The Geology of Tofua Island, Tonga[1]

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ABSTRACT: Tofua Island is an oval, steep-sided composite volcano, 5 miles by 6 miles in diameter, the summit of which has collapsed to form a caldera. Within the caldera, Lofia cone is still active.

Four units have been mapped: (1) the Hamatua Formation, of precaldera age, includes basaltic andesites, pyroxene andesites, and pyroxene dacites; (2) the Hokula Froth Lava, a microvesiculated lava flow of andesite; (3) the Kolo Formation, composed of air-laid lapilli tuff-breccia, tuff, unconsolidated ash and cinder, small basaltic andesite lava flows, and one thick pyroxene andesite lava flow; and (4) the Lofia Formation, composed of air-laid tuff, ash, basaltic andesite lava flows, and andesite lava flows. An erosional unconformity separates the Hamatua Formation from the Hokula Froth Lava, and another lies between the froth lava and the Kolo Formation.

The rocks are typical orogenic andesites and related types, unusually high in CaO, which is reflected in the calcic nature of the plagioclase. The pyroxenes of the groundmass are usually pigeonite and pigeonitic augite, whereas the phenocrysts are augite. Hypersthene is less common and occurs only as phenocrysts surrounded by reaction rims of pigeonite and/or pigeonitic augite.

Concentric normal faults associated with caldera collapse are common on the northern, eastern, and southern rims of the caldera. Some of the faults have served as conduits for rising magma of the Kolo Formation; others, on which caldera collapse is continuing, do not exhibit associated volcanism. Tensional cracks are abundant along the southern rim.

THE GEOLOGICAL INVESTIGATION of Tofua Island is part of a larger study of the Tonga and the Lau islands by the Hawaii Institute of Geophysics. The investigation includes paleomagnetic and gravity studies of many of the islands, but only the areal geology and petrology of Tofua are dealt with in this paper.

Field work on Tofua was performed during the first three weeks of June 1968. A base map showing the triangulation stations established by the Tongan Government Survey in 1961 was obtained from the Lands Department of Tonga, in Nuku'alofa. Although the triangulation stations were only temporary, it was not difficult to relocate them, since all were at prominent landmarks or villages. Using them as control, a topographic map of Tofua (Fig. 2 A) with 200-foot contour intervals was drawn up primarily for the gravimetric work, but it was also used as a base for the geologic mapping (Fig. 2 B). Elevations were obtained by aneroid altimeter. Most of the geologic mapping was done concurrently with the topographic mapping.

Tofua's flanks are heavily wooded: rock outcrops are especially difficult to locate on the windward, eastern, and southern slopes. Pyroclastic deposits of the Kolo Formation cover the northwestern flank and part of the western flank, and the bedrock is concealed. Approximately a week was spent working on the caldera rim and within the caldera, and two weeks were devoted to mapping the flanks of the cone.

PREVIOUS INVESTIGATIONS

Previous geological studies in the Tonga Islands (Lister, 1891; Hoffmeister, 1932) were primarily concerned with detailed descriptions

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of the Tertiary limestones. Descriptions of the igneous rocks were brief.

In 1643 Abel Tasman became the first European explorer to sight Tofua Island. He made note of sailing near two high islands (Tofua and Kao) and seemed surprised at their height, for he had just left the low limestone islands that lie east of Tofua. He sketched its profile, and called the island "Amatofua" (Woide, 1776).

The volcanic nature of Tofua was first noted by Capt. James Cook in 1774 when he wrote of "Tofooa" in his journal. Cook sailed a mile north of the island and noted that it was in eruption. His crew reported that raindrops from a localized rainstorm, caused by the eruption cloud, created a burning sensation in their eyes. Cook also wrote that the rocks along the northwest coast were cavernous and appeared to form columns, and that the foliage just below the summit of the island on the northwest flank had been recently burnt. He concluded that the summit of Tofua contained a crater (Cook and Forester, 1777, vol. 4, pp. 162–163).

The first Caucasian to set foot on Tofua was Capt. William Bligh, just after the 1789 mutiny aboard the "Bounty." He also described "Tofoa" as a volcanic mountain, and made reference to deep gullies on the southwestern side (Dalyell, 1812, p. 153).

Later, Lister, who visited the island in 1889, stated (1891, p. 593) that "Tofua is a volcano in a state of intermittent activity." He provided Alfred Harker, of Cambridge University, with a collection of rocks from Tonga, but rocks from Tofua were not among them (Harker, 1891).

Marshall (1911, p. 22) made collections on the island. He gave the first brief petrographic descriptions, stating that the rocks were "augite andesites." Daly (1916, p. 340) repeated Marshall's statement.

No further work was done on Tofua until 1959, when Richard (1962, p. 16) visited the island and collected two samples which were chemically analyzed. The analyses indicated that the rocks are quartz basalts in Rittmann's (1952) classification. However, the MnO content of the rocks as reported in the analyses is nearly 2 percent, which is much too high for rocks of this type. In the new analyses of Tofua rocks given in Table 1 of this paper, only normal amounts of MnO, in the vicinity of 0.16 percent, are shown.

GEOGRAPHICAL DESCRIPTION

The Tonga Archipelago lies between latitudes 15° and 22°S and longitudes 173° and 177°W. Its northern end lies approximately 400 miles south of Samoa, and it stretches on southward for approximately 160 miles. The northernmost islands are Niuafo'ou and Niuatoputapu. Farther south these islands fall into three recognized groups, or island clusters: Vava'u, the most northerly; Ha'apai, about 70 miles to the south; and Tongatabu, 90 miles farther south. Tofua is one of the westernmost islands of this Ha'apai Group (Fig. 1).

Just west of the Tonga Trench a series of coralline islands lies in a north-south alignment along the eastern side of the archipelago. The volcanic islands form a line paralleling the coralline islands on the western side. Along the volcanic line there are several active terrestrial and submarine volcanoes, Tofua being one of the more prominent of the terrestrial ones. According to Admiralty Chart 2421, the geographic center of Tofua is at 19°45′S and 175°05′W. The island is 17 miles northwest of Kotu Island, from which it is separated by the north-south-trending Tofua trough. The volcanic island of Kao lies 4 miles to the north. It is joined to Tofua by a submarine ridge. The "andesite line," marking the boundary between continental- and oceanic-type volcanics, lies along the Tonga Trench (Marshall, 1911; Macdonald, 1949, p. 1590), and the rocks of Tofua are all volcanic and of continental orogenic types.

GEOMORPHOLOGY

Tofua Island is oval in plan, and approximately 5 miles by 6 miles across (Fig. 2 A). It is a single composite volcano, the summit of which has collapsed to form a caldera. The lower slopes rise at an angle of about 35°, but the slope angle decreases near the summit. When viewed from the east, Tofua has an extremely regular profile. Elevation of the caldera rim varies less than 300 feet—from 1,400 to almost 1,700 feet.

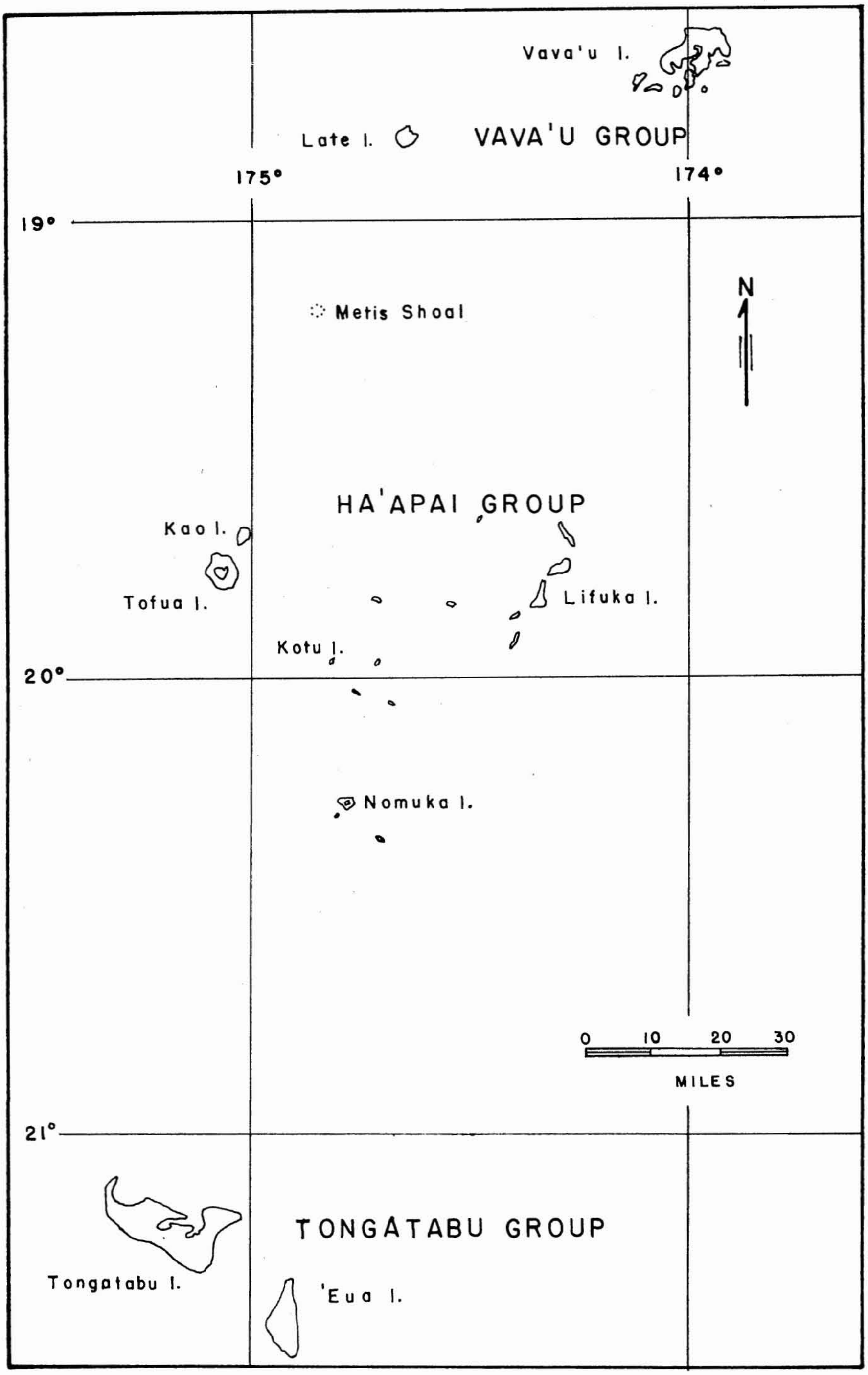


FIG. 1. Map of the main part of the Tonga Archipelago, showing the location of Tofua Island.

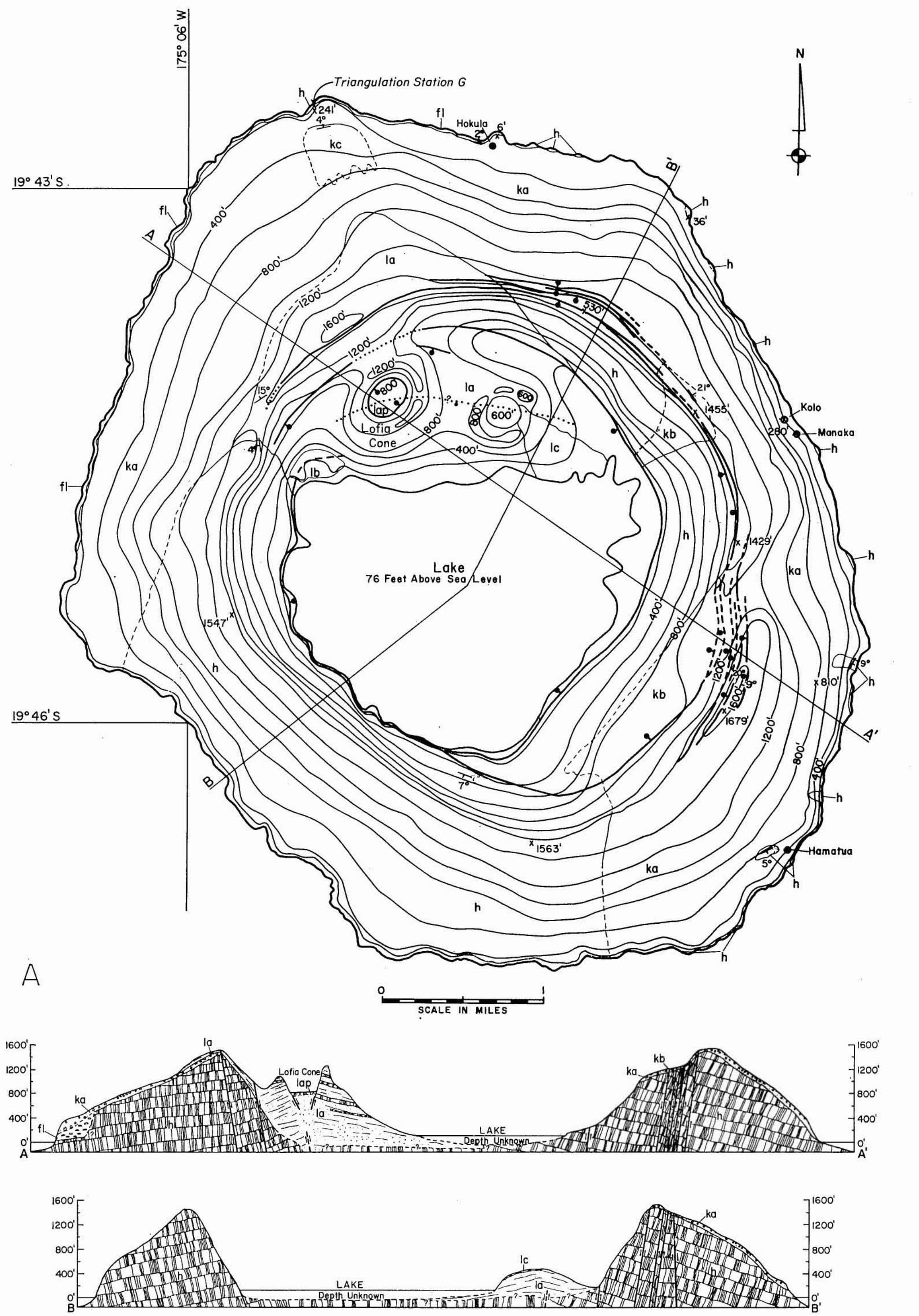
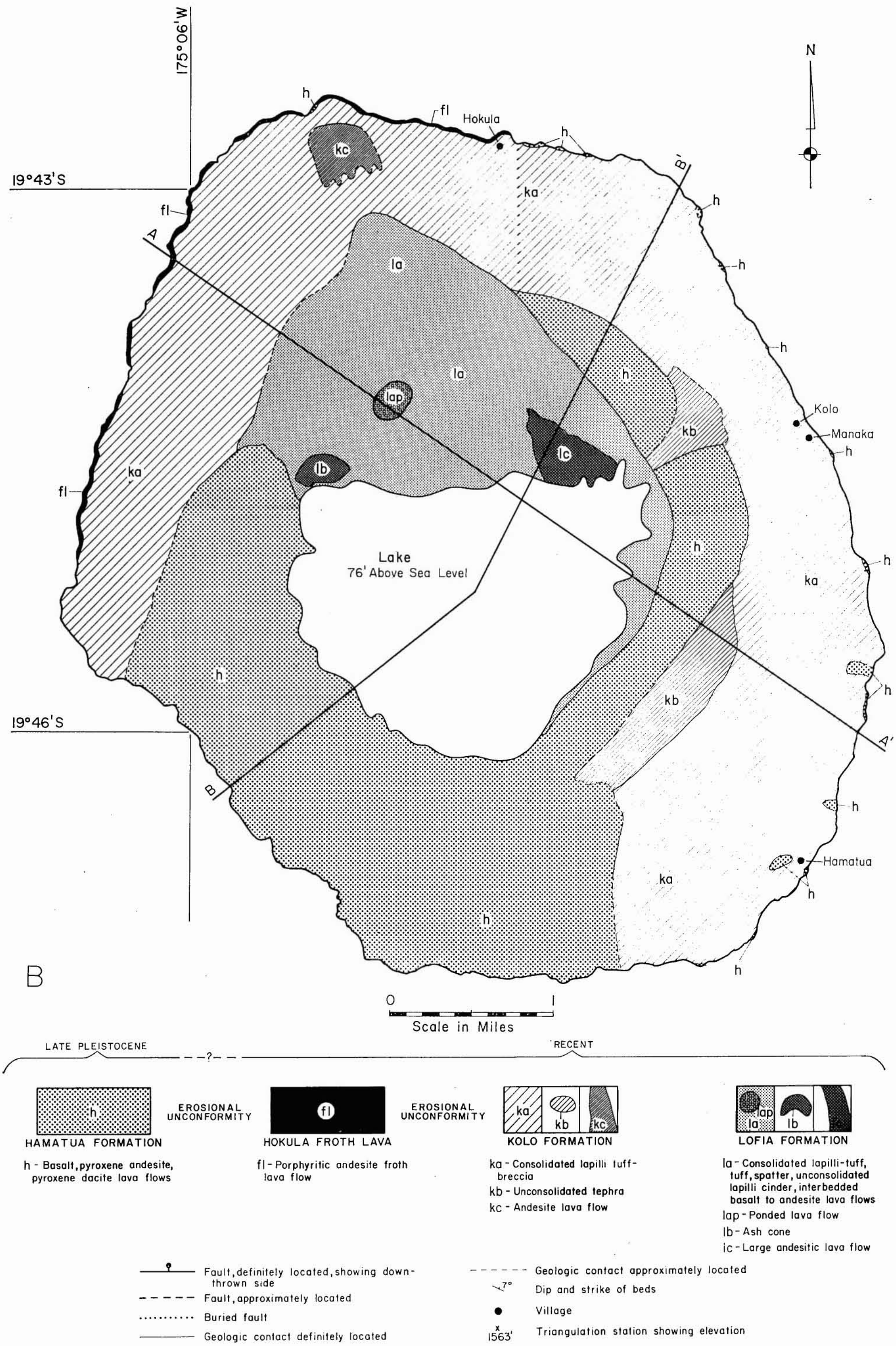


FIG. 2. Topographic map (A) and geologic map (B) of Tofua Island. Geology by Glenn R. Bauer, June 1968.


175°06'W
N
19°43'S
19°46'S
Hokula
Kolo
Manaka
Hamatua
Lake
76' Above Sea Level
A
A'
B
B'
h
fl
ka
kb
kc
la
lap
lb
lc
B
0
1
Scale in Miles
LATE PLEISTOCENE
RECENT
?
HAMATUA FORMATION
h - Basalt, pyroxene andesite, pyroxene dacite lava flows
EROSIONAL UNCONFORMITY
HOKULA FROTH LAVA
fl - Porphyritic andesite froth lava flow
EROSIONAL UNCONFORMITY
KOLO FORMATION
ka - Consolidated lapilli tuff-breccia
kb - Unconsolidated tephra
kc - Andesite lava flow
LOFIA FORMATION
la - Consolidated lapilli-tuff, tuff, spatter, unconsolidated lapilli cinder, interbedded basalt to andesite lava flows
lap - Ponded lava flow
lb - Ash cone
lc - Large andesitic lava flow
Fault, definitely located, showing downthrown side
Fault, approximately located
Buried fault
Geologic contact definitely located
Geologic contact approximately located
7°
Dip and strike of beds
Village
1563'
Triangulation station showing elevation

The caldera is subcircular, with an average diameter of 2.5 miles. Half of its floor is occupied by a crater lake of unknown depth, the surface of which is 76 feet above sea level. The walls of the caldera are extremely precipitous, but the southern, southwestern, and northern walls are not as steep as the others. In some places the caldera floor is more than 1,400 feet below the rim, but the mean difference in elevation is approximately 1,100 feet.

Two prominent spatter-and-cinder cones occupy the northern and eastern parts of the caldera. Less prominent is an older, deeply eroded ash cone near the western caldera wall.

Lofia cone, the northern cone, is still active, though currently it is in a fumarolic state. Its crater is about 400 feet deep, with a flat floor formed by a ponded lava flow. The eastern cone is dormant and has three vents, two of which are shown as craters on the topographic map. Its summit is 600 feet above the crater lake, though only 200 feet above the southern flank of Lofia cone.

The caldera is continuing to collapse along relatively minor faults on the northern, eastern, and southeastern sides. The fault displacements have given this part of the rim a hummocky topography, with small grabens and steps with escarpments averaging from 50 to 100 feet high.

Large stream valleys do not exist on Tofua: all the valleys are narrow and small, though some are deep. They are mostly on the southeastern to southwestern flanks—the windward side. These steep-sided windward valleys extend no more than a quarter of a mile inland. Some valleys near Hamatua village cut into rocks of the Hamatua Formation, but all valleys in the vicinity of Kolo and Manaka villages cut only postcaldera tuffs of the Kolo Formation. Earlier valleys, if they were present, have been buried beneath thick tuff deposits of the Kolo Formation. Small gullies of intermittent streams along the northern coast cut only rocks of postcaldera age.

Intermittent streams have gullied the soft tuff and ash fill in the northern and eastern parts of the caldera. The gullies are commonly 5 to 10 feet deep, with very steep walls. More extensive gullying has taken place on the southern and southwestern walls of the caldera, in rocks of precaldera age.

The wave-cut cliff that encircles most of Tofua averages 150 feet in height. The cliff is especially precipitous where froth lava is exposed, the steepness being due to undercutting in the lower clinker zone of the flow, with subsequent breaking of the overlying massive rock along joints.

STRATIGRAPHY AND LITHOLOGY

General statement

Four stratigraphic units have been mapped: (1) Hamatua Formation, (2) Hokula Froth Lava, (3) Kolo Formation, and (4) Lofia Formation. The sequence of the units was determined by superposition. Some rocks of the Kolo Formation are contemporaneous with some rocks of the Lofia Formation, but their spatial distribution is not the same and they have therefore been mapped separately in Figure 2 B.

Ninety-eight thin sections were examined in detail. The rocks were classified by color index and the amount of free silica present as observed silica minerals. However, the latter method is not completely dependable. Some of the more silicic chemically analyzed samples do not contain any observable silica minerals. The excess silica is probably contained largely in the glass. Rittmann's zonal method was used with four-axis universal stage to determine the composition of zoned plagioclase (Emmons, 1943, pp. 115–133). Combined albite-Carlsbad twinning and maximum extinction angles were used to determine the composition of unzoned plagioclase.

Hamatua Formation

The Hamatua Formation, which consists of lava flows erupted before the collapse of the caldera, is named for the village of Hamatua, on the southeastern edge of the island. The formation crops out directly behind the village as a thick hypersthene-bearing augite dacite lava flow (chemical analysis 3, Table 1), forming an abrupt cliff 50 feet high. Below the village it forms rocky points. Although it is the most voluminous rock unit on the island, the Hamatua Formation is exposed only in scattered patches on the flanks of Tofua cone, usually in the form of rocky points along the shore, or along stream beds. It is covered by residual soil on the southwestern flank, but is exposed in the sea cliff.

The Hamatua Formation is best exposed in the walls of the caldera, where it is more than 1,600 feet thick. The average thickness of individual flows is approximately 70 feet. Each flow consists of a thick, dense central portion, with relatively thin clinker zones above and below it. Poorly formed vertical joints are typical in the central mass. No columnar jointing was seen. The flows appear to be of the block lava variety (Macdonald, 1967, p. 23). The clinker fragments are less spinose than those of typical aa flows. In most cases they grade into the dense central portion of the flow.

The Hamatua rocks are light- to dark-gray basaltic andesites, hypersthene-bearing augite andesites, andesites, and hypersthene-bearing augite dacites. The lighter rocks display conspicuous flow structure, with alternate light and dark bands averaging about 2 cm thick, which are usually distorted due to deformation during flowage.

In hand specimens the andesites and dacites often appear vitreous. Thin-section examination shows that some are quite vitreous, though most are composed of microlites of plagioclase feldspar, clinopyroxene, magnetite, and silica minerals, with only a minor amount of glass. The texture is usually hyalopilitic, but intergranular and intersertal textures are also present. The feldspar laths sometimes exhibit subparallel flow structure. The basaltic andesites usually have intersertal to intergranular texture, though some are hyalo-ophitic.

A 400-foot type section of the Hamatua Formation was measured just below the rim in the caldera wall between triangulation stations B and B1 (Fig. 2 A). The lower 350 feet consists of thick flows of andesite containing phenocrysts of hypersthene and augite, and some nonporphyritic flows. The bottom flow is nearly 80 feet thick. At the top of the section is a basaltic andesite flow containing relatively large crystals of pigeonite.

A sample of hypersthene-bearing augite dacite was collected behind Hamatua village at an elevation of 500 feet (analysis 3, Table 1).

All varieties of rocks in the Hamatua Formation usually contain plagioclase phenocrysts and microphenocrysts, which commonly are zoned from a calcic core to a more sodium-rich rim. The cores of the phenocrysts range from An_{90} to An_{51}. The more sodic cores are found in the late flows, most of which are basaltic andesite. Groundmass plagioclase is generally more sodic than the phenocrysts, and sometimes is normally zoned. Its average composition is about An_{45}. When hypersthene is present it is always surrounded by a rim of either quasi-uniaxial pigeonite or pigeonitic augite. Augite phenocrysts usually do not show disequilibrium with the surrounding former liquid, though in some thin sections they are slightly embayed. Groundmass pyroxene ranges from entirely pigeonite in the more basic rocks to combinations of pigeonite, pigeonitic augite, and augite in the andesites and dacites. Small magnetite crystals are present in the groundmass, and some large grains appear in glomerocrysts of plagioclase, augite, hypersthene, and, in rare instances, pigeonite. Interspersed throughout the groundmass of the more silicic varieties are silica minerals which have been identified as quartz and tridymite. Neither alkali feldspar nor apatite was observed.

Small elongate angular inclusions of coarser rock are common in the more siliceous of the Hamatua lavas. They may be the result of local retention of volatiles during cooling. Quartz and tridymite are more abundant in these inclusions than in the rest of the rock.

Hokula Froth Lava

Forming the sea cliff on the northern and western shores of Tofua is a rock which in hand specimen appears tuffaceous, but which in outcrop shows evidence of emplacement by flowage. It resembles rocks which in other parts of the world have been called "froth lava" (Locardi and Mittempergher, 1965). It is here named the Hokula Froth Lava, after the nearby Hokula village.

The Hokula Froth Lava directly overlies the Hamatua Formation and is separated from it by an erosional unconformity. It is overlain by rocks of the Kolo Formation and is exposed only in the sea cliff. Consequently, its extent cannot be determined. It probably came from the upper part of the mountain, but it has not been found in the caldera wall.

The type section of the Hokula Froth Lava is approximately 0.1 mile west of Hokula village where two separate flow units of froth lava form a wave-cut cliff about 80 feet high. The lower of these units has been oxidized to a bright red color, whereas the upper is gray to green. Structurally, both units are identical, each consisting of three parts: a massive central portion grading into clinker zones above and below it. Usually, the lower clinker layer is thicker than the upper one. The basal clinker of the lower flow is approximately 5 feet thick, consisting of cobble-size blocks that were slightly welded together after the flow came to rest. The massive central portion of the flow has an average thickness of 10 feet. In it there are lenticular masses that are lighter in color than the surrounding rock. The masses are composed of the same material as the enclosing rock, but are more vesicular. A thinner clinker layer overlies the massive center with a gradational contact. Its nature is the same as that of the basal clinker. The upper flow unit repeats the sequence described, the only difference being that it is thinner, with a total thickness of only about 15 feet.

Columnar jointing is poorly developed in the froth lava, each of the columns being several feet across. The ocean waves erode the froth lava with ease, and the squarish caverns which they cut owe their shape to the joint pattern.

In thin section, the Hokula Froth Lava shows a great many microvesicles, which range in shape from round to angular. The rock is highly vitreous, containing small microlites of plagioclase and green pyroxene, and phenocrysts of hypersthene, augite, and plagioclase in a glass matrix. In the lower flow unit the glass is red; in the upper one it is greenish gray. Most of the glass is heavily clouded with dusty opaque material, but small amounts of clear glass are present in both units. The refractive index of the clear glass ranges from 1.552 to 1.535 ($\pm$.002). According to a graph published by George (1924, p. 365) of refractive index versus silica percentage, the froth lavas are andesitic. Tridymite has been identified in some of the samples, usually in the vesicles. Small lithic inclusions are present.

Locardi and Mittempergher (1965, 1967) have described froth flows in central Italy. They believe that the froth lava is the result of gas separation in a volatile-rich flow, and represents a transition between ordinary lava flows and ignimbrites. If vesiculation is extreme, the rock disintegrates and becomes an ash flow; but if vesiculation does not proceed far enough to cause disintegration, the rock remains pumiceous froth lava.

Lenticular pumice masses have been described by Locardi and Mittempergher (1967, pp. 133–134) within the central portion of the Italian froth lavas. They believe the elongated masses of pumice are caused by the pulling apart of certain bands where vesiculation was greatest. On Tofua Island the lenses of pumiceous material are found randomly scattered through the central portions of the flow units, but with their longest axes parallel to the top of the flow.

Inclusions in the Hokula Froth Lava

Angular cobble-size xenoliths are common in the Hokula Froth Lava. Less abundant are rounded boulder-size xenoliths. Both types are fragments of rocks of the Hamatua Formation, or of other rocks presumably from the basement, brought to the surface by the rising magma. The rocks range from fine to medium grain, the fine-grained varieties predominating.

The fine-grained xenoliths are texturally and mineralogically similar to the rocks of the Hamatua Formation described above. The coarser grained rocks, however, appear to have crystallized under deeper-seated conditions, and have been identified as augite diorite micropegmatite. Intergrowth of quartz and plagioclase feldspar is common and occurs as a matrix between the larger grains of normally zoned subhedral plagioclase and greatly altered augite. Most of the augite has been altered to a low-birefringent green mineral or mineraloid. One sample was stained for alkali feldspar, with a negative result. Except for the quartz-feldspar intergrowth, the texture between the larger crystals is hypidiomorphic granular.

Some of the finer grained xenoliths do not resemble the rocks of the Hamatua Formation in the nature of their pyroxenes. Frequently they contain phenocrysts of pigeonite, pigeonitic augite with cores of pigeonite, augite, and hypersthene with pigeonitic rims. The bulk of the groundmass pyroxene is pigeonite. These rocks commonly are coarser grained than the Hamatua lavas, but are not typically plutonic. They may have been derived from shallow intrusive bodies. Whether or not these rocks are directly related genetically to the Tofua volcano is not known.

Kolo Formation

The Kolo Formation consists of consolidated lapilli tuff-breccia, with local deposits of tuff and interbedded rootless basaltic andesite lava flows, unconsolidated ash and cinder, and one thick lava flow of porphyritic hypersthene-augite andesite. The lapilli tuff-breccia is by far the most abundant member. It is best seen near the village of Kolo.

The lapilli tuff-breccia is an air-laid deposit, poorly sorted, with weakly developed bedding. It is composed of approximately 50 percent angular lapilli-size blocks and cinder, 40 percent ash, and 10 percent blocks larger than lapilli. Locally, however, the proportions change and zones of tuff become abundant. Clasts of lapilli size and larger appear to have been derived from the Hamatua Formation. The ash and cinder are commonly vitreous and represent new magmatic material. The refractive index of the glass in them shows it to be basaltic. Within the lapilli tuff-breccia are small rootless basaltic andesite flows, which microscopically are similar to the andesitic lavas of the Hamatua Formation but relatively poor in phenocrysts. A flow near Hokula has been identified as hypersthene- and augite-bearing basaltic andesite. The phenocrystic feldspar is bytownite, and the groundmass feldspar is labradorite.

The consolidated lapilli tuff-breccia member rests unconformably upon the Hamatua Formation on the southern, eastern, and northern flanks of Tofua. It forms a blanket approximately 100 feet thick over the entire area, though its thickness increases where it fills valleys previously cut into the Hamatua rocks. Near Hamatua village it grades into consolidated black ash, which is as much as 200 feet thick, perhaps because it fills a valley.

Near Hokula village the lapilli tuff-breccia is separated from the underlying Hokula Froth Lava by an erosional unconformity and a layer of tuff. This unconformity can also be seen 0.25 mile west of triangulation station G (Fig. 2A). There, a deep valley cut into the froth lava is filled with 150 feet of interbedded ash and lapilli tuff-breccia. Conformably overlying this sequence is a thick and extensive porphyritic hypersthene-augite andesite block-lava flow (analysis 6, Table 1). The flow, which is 70 feet thick, forms a broad plateau in the vicinity of triangulation station G. In thin section the groundmass of the flow is seen to be hyalopilitic, with microlites of labradorite, clinopyroxene, and magnetite. Hypersthene and augite phenocrysts, usually clumped together as glomerocrysts, appear ragged and have been embayed by the groundmass. Phenocrysts of pigeonite also are present.

Source vents of the consolidated lapilli tuff-breccia dot the northeastern, eastern, and southern caldera rims. These vents are commonly shallow, with gradually sloping walls. They resemble maars in other parts of the world. A few small craters 30 feet across and 50 feet deep are found on the northeastern rim. Considering the number of blocks of rocks of the Hamatua Formation in the tuff-breccia, and the maarlike appearance of the craters, it is probable that the explosions that formed the tuff-breccia took place very near the surface, and probably were phreatic and phreatomagmatic.

The unconsolidated tephra of the Kolo Formation is younger than the tuff-breccia. Unconsolidated tephra overlies consolidated tuff-breccia near triangulation station B1 and on the southeastern rim of the caldera. The source of the unconsolidated tephra is a series of cinder cones that erupted on the caldera rim. Near triangulation station B1, recent faulting has truncated the cinder cones, debris from which now forms talus resting against the caldera wall. Most of the fragments in the tephra are pumiceous lapilli-size cinder, though some spindle bombs also are present. The refractive index of the glass in the cinder is 1.559 ($\pm$.002), indicating that it is basaltic.

The relationship of the source vents of the Kolo Formation on the caldera rim to the fault pattern is clear. Concentric faults formed during caldera collapse provided conduits for rising magma. However, it is not known whether the thick andesite flow near triangulation station G originated at the caldera rim. Its source has been buried beneath later deposits of the lapilli tuff-breccia and the pyroclastics of the Lofia Formation.

Lofia Formation

Rocks of the Lofia Formation are mainly confined within the caldera, though they are continuously exposed down to an elevation of 950 feet on the northern flank of the volcano. Those outside the caldera constitute only a thin veneer, and were derived from the large spatter-and-cinder cones in the caldera. For the most part they overlie the rocks of the Kolo Formation, but on the caldera rim the contact between the two formations is gradational, and in that area the rocks of the two formations were erupted partly simultaneously. Within the caldera, the Lofia Formation overlies rocks of the Hamatua Formation which have collapsed into the caldera.

The name Lofia Formation is derived from Lofia cone, the still-active vent within the caldera. Almost all of the members of the formation can be seen within Lofia cone itself. Pyroclastic rocks probably comprise 90 percent of the formation, and include lapilli tuff, tuff, spatter, and unconsolidated lapilli cinder. They are interbedded with small basaltic andesite and andesite lava flows. The older cone near the western caldera wall is composed mainly of weathered ash. The lava flow ponded on the floor of Lofia crater has been mapped as a separate unit (Fig. 2*B*). Only one other lava flow is large enough to be mapped separately. The flow is vesicular andesite.

The pyroclastic deposits of the Lofia Formation are thin bedded and friable, with only rudimentary size sorting. Near the cinder cones lapilli ash predominates, whereas the walls of the caldera are mantled by ash with few lapilli, indicating that most of the larger fragments fell closer to the vents. However, spatter and "cow-dung" bombs averaging 50 cm in diameter are plastered against the eastern wall of the caldera, half a mile from their source. From their position it is clear that they were formed by a directed blast from Lofia cone.

The lapilli ash and tuff of Lofia cone contains some angular blocks. A block selected at random for thin sectioning proved to be microscopically very similar to a small porphyritic basaltic andesite lava flow found interbedded with the tuff in the cone. Thin lava flows intercalated in the spatter and tuff are exposed in the walls of Lofia crater, and appear to be the same as the block and the basaltic andesite flow on the flank of the cone. In thin section, the porphyritic basaltic andesite flow (analysis 7, Table 1) is seen to be crowded with phenocrysts of calcic plagioclase, augite, pigeonitic augite, pigeonite, augite with pigeonite cores, and olivine. In addition, rounded and embayed xenocrysts of augite are present. The olivine grains do not have reaction rims, but are anhedral. Labradorite and pigeonite are present in the groundmass, surrounded by dark glass. In hand specimens small aggregates of olivine are seen.

The refractive index of glass from samples of cinder in the Lofia Formation ranged from 1.559 to 1.563 ($\pm$.002), indicating silica percentages of about 52 to 53, which are in the range of basaltic andesite. The glass is both red and greenish gray. The latter contains tiny needles of green clinopyroxene and plagioclase.

All the lava flows of the Lofia Formation are within the caldera, and all are relatively thin when compared with those of the Hamatua Formation. Most of them appear to be rootless, but this is not certain since the large volume of pyroclastics may cover their sources. Only one lava flow is seen to be continuous over any great distance. It is an andesitic aa flow, approximately 0.75 mile long and 0.25 mile wide, which poured out of the now-dormant southern vent and terminated at the crater lake.

GEOLOGIC STRUCTURE

Faults

The largest structural features on Tofua are faults associated with the caldera collapse. These can be grouped into three main classes: (1) the main faults bounding the sunken block of the caldera, (2) faults parallel to the main caldera-boundary faults along which volcanic eruptions have taken place, (3) faults along the rim of the caldera along which eruptions have not taken place.

The maximum displacement of the caldera-boundary faults is more than the 1,500-foot height of the caldera wall, since the base of the wall is buried by later volcanics. Even though part of the caldera-boundary fault zone is buried, its trace is visible as recent scarplets in the volcanics of the Lofia Formation.

Although the caldera-boundary fault is shown in Figure 2A as a single continuous fault, in actuality it appears to be a zone of many closely spaced fractures. Along the southern lakeshore the caldera-boundary fault zone consists of two major faults, between which is a large down-dropped portion of the rim that has the form of a giant step, with its surface sloping westward approximately 9°. Cinder cones along the fault that forms the east side of the step have erupted the unconsolidated tephra of the Kolo Formation.

The faults of the second class are the most numerous of the three. They are concentric to the caldera and are found on its northern, eastern, and southeastern rims outside the main caldera-boundary faults. They seem to represent an outward spreading of the zone of caldera collapse, but as yet displacements on them have been relatively small. They have acted as conduits for rising magma; along the eastern rim of the caldera were the loci for the source vents of the Kolo Formation. It is noteworthy that on Tofua no eruptions have taken place on radial fissures.

Faults of the third class comprise the high-angle normal faults occurring on the eastern rim of the caldera. Those associated with faults of the second class usually are found closer to the caldera. Commonly two or three parallel faults have given rise to step faulting and grabens. Vertical displacement on individual faults is as much as 50 feet, but averages about 25 feet. These faults represent rather superficial slumping along the main caldera-boundary scarps.

A few faults within the caldera north and east of Lofia cone, which have not been the loci of eruptions, are believed to be part of the caldera-boundary fault zone.

Tensional Cracks

Tensional cracks extend along the southeastern rim of the caldera, but are not found elsewhere. Many are a few inches wide, though some are several feet wide and are open to an estimated depth of 60 feet. Little or no vertical displacement has occurred on them. The larger cracks are concentric to the caldera, while the smaller ones meander, following local joint patterns. They are found with faults of the second and third classes, and it is inferred that the cracks may later develop into faults.

Pseudo-folds

Fold-like structures on Tofua were formed by mantling of preexisting topography by volcanic rocks. Near triangulation station F, mantle bedding in the tuff-breccia of the Kolo Formation along the caldera rim dips 20° in both directions from the rim and resembles a small anticline. A similar structure is found where pyroclastic rocks of the Lofia Formation rest on the northern rim of the caldera. Structures resembling plunging synclines are found along the western coast, where froth lava flows followed valleys cut into the precaldera surface. At the end of the froth lava eruption the fluid parts of the flows drained away, lowering the center of the flow but leaving chilled lava adhering to the valley walls. The resulting lava sheet is U-shaped in cross section and resembles a syncline. Similar "plastering" lava flows are found on the flanks of Haleakala volcano in Hawaii (Stearns and Macdonald, 1942, pp. 97–98). No true folding was found on Tofua.

MINERALOGY

Plagioclase Feldspar

Plagioclase is by far the most abundant mineral in the rocks of Tofua. Most of the rocks contain phenocrysts of plagioclase, and all have plagioclase in the groundmass. Even vitreous cinder contains fine needles of plagioclase.

The plagioclase is usually subhedral. In some rocks some phenocrysts are euhedral, whereas other nearby phenocrysts of the same composition are deeply corroded. Other rocks contain phenocrysts of widely varying composition. Phenocrysts of plagioclase range in size from about 2.0 to 0.3 mm long; groundmass laths range from about 0.5 to 0.08 mm. The smaller sizes are prevalent in the andesites. In the andesite and dacite of the Hamatua Formation, plagioclase phenocrysts often form glomerocrysts, either alone or with other minerals.

Whether as phenocrysts or in the groundmass, plagioclase laths usually show normal zoning, although reverse zoning may also be present in some crystals. Normal oscillatory zoning is common, and is probably due to a combination, as suggested by Vance (1962, p. 751), of falling temperatures and fluctuation in the supersaturation and undersaturation of the melt in the constituents of the feldspar. Rounded cores are very common in the zoned phenocrysts. The composition of the cores ranges from An_{90} to An_{40}, whereas that of the rims ranges from An_{53} to An_{32}. Zoned groundmass plagioclase is more sodic, the cores ranging from An_{59} to An_{38}, and the rims from An_{40} to An_{35}.

Some of the plagioclase phenocrysts and larger groundmass laths contain inclusions of glass, magnetite dust, and microlites of clinopyroxene. Similar inclusions have been reported by Kuno (1950, p. 968), Swanson (1966, p. 1303), and Macdonald and Katsura (1965). They are common in orogenic andesites and related rocks.

The forms of the inclusions are quite varied. In some cases they occur only as elongated blebs usually parallel to the (010) face in the core of the crystal. In the plagioclase of glomerocrysts the inclusions tend to form in zones of rounded blebs, giving the appearance of embayment and subsequent growth of the feldspar grains. In some examples blebs cut across oscillatory zoning. Commonly the inclusions form at the junction of the (001) plane with the (010) plane. When this occurs, the bleb may have a triangular cross section, suggesting that melting of the crystal took place along lines of inherent weakness in the crystal structure. In some cases almost all of the plagioclase crystal is crowded with dark blebs, but more commonly inclusions are found in only about 25 percent of the lath.

Kuno (1950, pp. 967–968) explains the occurrence of the glassy inclusions in the plagioclase by a remelting of the host crystal along its crystal faces when it is enclosed in a magma that is in equilibrium with more calcic plagioclase. He considers the plagioclase grains that show this phenomenon to be xenocrysts. Rapid crystal growth also can explain the trapping of blebs of liquid magma and mineral grains within the plagioclase.

Most of the feldspar phenocrysts in the basaltic andesites of the Lofia Formation are crowded with glassy inclusions, whereas the more acidic rocks of the earlier Hamatua Formation contain only small amounts of plagioclase with inclusions, and the coarse-grained xenoliths in the froth lava do not have any glassy blebs in the feldspar. This suggests a quieter magmatic history for the older rocks, and a more complex history, probably with a greater amount of contamination, for the more recent magmas.

Pyroxene

Pigeonite is the most abundant pyroxene in the groundmass of the Tofua rocks. It may also occur as phenocrysts in some basaltic andesites and rarely in andesites. The optic plane of the pigeonite is parallel to (010), indicating that it is a calcium-rich variety (Tröger, 1959, p. 57). Large pigeonite grains usually are rounded and embayed, though large subhedral lath-shaped grains do occur in a late basaltic andesite flow of the Hamatua Formation. Pigeonite is present as cores surrounded by rims of either augite or pigeonitic augite in the basaltic andesite flow of the Lofia Formation.

Pigeonitic augite is a common constituent of the groundmass, where its shape is generally anhedral. Phenocrysts of pigeonitic augite are typical of the basaltic andesites, but are rare in the other rocks. The phenocrysts sometimes have cores of pigeonite, and when this is the case the $2V_z$ of the pigeonitic augite tends to be small. On the other hand, if there is no core of pigeonite, the $2V_z$ of the pigeonitic augite approaches that of true augite (40°).

Some reaction rims around hypersthene appear to be pigeonitic augite, but the grains are so small that identification of the mineral is not certain.

Augite is the commonest phenocryst in the rocks of Tofua. It occurs also in the groundmass, but it is not as plentiful there as are pigeonite and pigeonitic augite. As a phenocryst, it is often a single crystal, but it is sometimes associated with plagioclase, hypersthene, and magnetite in glomerocrysts. Grain shape varies greatly from rock to rock, and sometimes within a single rock. The majority of augite phenocrysts are subhedral laths showing some resorption, but euhedral grains are not uncommon. Deeply embayed and rounded xenocrysts of augite are present in the basaltic andesite flow of the Lofia Formation.

Augite phenocrysts range from 3.0 to 0.5 mm in length, whereas groundmass augite is comparable in size to the pigeonite. In the augite andesites of the Hamatua Formation the phenocrysts are relatively uniform in size throughout the rock. In the more basic rocks there is greater variation in size.

Some augites are slightly pleochroic, with X = green, Y = green, and Z = grayish green. However, pleochroism is not common; crystals are usually gray green in thin section. The optic axial angle usually is between 44° and 47°. An augite phenocryst with $2V_z = 60°$ was found in the thick porphyritic augite-hypersthene andesite flow in the Kolo Formation. Extinction angles measured from flash figures show $Z\Lambda c = 44°$, and the refractive index N_y averages 1.692 (± .002). Hence the average weight percent composition of the augite is $Mg_{47}Fe_{28}Ca_{25}$ (Heinrich, 1965, p. 219). In some instances augite phenocrysts have overgrowths of augite with higher birefringence in the same crystallographic orientation, indicating an enrichment of either calcium or iron, or both, in the outer layer.

The augite sometimes contains small inclusions of other pyroxenes of lower birefringence, presumably pigeonitic (though no optic figures were obtained). Blebs of magnetite also are sometimes present, and both may occur in the same crystal.

Hypersthene is the least abundant pyroxene in the Tofua rocks. It has been identified only as phenocrysts, either alone or in glomerocrysts with augite and/or pigeonite, plagioclase, and magnetite. It always has a rim of either pigeonite or pigeonitic augite. It is usually present in the augite andesites and augite dacites of the Hamatua Formation, but it has not been found in the basaltic andesites.

Olivine

Olivine was found only in the basaltic andesite flow of the Lofia Formation, where it forms both small dunite inclusions and large individual grains. The latter are somewhat rounded, but have no reaction rims.

The olivine has an optic axial angle close to 90°. Its refractive indices are $N_x = 1.655$, $N_y = 1.673$, and $N_z = 1.690$ (±.002). Its composition is about Fo_{90} (Heinrich, 1965, p. 145).

Silica Minerals

Quartz and tridymite occur together in the more silicic andesites. They are also present in some inclusions in the Hokula Froth Lava. They commonly line vesicles or occur as microveinlets showing micropegmatitic intergrowth with plagioclase. This intergrowth is coarser than the surrounding rock, and it is postulated that the coarser grain of the veinlets resulted from retention of volatiles locally after the end of the main period of crystallization of the rock.

Opaque Minerals

Magnetite commonly forms euhedral to subhedral grains averaging 0.05 mm across. Herringbone magnetite is sometimes found between the feldspar grains of the groundmass, but it is rare. In a pyroxene dacite flow large octahedra of magnetite are found in glomerocrysts of plagioclase, augite, and hypersthene. Magnetite dust is very abundant in blebs of glass that are included in some plagioclase and augite phenocrysts.

Ilmenite also is present in the Tofua rocks, but it is much less abundant than magnetite.

CHEMICAL ANALYSES

Seven rocks from Tofua were analyzed chemically. The analyses, together with their respective CIPW norms and modal compositions of the rocks, are given in Table 1. The Hokula Froth Lava itself was not analyzed because of its high degree of oxidation. Each of the modes is based on a count of 1,000 points in thin sections of the analyzed samples. The compositions of the rocks are seen to be similar to those of rocks from other parts of the circum-Pacific region (Kuno, 1950, p. 1004; 1967, pp. 647–648; Coats, 1967, pp. 694–717). Rocks of the circum-Pacific orogenic belt commonly contain higher percentages of CaO than comparable rocks of most other parts of the world.

Kuno (1950, 1967) divided the andesites and related rocks of the Izu-Hakone region of Japan into two suites, the hypersthenic and the pigeonitic. The pigeonitic suite contains pigeonite in the groundmass, whereas the hypersthenic suite is oversaturated with silica and contains hypersthene in the groundmass. According to Kuno (1950, 1959), the magma of the hy-

TABLE 1

CHEMICAL ANALYSES OF ROCKS FROM TOFUA ISLAND
(Shiro Imai, analyst)

	SAMPLE NUMBER*						
	1	2	3	4	5	6	7
SiO_2	56.04	57.13	65.86	55.93	56.03	54.42	53.80
Al_2O_3	15.38	14.59	13.27	16.59	15.83	16.56	14.47
Fe_2O_3	3.63	2.58	1.83	6.25	3.47	4.65	2.71
FeO	6.92	8.43	6.12	4.41	7.32	5.32	7.07
MgO	4.46	4.22	1.84	3.15	3.61	4.71	7.34
CaO	9.86	9.17	6.01	10.03	9.95	10.89	11.92
Na_2O	2.07	2.23	3.13	1.98	2.29	2.00	1.48
K_2O	0.49	0.53	0.88	0.54	0.52	0.40	0.33
H_2O+	0.61	0.62	0.53	0.50	0.48	0.64	0.51
H_2O-	0.27	0.24	0.24	0.21	0.15	0.25	0.29
MnO	0.17	0.18	0.16	0.16	0.16	0.16	0.17
TiO_2	0.71	0.74	0.67	0.73	0.77	0.64	0.49
P_2O_5	0.14	0.15	0.23	0.15	0.14	0.12	0.09
Total	100.75	100.81	100.77	100.63	100.72	100.76	100.67
Total Fe as FeO	10.19	10.75	7.77	10.03	10.44	9.50	9.51
				CIPW Norms			
Q	14.2	14.2	27.7	18.6	13.6	13.0	10.6
or	2.8	3.3	5.0	3.3	3.3	2.2	2.2
ab	17.3	18.9	26.2	16.8	19.4	16.8	12.6
an	31.4	28.1	19.7	34.8	31.1	35.0	31.7
di wo	7.0	7.0	3.4	5.9	7.3	7.5	11.1
di en	3.8	3.6	1.0	4.3	3.5	4.9	6.7
di fs	2.9	3.2	2.5	1.1	3.7	2.1	3.8
hy en	7.4	7.0	3.6	3.6	5.5	6.9	11.7
hy fs	5.8	9.4	6.5	0.9	5.5	3.0	6.3
mt	5.3	1.4	2.6	9.0	5.1	6.7	3.9
il	1.4	3.7	1.2	1.4	1.5	1.2	0.9
ap	0.3	0.3	0.7	0.3	0.3	0.3	0.3
	Ab_{36}	Ab_{40}	Ab_{57}	Ab_{33}	Ab_{38}	Ab_{32}	Ab_{28}
				Modes			
Feldspar	17.0	21.4	42.4	58.8	39.4	12.2	29.8
Clinopyroxene	17.6	33.2	30.0	19.2	39.2	6.8	29.8
Orthopyroxene	—	—	0.8	0.4	—	2.6	—
Silica minerals	4.0	3.6	6.1	8.6	12.4	—	5.4
Opaque minerals	13.6	15.6	9.2	8.2	9.4	13.4	9.0
Olivine	—	—	—	—	—	—	tr.
Glass	42.0	25.8	9.8	—	—	28.6	9.0
Vesicles	3.8	0.4	1.6	4.8	—	36.4	14.0

* 1. Aphanitic hypersthene-bearing augite andesite (labradorite dacite in Rittmann's nomenclature) from a 30-foot lava flow of the Hamatua Formation, 300 feet below the caldera rim between triangulation stations B and Bl. (Field number Tofua 33.)

2. Aphanitic pyroxene andesite (labradorite dacite in Rittmann's nomenclature) from a 70-foot-thick block lava flow of the Hamatua Formation, 400 feet below the caldera rim between triangulation stations B and Bl. (Field number Tofua 32.)
3. Microporphyritic hypersthene-bearing augite dacite (dacite in Rittmann's nomenclature) from the Hamatua Formation at 500 feet altitude behind Hamatua village. (Field number Tofua 57.)
4. Labradorite andesite (labradorite dacite in Rittmann's nomenclature), 0.1 mile northwest of Hokula village, as an inclusion in the Hokula Froth Lava. (Field number Tofua 68.)
5. Medium-grained labradorite augite diorite inclusion in the Hokula Froth Lava on the beach below Hokula village. (Field number Tofua 4.)
6. Porphyritic hypersthene-augite andesite (quartz-bearing labradorite andesite in Rittmann's nomenclature) from a 70-foot lava flow of the Kolo Formation at triangulation station G. (Field number Tofua 50.)
7. Porphyritic augite basaltic andesite (quartz basalt in Rittmann's nomenclature) from a small lava flow on the southern flank of Lofia cone. (Field number Tofua 17.)

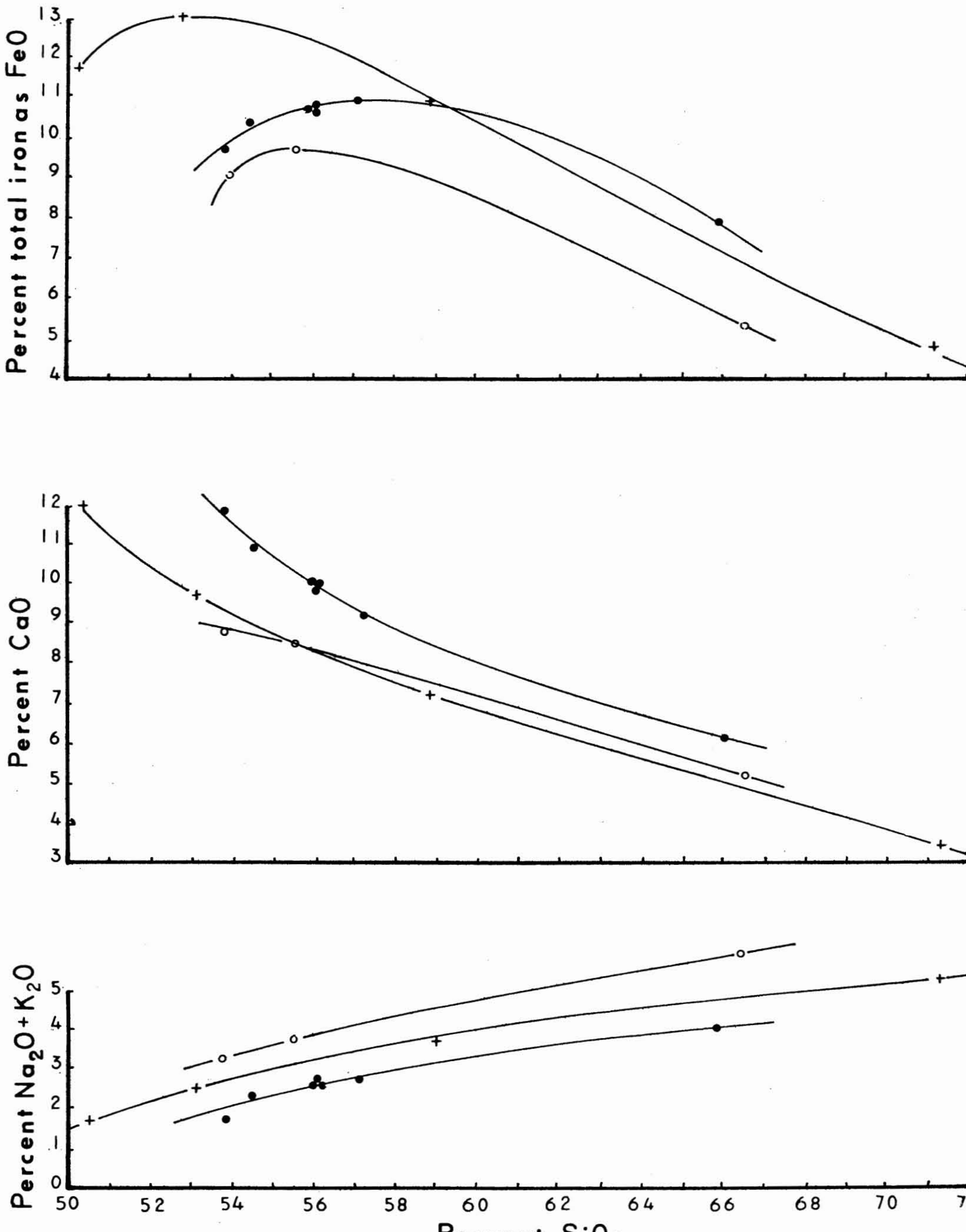


FIG. 3. Variation diagrams of the rocks of Tofua Island, compared with those of the pigeonitic and hypersthenic suites of the Izu-Hakone region in Japan. *Solid dots,* compositions of the Tofua lavas; *crosses,* averages of basalts, basaltic andesites, andesites, and dacites of the pigeonitic suite of Izu-Hakone; *open circles,* averages of basaltic andesite, andesite, and andesite-dacite of the hypersthenic suite of Izu-Hakone. Data on the Japanese rocks are from Kuno (1967, pp. 647–648).

persthenic suite was contaminated by sialic crustal material, whereas the magma of the pigeonitic suite was not. Later, Kuno (1965, 1967), following Osborn (1962, pp. 211–226), suggested that the hypersthenic (orogenic) suite could be derived from tholeiitic, high-alumina, and alkalic basalt magmas by differentiation under high partial pressure of oxygen, resulting in early crystallization of magnetite. In Figure 3 the compositions of the rocks of Tofua are compared with the variation curves for the rocks of the pigeonitic and hypersthenic suites of Izu-Hakone, and with the average compositions of the principal rock types of those suites. It will be seen that the CaO content of the Tofua rocks is higher than the average in either of the Izu-Hakone suites. The high CaO content is reflected in the norm calculations in Table 1 in the calcic nature of the plagioclase. Every rock except that of column 3 contains normative labradorite to bytownite. The high CaO content also explains the calcic nature of the plagioclase actually found in the rocks, even in the most siliceous varieties. The norm calculations show a high wollastonite content, which is reflected in the mode by calcic clinopyroxenes. Augite and pigeonite are very abundant, whereas noncalcic pyroxene (hypersthene) is rare.

The alkali:silica diagram at the bottom of Figure 3 shows a nearly linear increase in the alkalies with increasing silica, but the total alkali content is less than in the rocks of Izu-Hakone. It is interesting to note the parallel trends between the three suites. The K_2O content is low and is similar in the two regions. Dickinson (1968, pp. 2261–2267) notes that K_2O usually is low in andesites which are erupted near the trench side of the island arcs, which is the case with both the Tofua and the Izu-Hakone rocks. However, even the most siliceous Tofua sample does not display a large increase in the alkalies, as do the average pigeonitic and hypersthenic dacites of Izu-Hakone.

When total iron is plotted against SiO_2, as in the upper diagram of Figure 3, the iron content of the Tofua rocks falls in between those of the two Izu-Hakone suites when the SiO_2 content is less than 58 percent, though it is greater than those of the Japanese rocks at higher contents of SiO_2. In the pigeonitic series of Izu-Hakone, iron enrichment takes place at a lower SiO_2 content than in the Tofua rocks.

Normative orthoclase in the Tofua rocks ranges from 2.22 percent in the basaltic andesite to 5.00 in the dacite, but modal alkali feldspar was not observed. Normative orthoclase in the Tofua rocks is comparable in amount to that in the Izu-Hakone rocks. Normative quartz tends to be more abundant in the Tofua rocks than in the Japanese rocks, but the average dacite of the hypersthenic suite of Izu-Hakone has a normative quartz value close to that of the augite dacite of the Hamatua Formation (Table 1, column 3).

The alkali-lime index for the Tofua lavas is 63.5, which falls within the calcic division of Peacock's (1931, pp. 54–67) classification. The Tofua rocks belong to the calc-alkaline orogenic suite.

Data on minor elements in lavas of the Tonga Islands, including Tofua, will be published by Hubbard and Gast (in preparation).

GEOLOGIC HISTORY

The early geologic history of the Tonga Archipelago is unknown. The coralline islands of Tonga are primarily composed of Eocene limestone.

The eruption of the Hamatua lavas, building the main cone of Tofua Island, may have taken place during the late part of the Pleistocene epoch. No radioactive dates have as yet been obtained for the Hamatua rocks, and the age of the cone can only be estimated from the amount of erosion it has undergone.

A period of quiescence followed the eruption of the Hamatua lavas, during which moderately deep valleys were cut into the side of the cone. Eventually, the summit of the cone collapsed to form the caldera. It is not known whether the initial caldera collapse took place before or after the eruption of the Hokula Froth Lava. Field and petrographic evidence indicate that the froth lava contained a large amount of volatiles. It is possible that during the quiescent period following the eruption of the Hamatua lava, volatiles were concentrated in the upper part of the magma chamber, and that it was the eruption of the froth lava that initiated the caldera collapse. An unknown amount of the froth lava flowed into the sea, and the volume erupted may have been much greater than that now remaining above sea level.

Following its eruption, streams cut valleys into the Hokula Froth Lava. Tensional cracks and normal faults associated with the continually enlarging caldera provided conduits for rising magma which erupted at points along the caldera rim, building ash and cinder cones, mantling a large part of the outer slope of Tofua with pyroclastics, and filling the valleys in the Hokula Froth Lava. By the time of eruption of the Kolo Formation the composition of the magma had become more basic than that of the precaldera period, although occasional eruptions of andesite still occurred.

Within the caldera, rocks of the Lofia Formation were erupted, partly concurrently with eruptions of the Kolo Formation, but continuing after the Kolo eruptions had ceased. Frequent eruptions of Lofia cone have taken place in historic time. The last was in 1959 (Richard, 1962, p. 16).

ORIGIN OF THE TOFUA ROCKS

For the most part the features of the Tofua rocks are typical of rocks of the circum-Pacific orogenic belt. Basaltic andesites predominate, with lesser amounts of andesite and basalt, and a little dacite. The problem of the origin of the Tofua rocks is a part of that of the origin of the circum-Pacific orogenic suite in general. Both Macdonald (1960) and Gorshkov (1962) have pointed out the isolation of such island arcs as those of Tonga and the Marianas from the continental platforms, and the improbability that the assimilation of sial has played any important part in their petrogenesis. The rocks of these arcs must either have been derived directly from the mantle, or have resulted from partial remelting of previously formed suboceanic basalts. The many indications of instability, reaction, and melting in the feldspar, pyroxene, and olivine phenocrysts in the Tofua rocks strongly suggest the remelting of older basaltic rocks.

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LITERATURE CITED

COATS, R. R. 1967. Basaltic andesites. In: Basalts, The Poldervaart treatise on basaltic rocks, vol. 2, pp. 689–736. New York, Interscience Publishers.

COOK, JAMES, and GEORGE FORESTER. 1777. A voyage round the world performed in His Majesty's ships the Resolution and Adventure, in the years 1772, 1773, 1774, 1775, vol. 4. Dublin, 518 pp.

DALY, R. A., 1916, Petrography of the Pacific islands. Bulletin of the Geological Society of America, vol. 27, pp. 325–344.

DALYELL, JOHN. 1812. Shipwrecks and disasters at sea, vol. 3. Dublin, Ramsay and Co. 515 pp.

DICKINSON, W. R. 1968. Circum-Pacific andesite types. Journal of Geophysical Research, vol. 73, pp. 2261–2269.

EMMONS, R. C. 1943. The universal stage. Geological Society of America, Memoir 8, 205 pp.

GEORGE, W. O. 1924. The relation of the physical properties of natural glasses to their chemical composition. Journal of Geology, vol. 32, pp. 353–372.

GORSHKOV, G. S. 1962. Petrochemical features of volcanism in relation to the types of the earth's crust. In: Crust of the Pacific Basin, pp. 110–115. Geophysical Monograph 6, American Geophysical Union, Washington, D.C.

HARKER, ALFRED. 1891. Notes on a collection of rocks from the Tongan Islands. Geological Magazine, vol. 8, pp. 250–258.

HEINRICH, E. W. 1965. Microscopic identification of minerals. New York, McGraw-Hill. 414 pp.

HOFFMEISTER, J. E. 1932. Geology of Eua, Tonga. B. P. Bishop Museum Bulletin 96, 93 pp.

HUBBARD, N. J., and P. L. GAST. In preparation. Some chemical evidence about the origin of Tonga lavas.

KUNO, HISASHI. 1950. Petrology of Hakone volcano and adjacent areas, Japan. Bulletin of the Geological Society of America, vol. 61, pp. 957–1020.

——— 1959. Origin of Cenozoic petrographic provinces of Japan and surrounding areas. Bulletin volcanologique, vol. 20, pp. 37–76.

——— 1965. Origin of calc-alkaline rock series. Special Papers of the Geological Society of America, vol. 82, p. 116. (Abstract.)

——— 1967. Differentiation of basalt magmas. In: Basalts, The Poldervaart treatise on basaltic rocks, vol. 2, pp. 623–688. New York, Interscience Publishers.

LISTER, J. J. 1891. Notes on the geology of the Tongan Islands. Quarterly Journal of the Geological Society of London, vol. 47, pp. 590–617.

LOCARDI, E., and M. MITTEMPERGHER. 1965. Study of an uncommon lava sheet in the Bolsena District (Central Italy). Bulletin volcanologique, vol. 28, pp. 75–84.

——— 1967. On the genesis of ignimbrites, how ignimbrites and other pyroclastic products originate from a flowing melt. Bulletin volcanologique, vol. 31, pp. 131–152.

MACDONALD, G. A. 1949. Hawaiian petrographic province. Bulletin of the Geological Society of America, vol. 60, pp. 1541–1596.

——— 1960. Dissimilarity of continental and oceanic rock types. Journal of Petrology, vol. 1, pp. 172–177.

——— 1967. Forms and structures of extrusive basaltic rocks, In: Basalts, The Poldervaart treatise on rocks of basaltic composition, vol. 1, pp. 1–61. New York, Interscience Publishers.

MACDONALD, G. A., and TAKASHI KATSURA. 1965. Eruption of Lassen Peak, Cascade Range, California, in 1915: example of mixed magmas. Bulletin of the Geological Society of America, vol. 76, pp. 475–482.

MARSHALL, PATRICK. 1911. Oceania. Handbuch der regionalen Geologie, vol. 2, pp. 1–36. Heidelberg.

OSBORN, E. F. 1962. Reaction series for subalkaline igneous rocks based on different oxygen pressure conditions. American Mineralogist, vol. 47, pp. 211–226.

PEACOCK, M. A. 1931. Classification of igneous rocks. Journal of Geology, vol. 39, pp. 54–67.

RICHARD, J. J. 1962. Catalogue of the active volcanoes of the world including solfatara fields, Part 13. Kermadec, Tonga, and Samoa. International Association of Volcanology, Napoli. 38 pp.

RITTMANN, ALFRED. 1952. Nomenclature of volcanic rocks. Bulletin volcanologique, vol. 12, pp. 75–102.

STEARNS, H. T., and G. A. MACDONALD. 1942. Geology and ground-water resources of the island of Maui, Hawaii. Hawaii Division of Hydrography, Bulletin 7, 344 pp.

SWANSON, D. A. 1966. Tieton Volcano, a Miocene eruptive center in the southern Cascade Mountains, Washington. Bulletin of the Geological Society of America, vol. 77, pp. 1293–1314.

TRÖGER, W. E. 1959. Optische Bestimmung der gesteinsbildenden Minerale. Stuttgart, Schweizerbart'sche Verlag. 147 pp.

VANCE, J. A. 1962. Zoning in igneous plagioclase: normal and oscillatory zoning. American Journal of Science, vol. 260, pp. 746–760.

WOIDE, CHARLES (translator).1776. Abel Tasman's 1643 Journal, Microfilm copy 1205, University of Hawaii Library.