the tuffs and tuffaceous shales in being coarser grained and darker in color. They grade laterally and vertically into one another. With an increasing amount of black crystal and rock fragments, the beds become black and cindery and resemble mafic igneous rocks in massive field outcrops. The degree of induration ranges from beds which are easily crumbled in the hand to thoroughly cemented sandstones. As with the tuffs, the more thoroughly silicified sandy beds are green and range from lighter shades where silicification is slight to dark-green flintlike beds.

Most of the pyroclastic sandstones contain less than 25 percent of crystal fragments and are classified as vitric. There is, however, a greater amount of vitric-crystal (25 to 50 percent crystal fragments) and lithic (more than 33 percent of rock fragments) material in the tuffaceous sandstones than in the tuffs and tuffaceous shales. The crystal and rock fragments in the sandstones average between 0.5 and 2.0 mm in length, and they are embedded in a fine-grained clastic matrix of isotropic and opaque devitrified glass and dust particles. All degrees of alteration occur but, in general, the larger fragments are fresher and more easily identified than the commonly highly altered interstitial material.

Many thin sections show the microbreccia pattern of graywacke. In decreasing order of abundance the crystal fragments are plagioclase, pyroxene, and magnetite. Extremely small amounts of biotite and hornblende were noted in a few specimens. Angular fragments and shattered quartz grains are conspicuous in zones of brecciation and silicification. These zones are cut by numerous quartz grains and spotted with small nuclei of quartz. Some of the quartz may be from quartz amygdules of earlier flows involved in explosive action that formed the pyroclastic rock. The prominence of crystal quartz fragments in the silicified and brecciated zones suggests an origin associated with quartz veining. Repeated silicification and brecciation is clearly indicated in outcrops. This is supported by the extreme fracturing and separation of quartz and feldspar fragments in thin sections, showing that the grains were shattered after being incorporated as constituents of the bedded pyroclastics. Silica in the form of chalcedony, granular quartz, and quartz veins is abundant in brecciated zones.

A few small doubly terminated crystals of quartz were collected from loose debris resting on tuffaceous sandstone. The crystals average from 2 to 3 mm in diameter, are clear, and show slight rounding of the edges. Presumably they are weathered from the underlying pyroclastic rocks.

Calcite is present in all the pyroclastic sandstones that are rich in organic remains. It occurs as replacement of tests of Foraminifera, and Radiolaria, in irregular granular masses, and in extremely small grains scattered throughout the rocks.

The lithic fragments show the textures and mineral composition of the volcanic rock types. The interstitial material of the groundmass of the fragments ranges from clear small isotropic grains and shards to opaque mixtures of dusty material and devitrified glass particles. During devitrification the rock particles become greenish with the development of chlorite and chalcedony, and red and brown from oxidation of iron minerals to hematite and limonite. Most thin sections are clouded owing various degrees of alteration to clay minerals.

PYROCLASTIC CONGLOMERATE AND BRECCIA

Pyroclastic conglomerates and breccias are composed of lapilli, cobbles, blocks, and boulders which range in size from a fraction of an inch to several feet in diameter. The fine material of the matrix consists of tuffaceous shale and standstone. The coarse fragments are similar in texture and composition to the volcanic rock types previously described.

CHEMICAL COMPOSITION AND COMPARISON WITH ROCKS OF OTHER AREAS

Chemical composition and norms of the volcanic rocks of Guam are given in table 2. The rocks include 5 andesites and 4 basalts from the Alutom Formation, 3 andesites and 6 basalts from the Facpi Volcanic Member of the Umatac Formation, and 2 andesites and 1 basalt from the Dandan Flow Member at the top of the Umatac Formation.

The average composition of each group is shown in figure 3. The oldest (Alutom) and youngest (Dandan) andesites have a higher average silica content than the andesites of the Facpi. However, this range of silica content may be related in part to the alteration of the rocks. There is a strong possibility that secondary silica has been introduced into some of the rocks, and that a moderate amount of the more soluble oxides has been leached. It was noted earlier that relict boulders from the Dandan flows show a slightly higher silica content than do massive outcrops, and also that the quartz grains in some of the mafic flows may be xenocrysts rather than phenocrysts.

The average composition of seven andesites from Saipan is also shown in figure 3, and it approximates closely the composition of the average andesite of the Dandan Flow Member of the Umatac Formation of Guam.

According to Cloud, Schmidt, and Burke (1956, p. 40) "Risaburo Tayama (written communication to Cloud, July 13, 1949) reports a small inclusion of dacite in an andesitic conglomerate in Talofofo Valley on Guam, and the writers collected a few cobbles of porphyritic quartz dacite in a bed of andesite conglomerate at Mount Santa Rosa." A chemical analysis of the quartz-bearing blocks from Mount Santa Rosa is given in table 2, specimen 20 (Ss 9–1). The high silica content (68.89) is due to the abundance of quartz grains which are thought to be xenocrysts rather than phenocrysts. According to Kuno (oral communication, January 1954), the color index (11.5) and the pyroxene content are too high for the rock to be classified as a dacite. That dacites comparable to those of Saipan are present on Guam seems likely, however, for quartz-bearing rocks must have supplied the grains of quartz that occur as xenocrysts in the andesite and basalt flows and the small quartz crystals found in some of the sandy tuffs; but no rocks of dacitic composition, in either flow outcrop or pyroclastic beds, have been found on Guam.

As the analyses in table 2 are of porphyritic rocks (an attempt was made to select specimens relatively free of phenocrysts), the sum of the normative femic minerals (color index) in table 2 is probably slightly lower and the silica content slightly higher than that of the groundmass alone. It is probable that some secondary silica was added, as all the rocks show some alteration and weathering. Throughout the groundmass many flows and dikes have extremely small vesicles that contain small amounts of secondary minerals.

Figure 4 is a Harker variation diagram in which the weight percent of various oxides are plotted as ordinates against the weight percent of silica along the abscissa. Rocks with a composition intermediate between the basalts and andesites show anomalous ratios of color index and silica content. This transitional group is well illustrated on the diagram. Specimen 3 (Go 7–1) from the bottom of a flow has a color index of 36.3 (CIPW) or 38.3 (Niggli), and a silica content of 48.58 percent, which places it with the basalts. Specimen 10 (Go 7–1–c) from the top of the same flow shows a color index of 34.2 (CIPW) or 35.8 (Niggli), and a silica content of 53.50 percent. Both specimens appear fresh in outcrop, but under the microscope alteration in the larger crystals and in the groundmass is evident. Specimen 10 is called basalt in spite of the low color index because of its probable greater alteration and lesser bulk due to weathering. Similar anomalies occur in specimen 7 (Ee 4–2–c) and 8 (Ee 4–2), which are also from the middle and bottom of a single flow. The color index of specimen 7 (Ee 4–2–c) is 36.4, which is slightly less than the required 37 for basalt. This low index is believed to be due to alteration and weathering, and the rock is classed as a basalt.

Schmidt (1957, p. 153–163) has made a careful comparison between the volcanic rocks of Saipan and the rocks of Guam, the Palau Islands, the Bonin Islands, the northern Mariana Islands, the Volcano Islands, the Izu Peninsula of Japan, and the Hawaiian Islands. As the rocks of Guam appear to be closely related to those of Saipan, diagrams similar to those in Schmidt's report (1957) have been prepared for purposes of comparison. A detailed description of these diagrams is given in Schmidt's report.

TABLE 2.—*Chemical composition and norms of volcanic rock types of Guam*

[Samples 1, 7, 10, 12, 13, 14 by rapid methods]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
	Go 7-1d	Fo 10-1	Go 7-1	Df 2-1	Ie 3-1	Ch 4-3	Ee 4-2c	Ee 4-2	Fd 2-1	Go 7-1c	Ch 4-4	Fd 2-1b	Dh 6-1c	Dh 6-1b	Ie 2-1	Gm 25-1	If 6-1	Gm 1-2	Go 10-2	Ss 9-1	Go 6-1
	Basalt								Andesite	Basalt	Andesite		Basalt		Andesite						
SiO_2	47.7	48.48	48.58	50.85	51.06	51.63	51.7	52.09	53.19	53.5	53.53	54.1	54.2	55.0	55.73	58.43	60.02	64.49	65.19	68.89	69.04
Al_2O_3	15.6	15.99	16.53	13.55	18.05	14.10	14.6	15.81	17.51	14.9	16.28	14.8	14.6	13.8	19.50	14.80	16.74	14.01	15.65	13.73	12.71
Fe_2O_3	4.6	3.69	3.39	2.24	3.63	2.27	4.5	3.71	1.61	3.7	2.53	4.7	5.1	3.8	2.56	1.82	3.50	1.62	2.54	2.59	3.20
FeO	3.8	4.64	3.74	5.43	6.08	5.93	7.9	7.81	7.16	3.2	5.24	6.1	3.4	4.0	4.59	5.10	3.31	2.19	2.04	1.70	1.03
MgO	9.0	8.93	8.55	10.01	4.56	9.93	4.7	4.29	3.97	7.0	5.41	3.7	8.0	9.4	1.98	6.58	2.86	3.23	2.41	2.11	1.96
CaO	10.3	10.90	9.88	9.55	10.09	9.47	9.1	9.44	9.20	7.8	5.59	8.0	7.9	7.9	8.03	7.77	6.67	7.73	5.36	4.42	5.79
Na_2O	2.0	1.80	2.01	1.58	2.45	2.21	2.6	2.48	2.71	2.9	5.14	2.8	2.4	2.3	3.24	2.57	3.35	2.65	3.29	3.50	2.50
K_2O	.36	.14	.45	.16	1.02	.52	.70	.76	.94	.62	1.77	.82	1.4	.88	2.14	.54	1.52	.80	1.04	1.00	1.00
H_2O-	5.8	2.83	3.95	4.13	.81	1.84	3.0	1.18	.85	5.4	1.09	3.8	2.9	2.6	.26	.73	.65	.86	.72	.77	1.23
H_2O+		1.91	1.93	1.91	.71	1.42		1.12	1.25		2.45				.75	.93	.30	.69	1.08	.95	.81
TiO_2	.54	.57	.62	.34	.73	.43	.92	.97	1.04	.50	.60	1.00	.36	.34	.67	.50	.56	.39	.44	.23	.36
CO_2	.05	--------	--------	.07	.15	.07	<.05	.01	.01	.50	.11	.05	.05	.05	.02	.02	.01	.94	.01	.07	.09
P_2O_5	.08	.07	.09	.03	.22	.05	.25	.24	.26	.10	.08	.26	.08	.07	.36	.08	.19	.08	.11	.05	.05
MnO	.13	.14	.13	.14	.20	.15	.20	.20	.19	.12	.12	.15	.12	.11	.15	.14	.13	.08	.06	.05	.05
Total	100	100.09	99.85	99.99	99.76	100.02	100	100.11	99.89	100	99.94	100	100	100	99.98	100.01	99.81	99.76	99.94	100.06	99.82
Norms, in weight percent																					
Q	2.00	2.73	2.99	5.70	4.47	2.05	7.40	7.43	6.26	9.60	--------	12.60	7.90	8.10	7.81	13.43	15.85	25.78	26.00	31.20	36.09
or	2.40	.58	2.93	1.18	6.30	2.85	4.10	14.64	5.74	3.60	10.75	5.30	8.60	5.70	13.02	3.40	9.09	5.20	6.30	6.40	6.41
ab	18.80	16.87	18.78	14.70	22.91	20.54	24.60	23.22	25.26	27.40	46.95	26.50	22.20	21.00	29.45	23.23	30.68	24.86	30.36	32.10	23.32
an	34.40	36.94	36.67	31.16	36.08	27.67	27.50	31.05	33.87	27.20	16.40	26.80	25.40	24.90	32.84	27.76	26.70	24.57	25.49	19.20	21.57
di	15.80	15.82	11.27	15.29	10.54	16.43	14.40	12.77	8.96	8.40	8.82	10.60	11.80	12.00	3.85	8.61	5.00	11.56	.92	2.80	6.76
hy	20.70	22.22	22.41	29.04	14.09	27.50	15.20	14.86	16.07	17.70	2.83	10.90	18.00	23.80	8.49	20.74	7.84	5.43	7.22	5.20	2.33
mt	5.10	4.01	3.70	--------	3.95	2.40	4.90	4.00	1.72	4.10	2.71	5.10	5.50	4.10	2.72	1.87	3.75	1.73	2.75	2.80	1.75
hm	--------	--------	--------	2.47	--------	--------	--------	--------	--------	1.30	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	1.17
il	.80	.81	.94	.47	1.03	.57	1.30	1.39	1.49	.70	.91	1.50	.60	--------	.91	.68	.80	.58	.69	.30	.58
ap	--------	--------	.29	--------	.63	--------	.60	.64	.63	--------	.28	.70	--------	.40	.91	--------	.29	.29	.29	--------	--------
ol	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	10.35	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
Total	100.00	99.98	99.98	100.01	100.00	100.01	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.02	100.00	99.98
Normative plagioclase, in mol percent																					
or	4.2	1.1	5.1	2.5	9.8	5.7	7.2	8.3	9.1	6.0	15.0	9.3	15.2	11.0	17.7	6.4	14.1	9.8	10.4	11.1	12.8
ab	33.9	29.8	30.9	30.0	33.8	38.8	43.8	38.0	37.5	47.3	62.0	43.6	39.6	40.6	37.7	41.3	44.7	44.0	47.4	55.6	44.0
an	61.9	69.1	64.0	67.5	56.4	55.5	49.0	53.9	53.4	46.7	23.0	47.1	45.2	48.4	44.6	52.3	41.2	46.2	42.2	33.3	43.2
Normative pyroxene, in mol percent																					
wo	21.6	20.8	16.7	17.2	21.4	18.7	24.4	23.1	17.9	15.6	37.9	24.7	19.9	16.8	15.6	14.7	19.5	34.0	5.6	17.1	37.2
en	72.3	68.2	74.6	67.1	53.0	64.4	45.6	45.0	45.4	77.7	44.6	50.6	76.3	74.4	45.9	63.7	63.7	55.1	84.5	75.8	62.8
fs	6.1	11.0	8.7	15.6	25.6	16.9	29.1	31.9	36.7	6.7	17.5	24.7	3.8	8.8	38.5	21.6	16.8	10.9	9.9	7.1	--------

Alutom formation:
1. Go 7-1-d Basalt flow, near bottom, Spruance Drive. Harry F. Phillips, Paul L. D. Elmore, Katherine E. White, analysts.
2. Fo 10-1 Basalt flow, Spruance Drive roadcut. Edwin J. Tomasi, analyst.
3. Go 7-1 Basalt flow, Spruance Drive roadcut. Edwin J. Tomasi, analyst.

Umatac formation:
4. Df 2-1 Lower flows in Facpi Volcanic Member. Olivine basalt flow, old road to Umatac. Edwin J. Tomasi, analyst.
5. Ie 3-1 Dandan Flow Member. Basalt boulder, Martinez Pasture, Dandan area. Edwin J. Tomasi, analyst.
6. Ch 4-3 Lower part of Facpi Volcanic Member. Basalt dike, 3,600 ft northeast of Facpi Point. Edwin J. Tomasi, analyst.
7. Ee 4-2-c Upper flows in Facpi Volcanic Member. Basalt flow (near middle) above Umatac Springs. Harry F. Phillips, Katherine E. White, analysts.
8. Ee 4-2 Upper flows in Facpi Volcanic Member. Basalt flow (near bottom) above Umatac Springs. Edwin J. Tomasi, analyst.
9. Fd 2-1 Upper flows in Facpi Volcanic Member. Sodic andesite, 520 ft upstream from road above Merizo Dam. Edwin J. Tomasi, analyst.

Alutom formation:
10. Go 7-1-c Basalt flow, near top, Spruance Drive. Harry F. Phillips, Paul L. D. Elmore, Katherine E. White, analysts.

Umatac formation:
11. Ch 4-4 Lower flows in Facpi Volcanic Member. Sodic andesite dike, 3,600 ft northeast of Facpi Point. Edwin J. Tomasi, analyst.
12. Fd 2-1-b Upper flows in Facpi Volcanic Member. Calcic andesite (near top) above Merizo Dam. Harry F. Phillips, Paul L. D. Elmore, Katherine E. White, analysts.
13. Dh-6-1-c Upper flows in Facpi Volcanic Member. Basalt flow (near top) Lamlam Road cut. Harry F. Phillips, Paul L. D. Elmore, Katherine E. White, analysts.
14. Dh 6-1-b Lower flows in Facpi Volcanic Member. Basalt flow (near bottom) Lamlam Road cut. Harry F. Phillips, Paul L. D. Elmore, Katherine E. White, analysts.
15. Ie 2-1 Dandan Flow Member. Andesite boulder, Martinez Pasture, Dandan area. Edwin J. Tomasi, analyst.

Alutom formation:
16. Gm 25-1 Calcic andesite boulder, east of Mount Tenjo. Edwin J. Tomasi, analyst.

Umatac formation:
17. If 6-1 Dandan Flow Member. Sodic andesite, Martinez Pasture, Dandan area. Edwin J. Tomasi, analyst.

Alutom formation:
18. Gm 1-2 Sodic andesite boulder, east of Mount Alutom. Edwin J. Tomasi, analyst.
19. Go 10-2 Sodic andesite boulder in pyroclastic conglomerate, Spruance Drive. Edwin J. Tomasi, analyst.
20. Ss 9-1 Sodic andesite boulder in pyroclastic conglomerate, southeast slope Mount Santa Rosa. L. O. Trumbull, analyst.
21. Go 6-1 Andesite boulder, pyroclastic conglomerate, Spruance Drive. Edwin J. Tomasi, analyst.

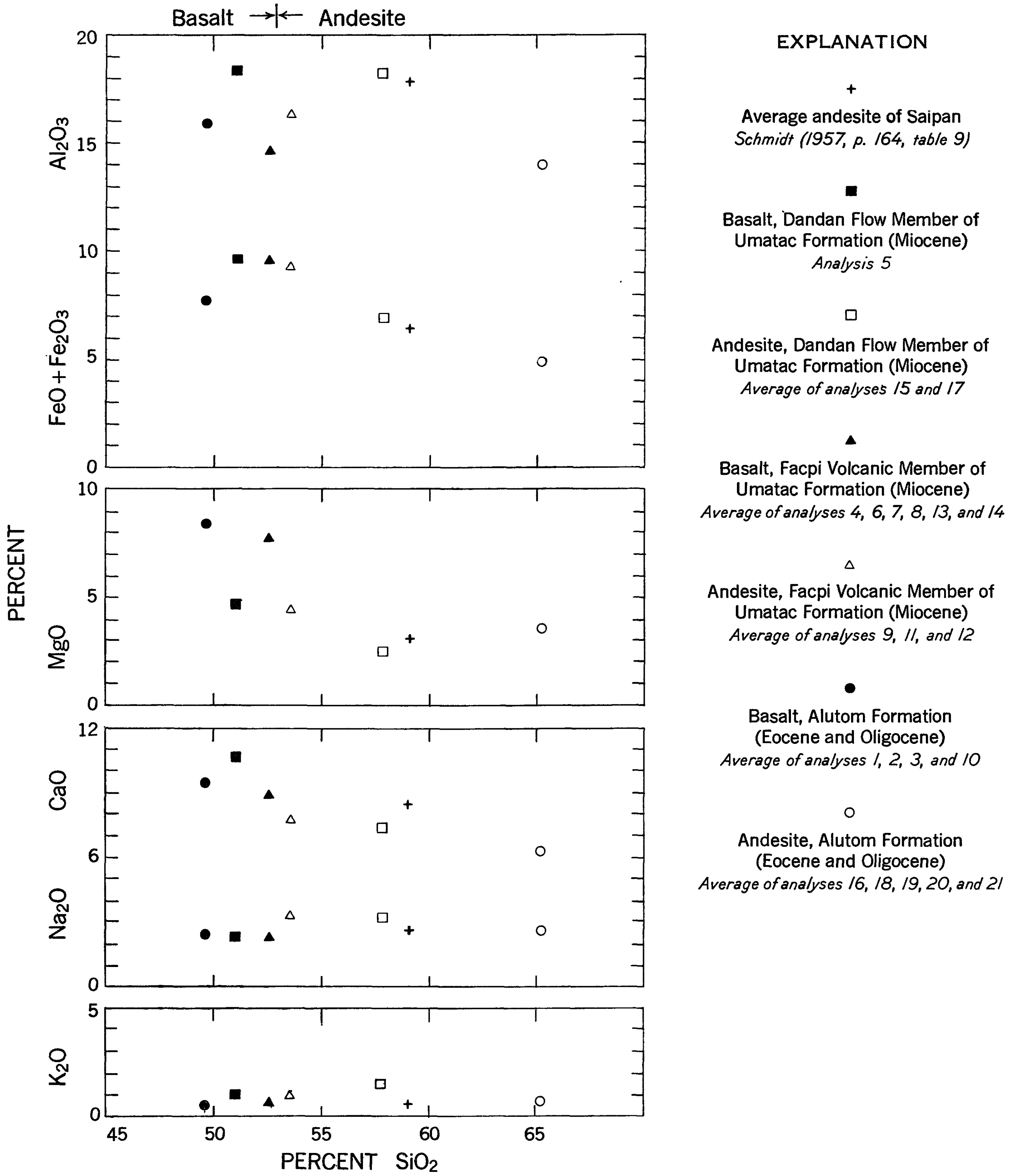


FIGURE 3.—Average oxide composition of volcanic rocks of Guam by age. Analyses referred to are given in table 2.

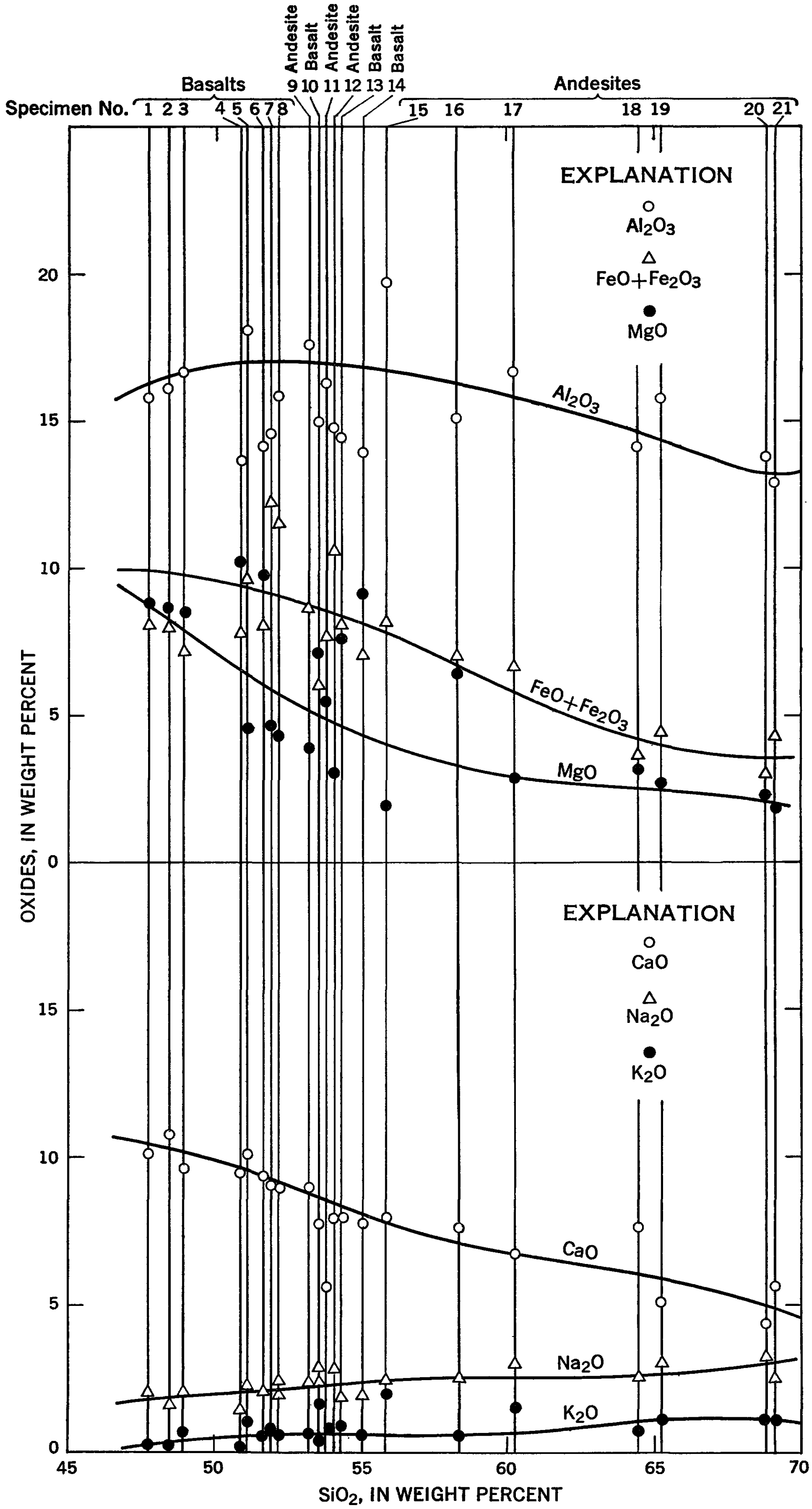


FIGURE 4.—Harker variation diagram of volcanic rocks of Guam. Numbers refer to analyses and corresponding rock specimens in table 2.

In figure 4 as in a similar variation diagram for the volcanic rocks of Saipan, there is a characteristic difference in the silica content of the andesites and the dacites. The silica content of the analyzed dacites of Saipan exceeds 76 percent. The highest silica content of the analyzed rocks of Guam is 69.04 percent (specimen 21, Go 6–1). The quartz grains in this rock are believed to be xenocrysts, and secondary silica is probably also in the fine-grained groundmass. In the Harker variation diagram of the rocks of Saipan, the alkali-lime index is about 65, whereas that of the rocks of Guam is about 70. Here, as on Saipan, the exact index is uncertain, but it would appear that the index of the rocks of Guam is slightly more calcic.

Figure 5 is a standard ACF diagram which shows the composition of the analyzed rocks of Guam 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=$MgO+FeO-Fe_2O_3-TiO_2$. On this diagram the Guam andesites fall within the triangle anorthite-diopside-hypersthene. The andesites of Saipan (Schmidt, 1957, fig. 17) also lie within this triangle (with two exceptions), but, in general, they are closer to the anorthite apex than are the rocks of Guam. Five of the andesites from Guam fall in the region of the basalts, but they are closer to the diopside-hypersthene join and indicate the transitional character of the rocks. The 11 basalts from Guam all fall closer to the diopside-

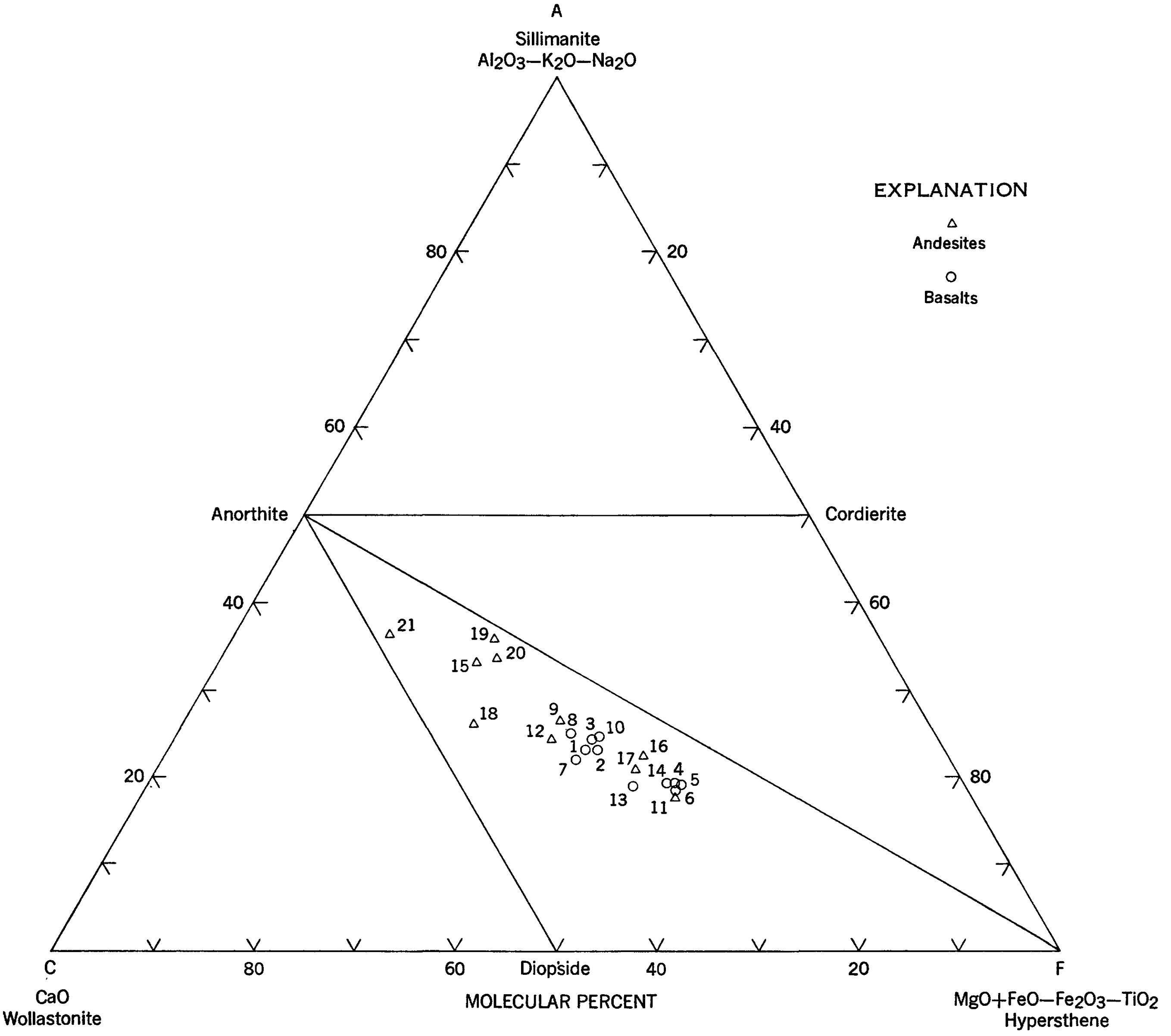


FIGURE 5.—Triangular ACF diagram of specimens of volcanic rocks of Guam. Numbers refer to analyses and corresponding rock specimens in table 2.

hypersthene join than do any of the andesites from Saipan.

Figure 6 is an ACF diagram showing the average andesite and basalt of Guam, average dacite and andesite of Saipan, average basalt of the Izu Peninsula, and average olivine basalt of the Hawaiian Islands. Part of the data is taken from figures 20 and 21 of Schmidt (1957). The average andesite of Guam falls close to the average basalt of Izu, and the average basalt of Guam lies between the average basalt of Izu and the average olivine basalt of the Hawaiian Islands.

Figure 7 is an ACF diagram in which the rocks of Guam and Saipan are compared with Daly's average rock types (Daly, 1933). The average basalt of Guam

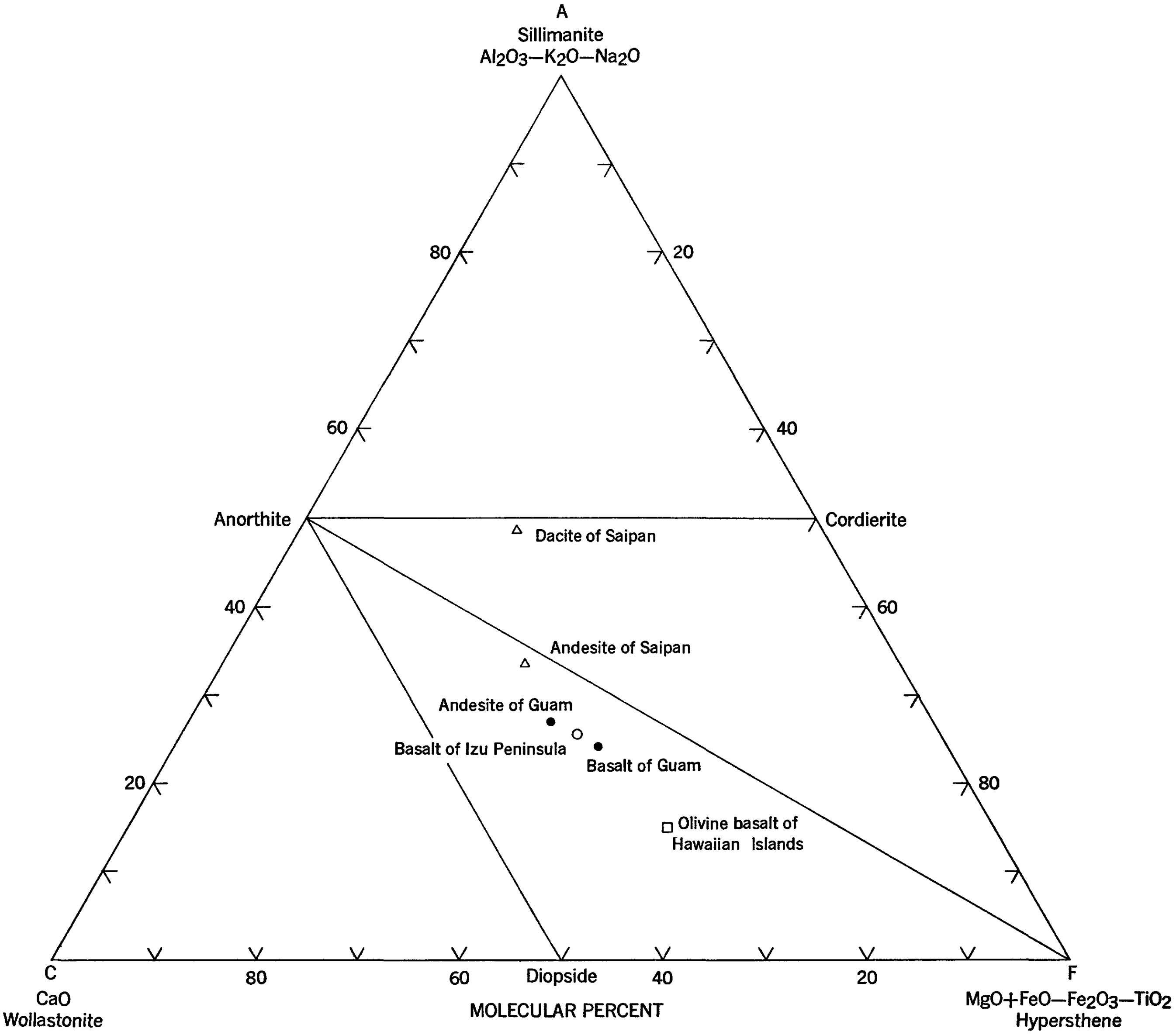


FIGURE 6.—Triangular ACF diagram of average volcanic rocks of Guam, Saipan, the Izu Peninsula of Japan, and the Hawaiian Islands. Data for rocks of Saipan, Izu, and Hawaii from Schmidt (1957, figs. 20, 21).

lies close to Daly's average basalt, but the average andesite of Guam is considerably more mafic than Daly's average for all andesites.

Figures 8–10 are SKM diagrams in which the composition of the analyzed rocks is shown 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 $M=MgO+FeO-Fe_2O_3-TiO_2-CaO-Na_2O-K_2O+Al_2O_3$.

In figure 8 the andesites and basalts of Guam, with a single exception, lie above the silica saturation line (the horizontal line at 50) in the triangle quartz-alkali feldspar-hypersthene. The exception, specimen 11 (Ch 4–4), is from a dike that cuts basaltic rocks of the Facpi Volcanic Member on a point of land just north of Facpi Point. In thin section the rocks shows a devitrified groundmass and considerable alteration of the feldspar phenocrysts. The pyroxene phenocrysts are augite and hypersthene, and both appear fresh in contrast to the altered feldspar grains. In the SKM diagram given by Schmidt (1957, fig. 17), all the dacites and andesites of Saipan fall in the triangle quartz-alkali feldspar-

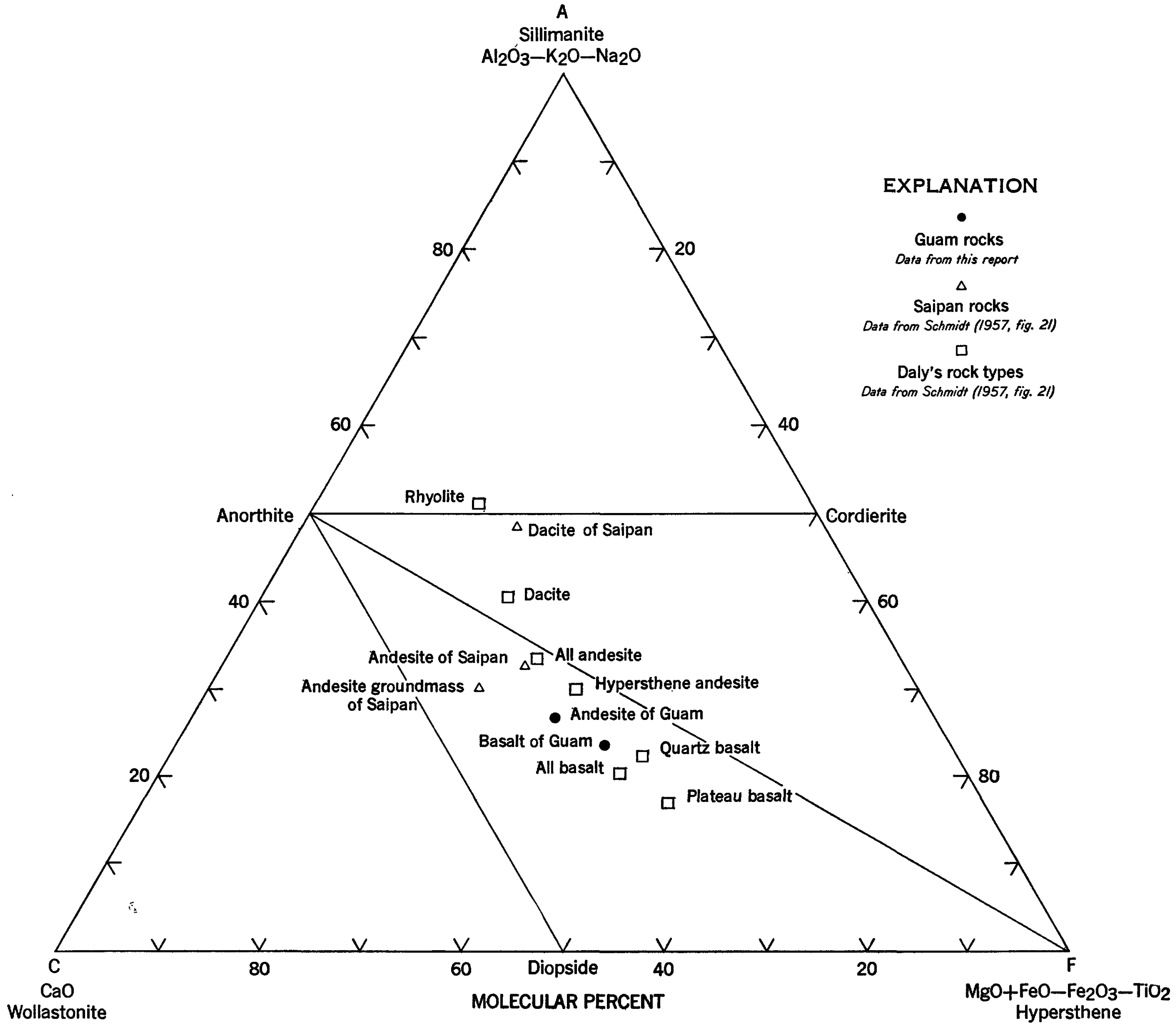


FIGURE 7.—Triangular ACF diagram of average volcanic rocks of Guam, Saipan, and Daly's average rock types.

hypersthene, the dacites lying above a horizontal line at 70 and the andesites above a horizontal line at 60. The basalts of Guam (fig. 8) fall below the 70 percent line and are scattered between the horizontal lines at 52 and 70. The andesites of Guam tend to be higher in silica and to lie toward the alkali feldspar side of the diagram, and the basalts tend to be lower in silica and to lie toward the hypersthene side of the diagram. Between these rocks is a group transitional to the andesites and basalts.

Figures 9 and 10 show a close correspondence in composition between the average andesites of Guam and Saipan and between the average basalts of Guam and Izu.

Figure 11 is a triangular diagram in which the normative feldspar composition and the normative femic mineral-quartz-feldspar ratios of the volcanic rocks of Guam are plotted according to the method suggested by Larsen (1938). The two values for each rock are connected by lines, and the general increase in quartz and feldspar with increase of albite content of the feldspar is shown by the changing slopes of the lines. The single undersaturated andesite of Guam, specimen 11 (Ch 4-4), because of its approximate 10 percent of normative

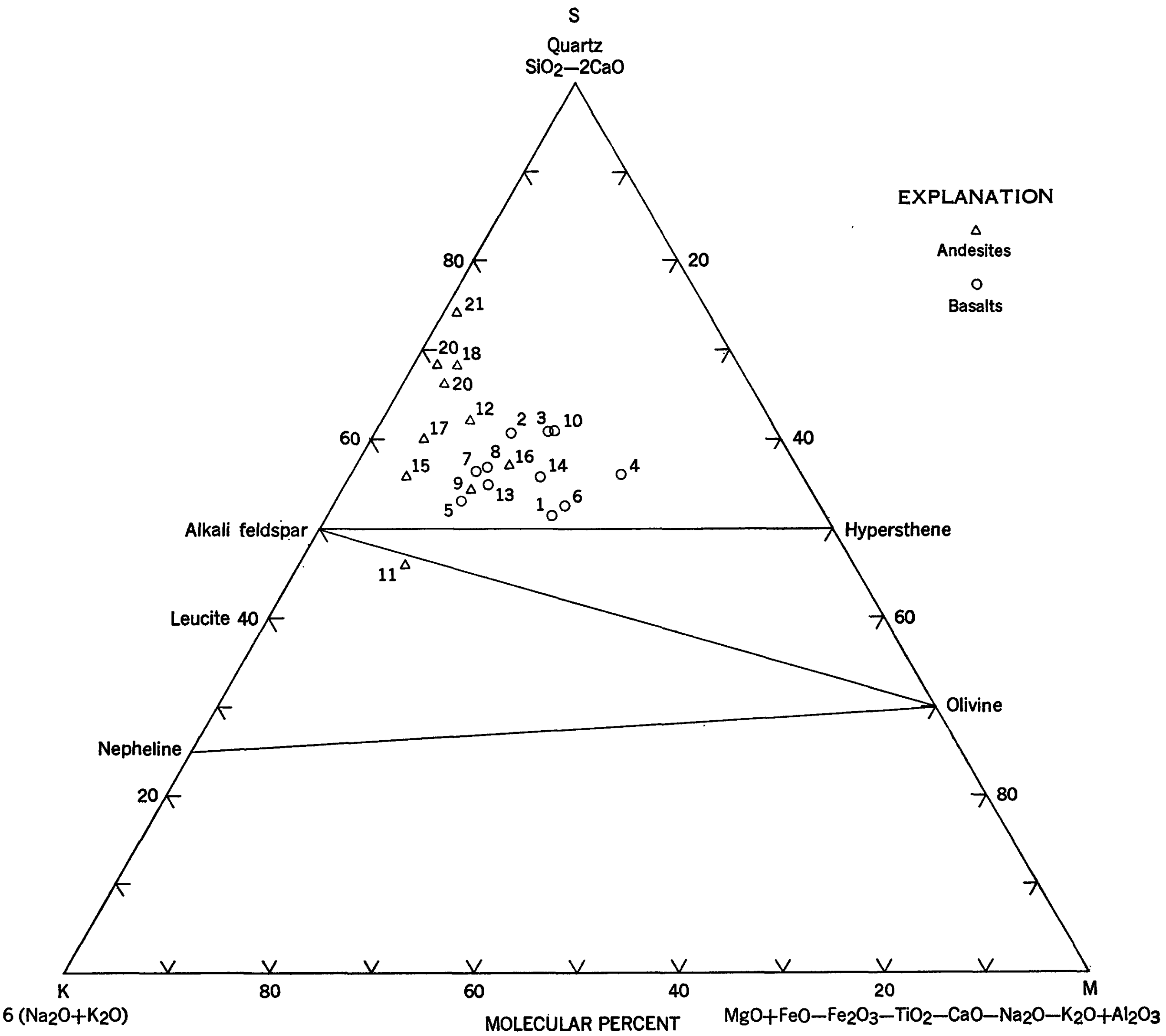


FIGURE 8.—Triangular SKM diagram of specimens of volcanic rocks of Guam. Numbers refer to analyses and corresponding rock specimens in table 2.

olivine, stands out as the only rock with a femic to felsic ratio greater than anorthite to albite plus orthoclase ratio.

Figures 12 and 13 are triangular diagrams which show, respectively, the composition of normative feldspar and normative pyroxene of the average andesite and basalt of Guam and also the average normative feldspar and pyroxene of Daly's average rock types. The normative feldspar of the average andesite of Guam (fig. 12) is very close to that of Daly's average basalt. The normative feldspar of the average basalt of Guam contains slightly more normative anorthite than that of the average world basalt. The normative pyroxene of the average andesite of Guam (fig. 13) is close to that of the average world basalt. The normative pyroxene of the average basalt of Guam contains more normative enstatite and slightly less normative wollastonite than the normative pyroxene of Daly's average basalt.

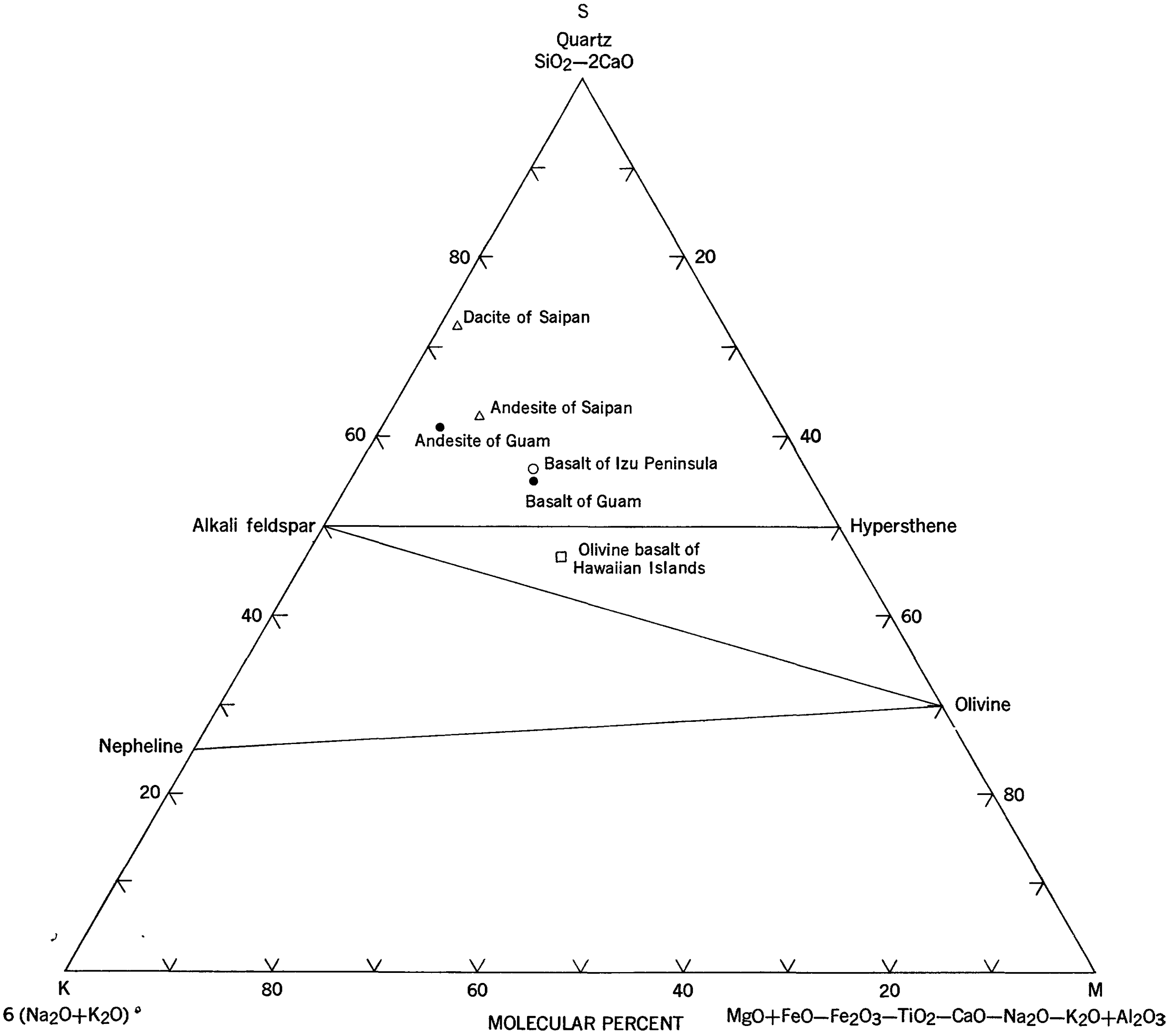


FIGURE 9.—Triangular SKM diagram of average volcanic rocks of Guam, Saipan, the Izu Peninsula of Japan, and the Hawaiian Islands. Data for rocks of Saipan, Izu, and Hawaii from Schmidt (1957, figs. 20, 21).

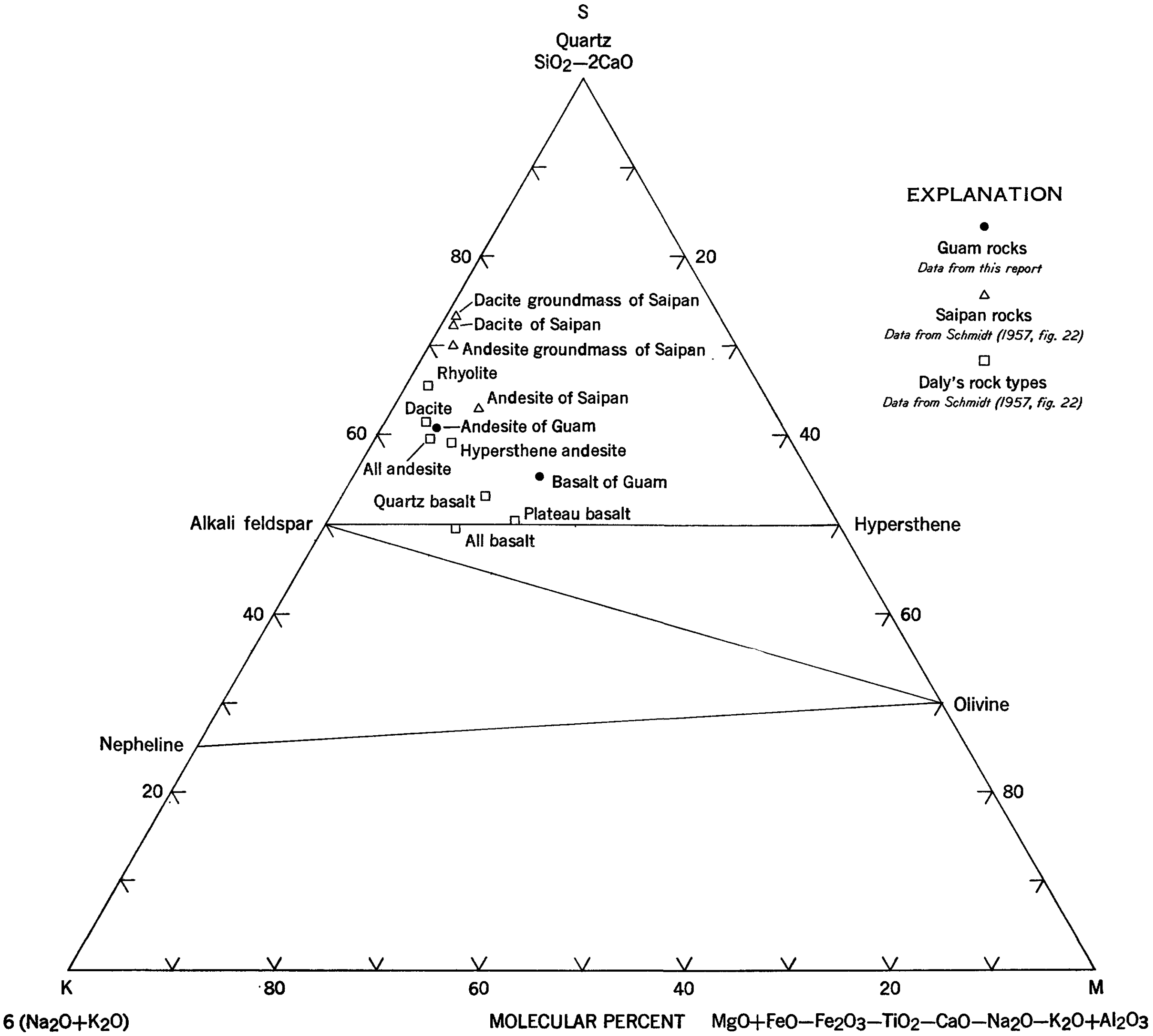


FIGURE 10.—Triangular SKM diagram of average volcanic rocks of Guam and Saipan and of Daly's average rock types.

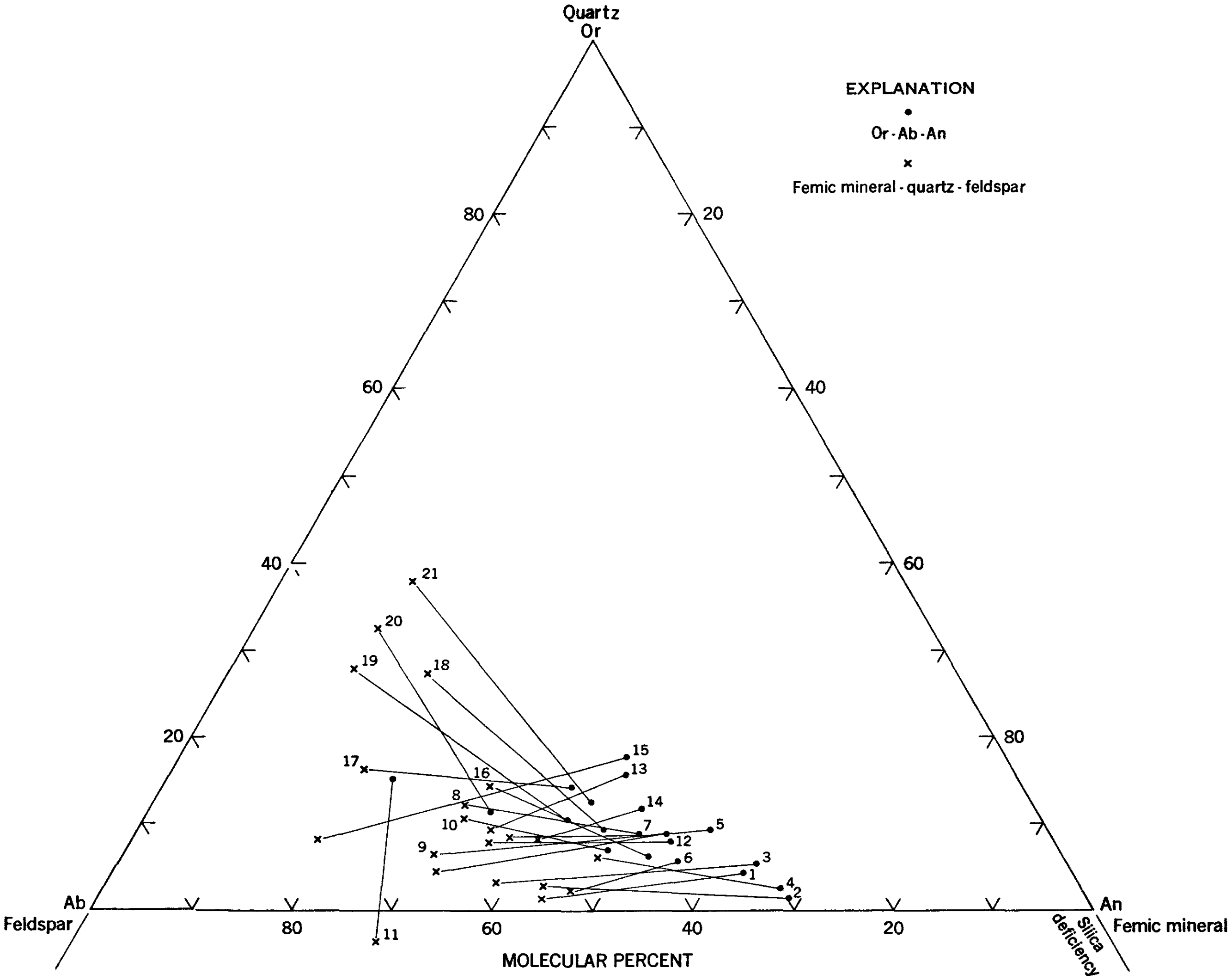


FIGURE 11.—Triangular diagram of the norms of the andesites and basalts of Guam showing the ratios of Or-Ab-An, and of femic mineral-quartz-feldspar.

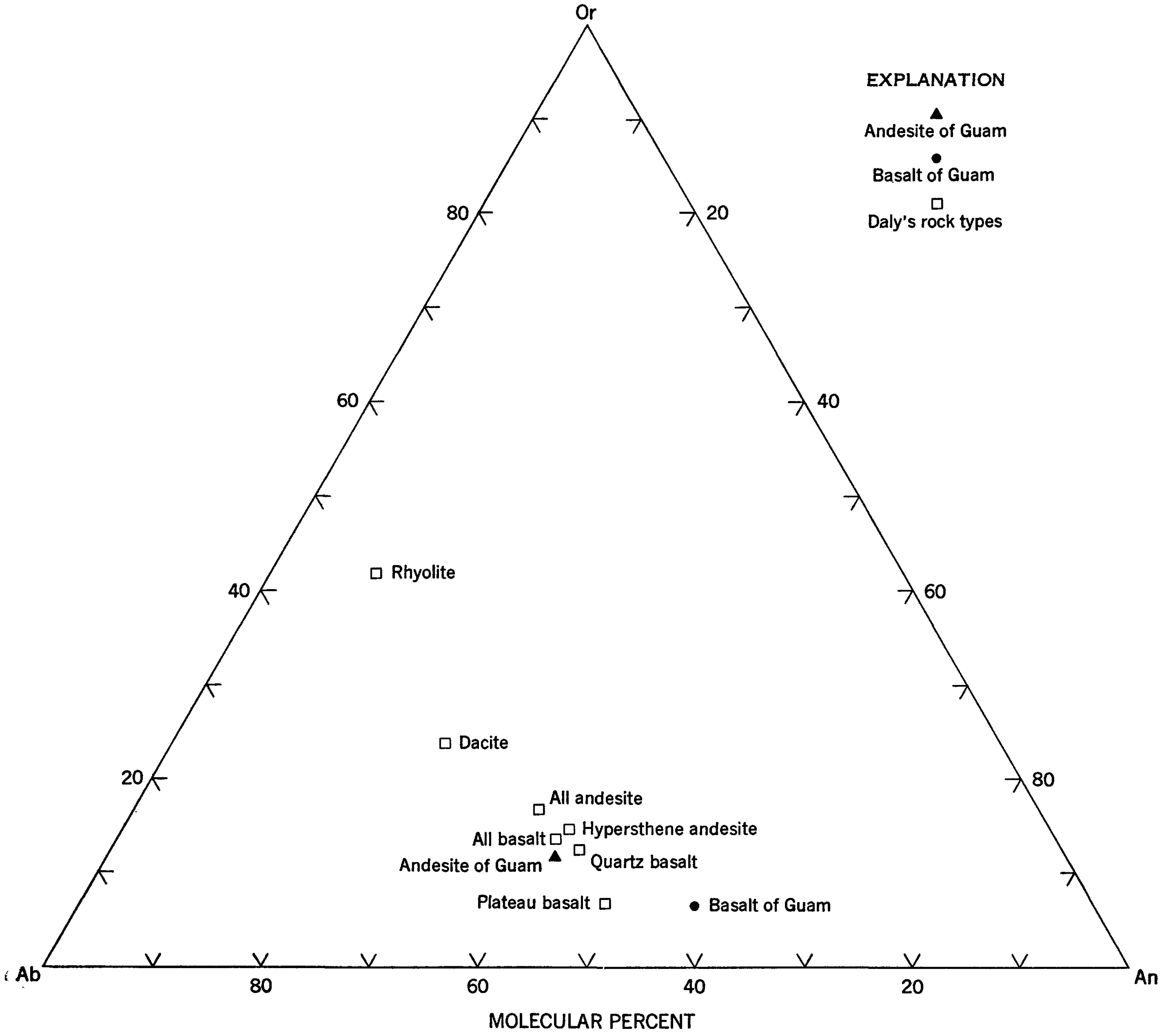


FIGURE 12.—Composition of normative feldspar of average rocks of Guam and of Daly's average rock types.

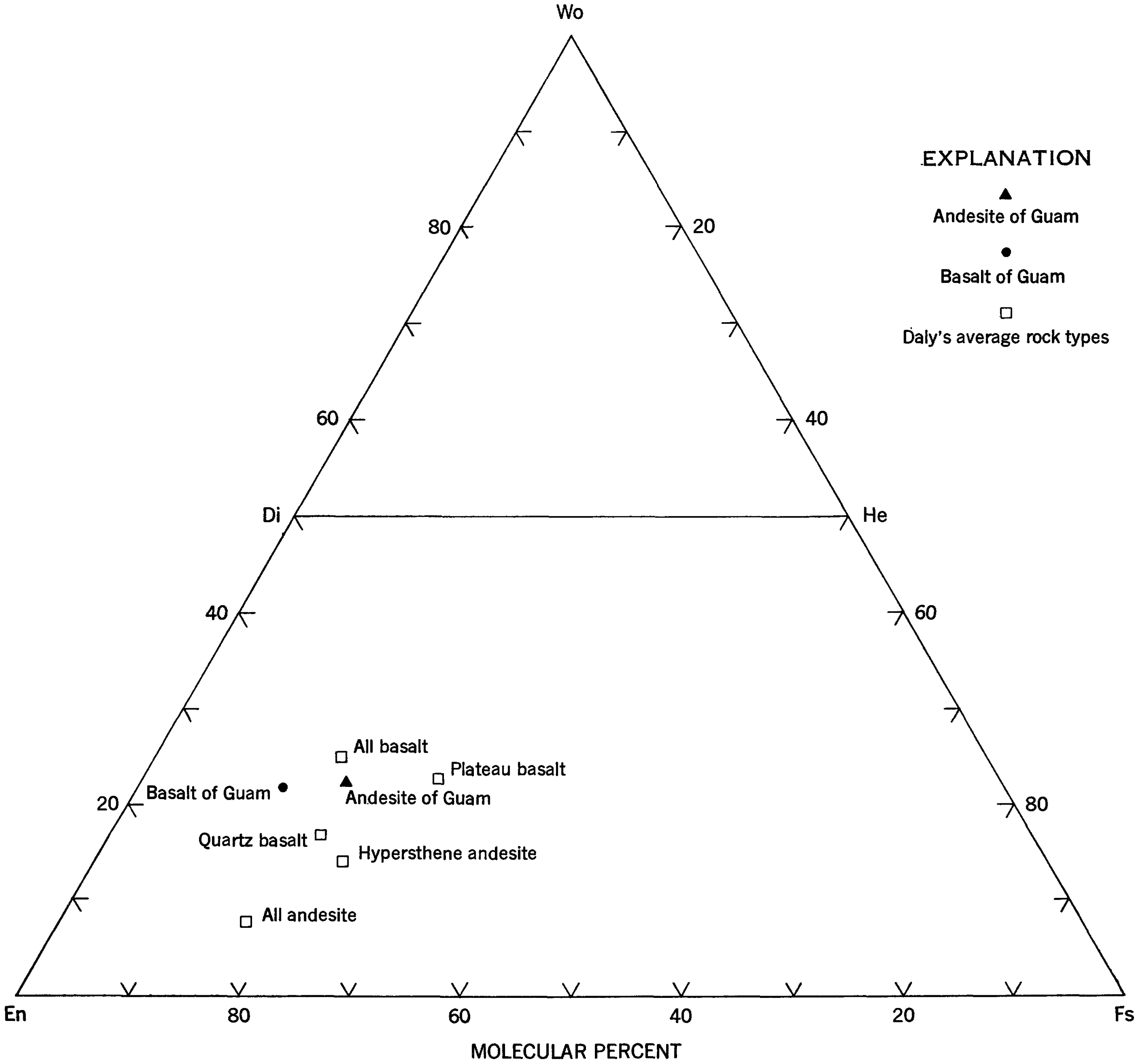


FIGURE 13.—Composition of normative pyroxene of average rocks of Guam and of Daly's average rock types.

Figures 14 and 15 are triangular diagrams which show, respectively, the composition of normative feldspar and the composition of normative pyroxene of average rocks from Guam, Saipan, the Izu Peninsula of Japan, the northern Mariana Islands, and the Hawaiian Islands. The normative feldspar of the andesites of Guam (fig. 14) contains slightly more orthoclase than the normative feldspar of the andesites from the other areas. The normative plagioclase of the andesites and basalts of Guam averages about An_{50}; the rocks from the other areas generally contain more calcic plagioclase and range from An_{48} to An_{75}. The normative pyroxene of the average andesites and basalts of Guam (fig. 15) contains approximately the same amount of normative wollastonite as the average andesite of Saipan, but it generally contains more normative enstatite (En_{59}–En_{65}) than the normative pyroxene of the rocks of other areas, which range from En_{43} to En_{54}.

The andesites and dacites of Saipan and the andesites and basalts of Guam are close in composition to the volcanic rocks of the Hakone region of Japan. Kuno (1950, p. 993; 1953, p. 268) divides the Hakone rocks into (1) a pigeonitic rock series which he believes was formed by fractional crystallization of parent olivine basalt, and (2) a hypersthenic rock series which he believes originated through contamination of the parent olivine basalt by granitic material. Schmidt (1957, p. 159) points out the close correspondence between the rocks of Saipan and the hypersthenic rock series of the Hakone region. A similar correspondence is apparent for the andesites and basalts of Guam.

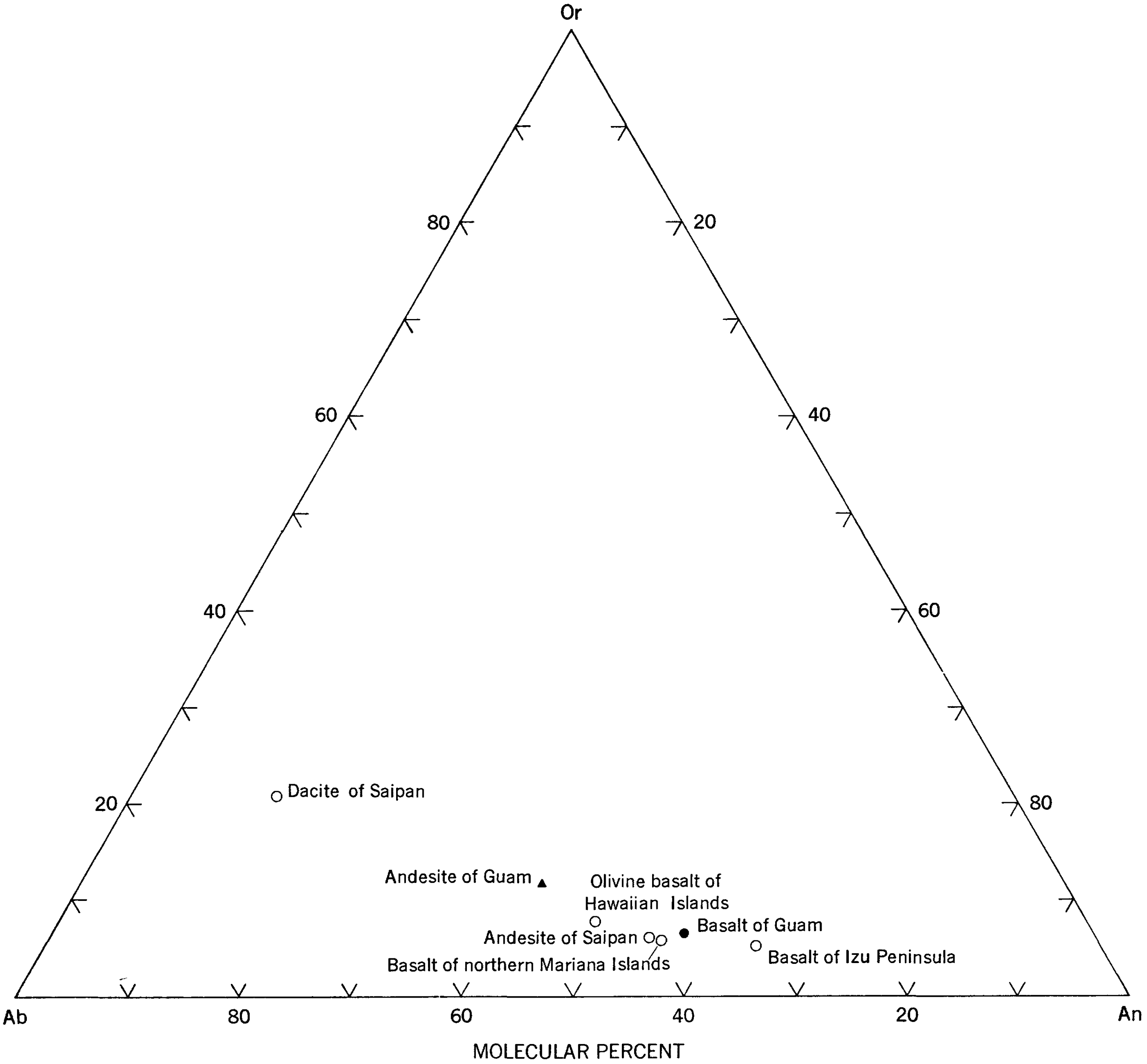


FIGURE 14.—Composition of normative feldspar of average volcanic rocks of Guam, Saipan, the northern Mariana Islands, the Hawaiian Islands, and the Izu Peninsula of Japan. Data for rocks of Saipan, northern Mariana Islands, Hawaii, and Izu from Schmidt (1957, fig. 23).

This relationship is further illustrated in figure 16, in which the rocks of Guam are plotted on a triangular MgO-FeO-alkali diagram. A comparison of figure 16 with a similar diagram for the nonporphyritic rocks of the Izu and Hakone regions (fig. 16, inset) shows that the trend of the variation of rocks of Guam follows closely that of the hypersthenic rock series of Japan.

PETROGENESIS

The volcanic rocks of Guam are generally similar in composition to the rocks of Saipan and to the rocks of the island groups scattered along the western margin of the Pacific Basin, all of which belong to the circum-pacific petrographic province. The volcanic rocks of this province are decidedly less alkalic than the volcanic rocks of those islands lying within the more orogenically stable Pacific Basin, which form the intrapacific province. The writer believes that the volcanic rocks of Guam originated through the same processes that were responsible for the volcanic rocks of Saipan.

Schmidt (1957, p. 170) considers the high silica content and the peraluminous character of the dacites of

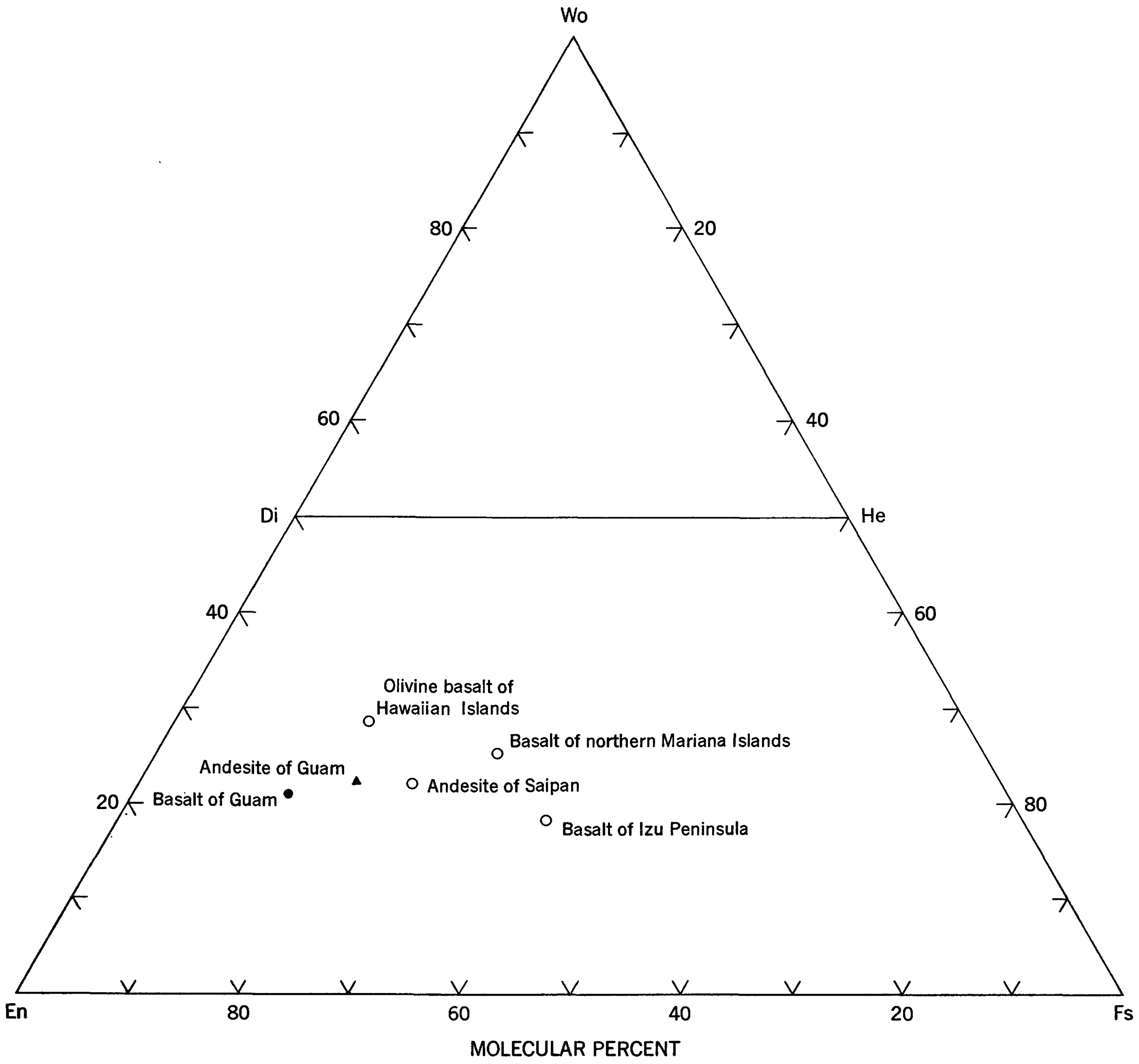
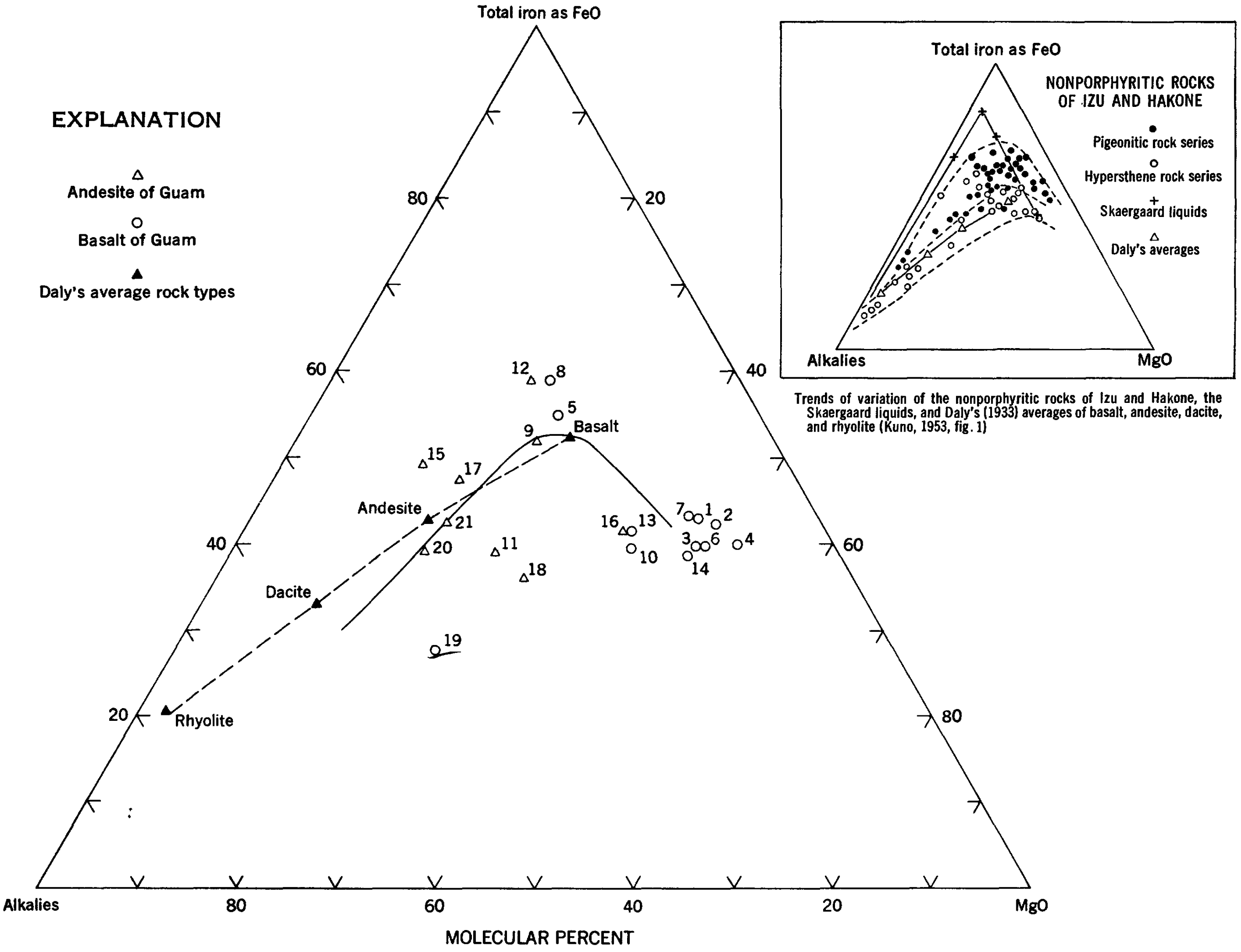


FIGURE 15.—Composition of normative pyroxene of average volcanic rocks of Guam, Saipan, the northern Mariana Islands, the Hawaiian Islands, and the Izu Peninsula of Japan. Data for rocks of Saipan and northern Mariana Islands selected from Schmidt (1957, tables 5, 6), Hawaii from Macdonald (1949, table 5), and Izu from Kuno (1950, tables 12, 14).



Trends of variation of the nonporphyritic rocks of Izu and Hakone, the Skaergaard liquids, and Daly's (1933) averages of basalt, andesite, dacite, and rhyolite (Kuno, 1953, fig. 1)

FIGURE 16.—Triangular FeO-MgO-alkali diagram of andesites and basalts of Guam, and Daly's average rock types. Numbers refer to analyses and corresponding rock specimens in table 2.

Saipan difficult to reconcile with any hypothesis of simple fractional crystallization, and he believes it is "necessary to assume some special process such as perhaps extreme fractionization of an andesitic magma coupled with assimilation of significant amounts of siliceous and aluminous crustal material" to account for their composition. If beneath the rocks now exposed on Saipan there are basaltic flows comparable to the basalts of Guam, and if rocks of dacitic composition were once on Guam and have since been removed by erosion, as is suggested by the occurrence of quartz crystals in the sandy tuffs and quartz xenocrysts in some of the basic flows, it would seem probable that the rocks of both islands have had a similar mode of origin and have been derived from the same type of parent magma.

TRACE ELEMENTS IN THE VOLCANIC ROCKS OF GUAM

By JOSHUA I. TRACEY, JR., and JOHN T. STARK

The results of spectrographic determinations of trace elements and the chemical analyses of 6 basalts and 5 andesites of Guam are presented in table 3. Also given are chemical analyses and trace elements of basalts and andesites of the Hawaiian Islands, quoted from Wager and Mitchell (1953, p. 218, table 1). The samples from Guam are arranged stratigraphically, rather than according to their silica content as in table 2, in order to show possible variations with time. Locations, field numbers, and descriptions of the samples are given in table 2, and localities are shown in figure 2. Samples within each stratigraphic subdivision are arranged from left to right in order of decreasing MgO content.

TABLE 3.—*Trace elements of lavas of Guam and the Hawaiian Islands*

[Field numbers and descriptions given in table 2]

	Guam										
	(Spectrographic analyses by Paul R. Barnett. Chemical analyses from table 2)										
	Alutom Formation					Umatac Formation					
						Facpi Volcanic Member				Dandan Flow Member	
						Lower		Upper			
	2	3	16	18	21	4	6	8	9	5	15
	Flow		Boulders			Flow	Dike	Flow		Boulders	
	Chemical analyses, in percent										
SiO_2	48.48	48.58	58.43	61.49	69.04	50.85	51.63	52.09	53.19	51.06	55.73
Al_2O_3	15.99	16.53	14.80	14.01	12.71	13.55	14.10	15.81	17.51	18.05	19.50
Fe_2O_3	3.69	3.39	1.82	1.62	3.20	2.24	2.27	3.71	1.61	3.63	2.56
FeO	4.64	3.74	5.10	2.19	1.03	5.43	5.93	7.81	7.16	6.08	4.59
MgO	8.93	8.55	6.58	3.23	1.96	10.01	9.93	4.29	3.97	4.56	1.98
CaO	10.90	9.88	7.77	7.73	5.79	9.55	9.47	9.44	9.20	10.09	8.03
Na_2O	1.80	2.01	2.57	2.65	2.50	1.58	2.21	2.48	2.71	2.45	3.24
K_2O	.14	.45	.54	.80	1.00	.16	.52	.76	.94	1.02	2.14
H_2O-	2.83	3.95	.73	.86	1.23	4.13	1.84	1.18	.85	.81	.26
H_2O+	1.91	1.93	.93	.69	.81	1.91	1.42	1.12	1.25	.71	.75
TiO_2	.57	.62	.50	.39	.36	.34	.43	.97	1.04	.73	.67
CO_2	-----	-----	.02	.94	.09	.07	.07	.01	.01	.15	.02
P_2O_5	.07	.09	.08	.08	.05	.03	.05	.24	.26	.22	.36
MnO	.14	.13	.14	.08	.05	.14	.15	.20	.19	.20	.15
	Trace constituents, in parts per million										
Ag	0	0	0	0	0	0	2	0	0	0	0
B	0	0	20	20	20	0	0	0	0	20	30
Ba	20	20	60	80	60	20	70	200	200	400	500
Co	200	200	100	80	50	200	200	200	200	200	70
Cr	500	500	500	400	300	900	700	10	9	10	2
Cu	70	80	60	10	200	70	100	200	200	200	100
Ga	7	8	6	6	7	7	10	10	10	8	9
Ni	100	100	200	90	40	300	200	10	10	100	2
Pb	0	0	0	0	0	0	50	0	0	0	0
Sc	40	50	30	20	20	40	40	40	40	30	20
Sr	200	300	200	200	200	200	300	800	900	1,000	1,000
V	50	40	40	40	20	30	40	60	60	50	30
Y	30	30	30	50	20	30	30	50	50	30	30
Yb	2	2	2	3	1	2	3	4	5	3	3
Zr	10	20	40	40	40	10	10	30	40	30	80

NOTE.—Looked for but not found: As, Au, Be, Bi, Cd, Ge, In, La, Mo, Nb, Pt, Sb, Sn, Ta, Th, Tl, U, W, and Zn.

	Hawaiian Islands									
	(Chemical and spectrographic analyses from Wager and Mitchell (1953, table 1)									
	Picrite basalt	Picrite basalt	Olivine basalt	Basalt		Andesine andesite	Andesine andesite	Oligoclase andesite	Oligoclase andesite	Soda trachyte
	Chemical analyses, in percent									
SiO_2	47.25	49.27	50.52	52.28	51.55	-----	50.68	51.99	52.27	62.02
Al_2O_3	9.07	9.38	13.85	10.83	13.59	-----	16.42	16.30	17.05	18.71
Fe_2O_3	1.45	1.28	0.98	1.90	2.33	-----	5.79	2.75	3.51	4.30
FeO	10.41	10.31	9.77	9.30	9.04	-----	6.22	7.44	7.20	0.10
MgO	19.96	17.74	7.07	7.69	8.02	-----	4.25	3.19	3.13	0.40
CaO	7.88	7.46	11.33	10.03	10.31	-----	6.47	6.67	5.82	0.86
Na_2O	1.38	1.80	1.51	2.29	2.43	-----	4.70	5.64	5.40	6.90
K_2O	.35	.42	.47	.51	.27	-----	2.16	2.13	2.22	4.93
H_2O-	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
H_2O+	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
TiO_2	1.61	2.58	3.63	4.43	1.98	-----	2.64	3.02	2.13	0.31
CO_2	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
P_2O_5	.21	.26	.22	.32	.24	-----	.17	1.25	.62	.24
MnO	.13	.09	.14	.12	.12	-----	.22	.11	.16	.15
	Trace constituents, in parts per million									
Ag	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
B	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Ba	150	70	150	100	100	600	600	1,000	1,000	800
Co	70	80	30	40	30	12	16	7	4	2
Cr	1,000	2,500	400	500	500	-----	-----	-----	-----	20
Cu	150	150	200	100	200	<10	<10	<10	<10	<10
Ga	15	20	25	25	20	20	20	25	20	25
Ni	400	1,500	80	100	70	6	7	10	15	15
Pb	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Sc	-----	-----	10	10	-----	-----	-----	-----	-----	-----
Sr	400	200	800	600	1,000	2,000	3,000	4,000	3,000	100
V	300	200	400	250	200	70	70	30	8	-----
Y	20	20	20	25	20	60	50	150	100	150
Yb	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Zr	100	50	100	50	150	300	400	1,000	1,500	1,500
Be	-----	-----	-----	-----	-----	-----	-----	-----	-----	8
Mo	1	2	-----	1	-----	-----	-----	-----	-----	4
Li	1	1	1	1	3	20	10	15	25	30
La	-----	-----	-----	-----	-----	30	20	70	150	100
Rb	-----	-----	-----	-----	-----	40	30	70	40	300

Rocks from the Alutom Formation shown in table 3 range from 48.48 to 69.04 percent SiO_2 and from 8.93 to 1.96 percent MgO. Samples comparatively low in silica are from lava flows, whereas those comparatively high in silica are from boulders in pyroclastic breccias or conglomerates. The stratigraphic position of the samples relative to each other within the formation is not certainly known; therefore all samples are arranged in order of increasing MgO content.

Rocks from the Umatac Formation shown in table 3 range from 50.85 to 55.73 percent SiO_2 and from 10.01 to 1.98 percent MgO. These samples come from known stratigraphic positions relative to each other within the formation (fig. 17), which is more than 2,000 feet thick. Samples analyzed for trace elements from the thick Facpi Volcanic Member represent lower pillow basalt flows near the coast (sample 4, 13, 14), dikes that cut these flows (sample 6) several hundred feet below the tongues of the Maemong Limestone Member, and upper basalt and andesite flows above the tongues of the Maemong Limestone Member close to the top of the Facpi Volcanic Member (samples 8, 9). The remaining samples are from large residual boulders from the Dandan Flow Member at the top of the Umatac Formation (samples 5, 15). A general decrease in MgO is evident from bottom to top of the formation.

Ranges for each minor element, relative to decreasing MgO, are considered below for each of the two formations.

Boron was not detected in any flow samples, but it is present (20 ppm; parts per million) in boulders from pyroclastic breccias from the Alutom, and (20 to 30 ppm) in residual boulders from the Dandan Flow Member.

Barium increases in the Alutom from 20 to 80 ppm and in the Umatac from 20 to 500 ppm. Distinct increases are evident between lower and upper flows of the Facpi and between the Facpi and the Dandan.

Cobalt decreases in the Alutom from 200 to 50 ppm In the Umatac it remains constant at 200 ppm, except for sample 15, which contained 70 ppm.

Chromium decreases from 500 to 300 ppm in the Alutom. In the Umatac it decreases from 900 to 2 ppm and shows a very sharp break between lower and upper flows of the Facpi.

Copper ranges from 10 to 200 ppm throughout, but shows no significant trend. It is generally higher in samples from the Umatac than in those from the Alutom.

Gallium ranges from 6 to 10 ppm in all samples, but shows no consistent trend.

Nickel ranges from 200 to 40 ppm in the Alutom and from 300 to 2 ppm in the Umatac. It decreases in a general way within each formation, and, like chromium, shows the greatest break between samples from the lower and upper flows of the Facpi Volcanic Member.

Lead was found only in sample 6.

Scandium generally decreases in each formation and ranges in all samples from 50 to 20 ppm.

Strontium remains nearly constant in the Alutom, ranging from 200 to 300 ppm. In the Umatac Formation strontium ranges from 200 to 300 ppm in the lower flows of the Facpi to 800 to 900 ppm in the upper flows, and to 1,000 ppm in the Dandan.

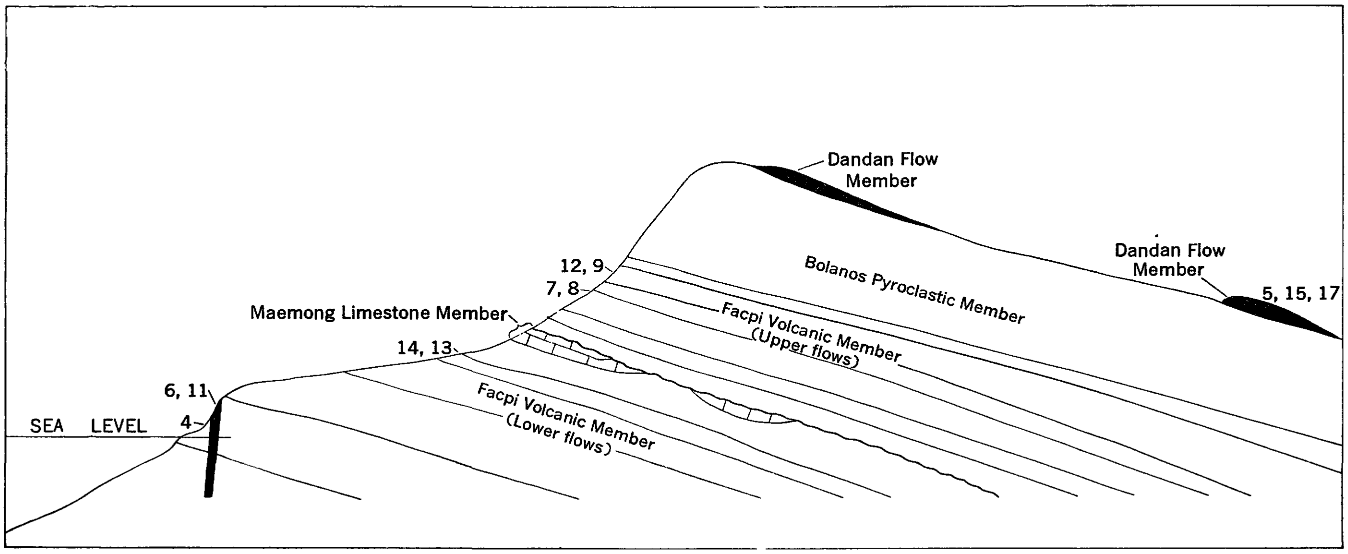


FIGURE 17.—Schematic diagram of the Umatac Formation. Relative stratigraphic positions of volcanic rock samples from the Facpi Volcanic Member and the Dandan Flow Member are shown. Sample descriptions are given in table 2, and locations are shown in figure 2.

Vanadium ranges from 20 to 60 ppm, but shows no notably consistent trend.

Yttrium ranges from 20 to 50 ppm without any significant trend.

Ytterbium ranges from 1 to 5 ppm and generally fluctuates with yttrium.

Zirconium ranges from 10 to 80 ppm and consistently increases with decreasing MgO in each formation. The amount of zirconium is extremely low in all samples, relative to most igneous rock provinces.

As is evident from table 3, several of the minor constituents show systematic variations within each formation and suggest the possibility that the volcanic rocks of Guam can be divided into two differentiation series. The first, consisting of the rocks of the Alutom Formation, of Tertiary *b* and *c* age (late Eocene and early Oligocene), shows a greater range in silica content and lesser ranges in some of the minor elements. The second, consisting of the volcanic rocks of the Umatac Formation of Tertiary *e* age (early Miocene), shows a smaller range in silica content, but greater ranges in minor elements.

Each of these series of rocks shows, with decreasing MgO, a general increase in barium, strontium, and zirconium, and a general decrease in cobalt, chromium, and nickel, similar to variations shown in the rocks of the Hawaiian Islands given in table 3. A quantitative appraisal will not be attempted because of the differences in average amounts of minor elements in each suite of rocks, and because the rocks of Guam do not include rock types at either end of the Hawaiian suite, nor are individual types common to both places closely similar, as is explained earlier in this chapter. Wager and Mitchell (1953, p. 222) concluded that the "close qualitative, and in many cases quantitative similarity in trace element variation of the Hawaiian and Skaergaard series" supported a view that both resulted from the same process, which on other grounds is considered to be fractional crystallization. The general correspondence in variation of some of the trace elements from Guam with those from the Hawaian Islands suggests that the same process has operated for the volcanic rocks from Guam, with the additional factor of incorporation of silicic rocks in the formation of the types containing quartz xenocrysts.

Systematic variations in trace elements are evident when the rocks of Guam are considered as two stratigraphic suites. Variations are not nearly so systematic if the rocks are combined to form one petrographic suite ranging from olivine basalt to sodic andesite; or if all the rocks are arranged as a series with respect to increasing silica (as in table 1) or decreasing magnesia. The difference between the two stratigraphic suites is shown in figure 18, in which chromium, nickel, barium, and strontium are plotted against the MgO content for samples from the Alutom Formation (triangles) and from the Umatac Formation (squares). For each of these minor elements, the Alutom and the Umatac series slope in the same direction; but for each the slope of the Alutom is gentle, whereas that of the Umatac is steep.

A further confirmation of the stratigraphic nature of the variations in the minor elements is obtained by rearranging stratigraphically (table 4) the samples analyzed in table 1. Chemical analyses are given for SiO_2, MgO, K_2O, CaO, and P_2O_5 in percent. Spectrographic results for chromium, nickel, barium, and strontium in parts per million are given for 11 of the samples. Within the Alutom, samples are arranged generally in order of decreasing MgO from bottom to top of the group. Samples 1, 3, and 10 are from the bottom, middle, and top of one flow; sample 2 is from a second flow a little lower stratigraphically. Within the Umatac all samples are arranged in stratigraphic order (fig. 17), and within each subdivision they are arranged in order of decreasing magnesia content upward.

In the Alutom series, CaO decreases with decreasing MgO in most samples. In the Umatac series, CaO decreases with decreasing MgO in the lower flows of the Facpi; but CaO increases again in the upper part and in the Dandan, although MgO continues to decrease. In each series the K_2O generally increases with decreasing MgO, but in the series from the Umatac Formation a break occurs between the lower and the upper parts of the Facpi member. P_2O_5 ranges irregularly from 0.03 to 0.11 percent in the Alutom and in the lower part of the Facpi. Samples from the upper part of the Facpi and the Dandan, however, contain from 0.19 to 0.36 percent P_2O_5. The significance of this jump in phosphate content is not known, but it happens at the same stratigraphic break that separates large changes in chromium, nickel, barium and strontium. Wager and Mitchell (1951, p. 178) report that apatite appears in a flood in late stages of the Skaergaard series, but in the Guam rocks apatite was noted only as rare inclusions in olivine basalt.

The available chemical and trace element data, therefore, suggest that the volcanic rocks of Guam belong to two differentiation series. The first formed the Alution Formation of late Eocene and early Oligocene age, and the second formed the Umatac Formation of early Miocene age. Rocks from these two series cannot be distinguished megascopically or petrographically except in a general way. Further reason for a twofold division of the volcanic rocks is seen in the geologic and bathymetric evidence presented in the section on structure in Tracey and others (1963),

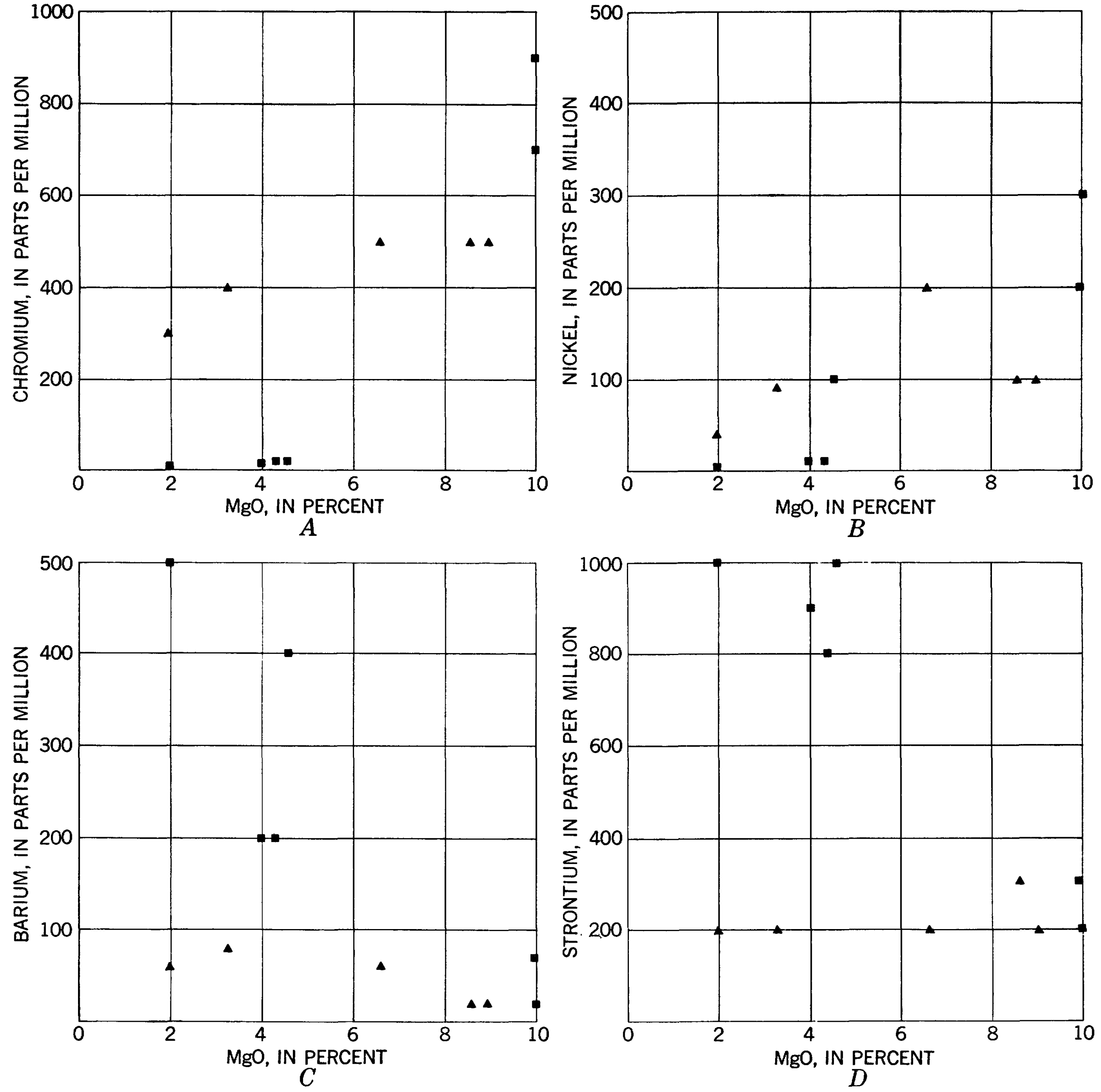


FIGURE 18.—Relation of chromium, nickel, barium, and strontium to MgO in rocks of Guam. Samples from the Alutom Formation are shown by triangles; samples from the Umatac Formation are shown by squares.

which indicates that the volcanic rocks of the Alutom and the Umatac Formations originated from two separate volcanic centers west of the present island.

A considerable break in the trend of a number of the constituents, notably CaO, K_2O, P_2O_5, Cr, Ni, and Sr, occurs within the Facpi Volcanic Member of the Umatac Formation. This break is marked geologically by lenses of the Maemong Limestone Member of the Umatac Formation and at two localities by an unconformity (fig. 17) associated with the Maemong Limestone Member. It is possible, therefore, that the break between the lower and upper parts of the Umatac Formation might be emphasized by contamination by limy rocks. No detailed systematic collections were made,

TABLE 4.—*Selected chemical and spectrographic analyses of volcanic rocks of Guam*

[Field numbers and descriptions given in table 2; locations in figure 2]

			Description	Sample	Andesite (A) Basalt (B)	SiO_2	MgO	K_2O	CaO	P_2O_5	Cr	Ni	Ba	Sr
						Percent					Parts per millions			
UMATAC FORMATION	Dandan Flow Member		Residual boulders	15	A	55. 73	1. 98	2. 14	8. 03	0. 36	2	2	500	1, 000
				17	A	60. 02	2. 86	1. 52	6. 67	. 19	------	------	------	------
				5	B	51. 06	4. 56	1. 02	10. 09	. 22	10	100	400	1, 000
	Facpi Volcanic Member	Upper flows	Flow, near top	12	A	54. 1	3. 7	0. 82	8. 0	0. 26	------	------	------	------
			Bottom	9	A	53. 19	3. 97	. 94	9. 20	. 26	9	10	200	900
			Flow, near middle	7	B	51. 7	4. 7	. 70	9. 1	. 25	------	------	------	------
			Bottom	8	B	52. 09	4. 29	. 76	9. 44	. 24	10	10	200	800
		Lower flows	Dike	11	A	53. 53	5. 41	1. 77	5. 59	0. 08	------	------	------	------
			Flow, near top	13	B	54. 2	8. 0	1. 40	7. 9	. 08	------	------	------	------
			Bottom	14	B	55. 0	9. 4	. 88	7. 9	. 07	------	------	------	------
			Dike	6	B	51. 63	9. 93	. 52	9. 47	. 05	700	200	70	300
			Flow	4	B	50. 85	10. 01	. 16	9. 55	. 03	900	300	20	200
ALUTOM FORMATION			Boulders in pyroclastic breccia	21	A	69. 04	1. 96	1. 00	5. 79	0. 05	300	40	60	200
				20	A	68. 89	2. 11	1. 00	4. 42	. 05	------	------	------	------
				19	A	65. 19	2. 41	1. 04	5. 36	. 11	------	------	------	------
				18	A	64. 49	3. 23	. 80	7. 73	. 08	400	90	80	200
				16	A	58. 43	6. 58	. 54	7. 77	. 08	500	200	60	200
		Basalt flows	Flow, near top	10	B	53. 5	7. 0	0. 62	7. 8	0. 10	------	------	------	------
			Middle	3	B	48. 58	8. 55	. 45	9. 88	. 09	500	100	20	300
			Bottom	1	B	47. 7	9. 0	. 36	10. 3	. 08	------	------	------	------
			Flow	2	B	48. 48	8. 93	. 14	10. 90	. 07	500	100	20	200

however, from base to top of the Umatac whereby the actual flow-by-flow variation in mineral and trace constituents might be shown.

The total number of chemical analyses and particularly of spectrographic analyses from Guam is not large, but the data strongly suggest the existence of two differentiation series. The hypothesis is reasonable because of the accordance with several kinds of field evidence, and because no serious anomalies exist within the suite of samples studied.

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