THE GEOLOGY OF
TOFUA ISLAND, TONGA

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We certify that we have read this thesis and that in our opinion it is satisfactory in scope and quality as a thesis for the degree of Master of Science in Geosciences-Geology.

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ABSTRACT

Tofua Island, approximately five by six miles in diameter, is one of the more prominent volcanoes situated along the inner volcanic arc of the Tongan Archipelago and tectonic system. Tofua is an oval, steep-sided composite volcano, the summit of which has collapsed to form a caldera. Within the caldera is a still active vent, Lofia cone.

Four formations have been mapped: 1) the Hamatua Formation consists of rocks of pre-caldera age and includes basaltic andesites, pyroxene andesites, and pyroxene dacites; 2) the Hokula Froth Lava is a microvesiculated lava flow of andesite; 3) the Kolo Formation consists of air-laid lapilli-tuff-breccia, consolidated ash, unconsolidated tephra, small basaltic andesite lava flows, and a thick pyroxene andesite lava flow; 4) the Lofia Formation is composed of air-laid tuff, ash, basaltic andesite lava flows, and andesite lava flows. An erosional unconformity exists between the Hamatua Formation and the Hokula Froth Lava, and another between the froth lava and the Kolo Formation.

The rocks are typical orogenic andesites and related rocks, though they have a greater CaO content than comparable rocks from Japan and other Circum-Pacific regions. This accounts for the presence of calcic plagioclase feldspar and clinopyroxene, even in the most siliceous rocks. Total alkali percentage increases with increasing silica, but does not become greater than 4.20 percent. The more mafic rocks show iron enrichment with increasing silica; however, beyond 57 percent silica, total iron percent decreases steadily.

Clinopyroxenes are common. Pigeonite and pigeonitic augite are usually found in the groundmass, while augite is typically phenocrystic.

Hypersthene is less common and only occurs as phenocrysts. Hypersthene phenocrysts are always surrounded by a reaction rim of pigeonite and/or pigeonitic augite. Pigeonite occasionally forms phenocrysts.

Concentric normal faults associated with caldera collapse are common on the northern, eastern, and southern rim of the caldera. Many of them have served as conduits for rising magma of the Kolo Formation. Others are due to continuing caldera collapse and do not have associated volcanism. Tensional cracks are common along the southern rim.

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INTRODUCTION

Background and Purpose

The geologic details of the Islands of Tonga, which are located within an island-arc tectonic system, are imperfectly understood. Partly for this reason the Hawaii Institute of Geophysics was awarded a National Science Foundation grant to study the volcanic islands of Tonga and the Lau Group of Fiji. In these islands, rock samples are being collected for chemical analysis, petrographic examination, and paleomagnetic study, and gravimeter measurements are being taken.

Previous investigators in the Tongan Islands (Lister, 1891, and Hoffmeister, 1932) were primarily concerned with detailed descriptions of the fossiliferous Tertiary limestone, which is the most abundant rock type. Descriptions of the igneous rocks were usually dispensed with in a few short paragraphs or pages.

The author chose Tofua Island as a thesis research problem because of its size, petrological variations, and the existence of a suitable base map of the island. The island's structure and stratigraphy were examined and mapped in detail. Rock specimens collected for thin-section study were used not only for petrological analysis, but also as an aid for the correlation of different formations. The foremost purpose of this thesis is to write a detailed geological and petrological description of Tofua.

Field Methods

Field work on Tofua was performed during the first three weeks of June, 1968. The writer procured a very adequate base map from the Lands Department of Tonga in Nuku'alofa prior to sailing for Tofua. The Tongan

Government survey of the island in 1961 resulted in the establishment of ten triangulation stations and their respective elevations. Although they were only temporary, it was not difficult to relocate them; all were at prominent landforms or villages.

A contour map of Tofua was made primarily for the gravimetric work, but also as an aid in mapping stratigraphic and fault contacts. Due to limitations of time and difficulty of terrain, a map with 200-foot contour intervals and of moderate detail was made. Usually geological mapping was done concurrently with the contour mapping. Elevations were obtained by an aneroid altimeter (calibrated in meters) on as many trails from the sea to the summit as possible. The stations were located by bearing angles off of Kao or triangulation stations already established. This, in conjunction with the elevations taken with the gravimeter measurements, provided reasonably good coverage. In addition, a graph was constructed by plotting the variations of altimeter readings at a constant elevation against time of day. The employment of this graph enabled the author to correct for barometric variations. The graph was similar to that given by Lahee (1961, p. 494).

The location of geologic structures near or on the rim of the caldera was best done by taking two or more bearings on the triangulation stations. Coastal geology was easily located by using the base map. This method proved to be more accurate than the traditional compass and pace traverse method most often used.

The northwestern and parts of the western flanks of Tofua are covered by the Kolo Formation. In order to map the froth lava rocks, which form a prominent sea cliff, a Tongan canoe was used. The location of geological structures was done by matching shoreline configuration with the base map, and by taking bearings on summit features that had been previously mapped.

Tofua's flanks are heavily wooded; especially on the windward eastern and southern slopes. Many of the outcrops would have been impossible to find, and valuable time wasted looking for them, had not the author employed the help of native guides. The best guides were the wild-boar hunters, who knew from experience where good outcrops could be found. On the other hand, some excellent outcrops were virtually impossible to sample because of precipitous cliffs.

A week was spent working on the volcano's rim and in its caldera and approximately two weeks were devoted to mapping the flanks. Even though the rim and caldera were more structurally complex, the author thought it wiser to spend extra time on the flanks where the underbrush masked the geology.

Previous Investigations

The first westerner to discover Tofua was Abel Tasman, in 1643. He made note of sailing near two high islands (Tofua and Kao) and seemed surprised by their height, for he had just visited the low limestone islands east of Tofua. He drew the island's profile and called it "Amatofoa" (Woide, 1776, no page numbers).

Tofua's volcanic origin was first mentioned by Captain James Cook in 1774, in his journal, where he writes of "Tofooa". Cook sailed a mile north of the island and noted that it was in eruption. A localized rainstorm was caused by the eruption, and when the rain dropped into the eyes of his crew it caused a burning sensation. Cook postulated that this was caused by ejecta from the eruption. He also noticed that the rocks along the northwest coast were cavernous and appeared to form columns, while the foliage just below the caldera rim on the northwest flank had been recently burnt. Cook thought that the summit of Tofua formed a crater (Cook and Forester, 1777, v. IV, pp. 162-3).

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

Lister (1891, p. 593), who visited the island in 1889, states 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 Tofua was not represented.

Marshall (1912, p.22) collected and gave the first brief petrographic description of the rock types, stating that they are "augite andesites". Daly (1916, p. 340) reiterates what Marshall found.

No further work was done on Tofua until 1959, when J. Richard (1961, p. 16) visited the island and collected two samples which were chemically analyzed. The analyses indicate that the rocks are quartz basalts, using Rittmann's (1952) nomenclature. However, the MnO content of the rocks, as indicated in the analyses, is nearly 2 percent, which is much too high for rocks of this type. Macdonald (personal communication, 1969) believes because of this that the analyses are not dependable. The new analyses given in Table I, in contrast, show only normal abundances of MnO.

Geographical Description

The Tonga Archipelago lies approximately 400 miles south of Samoa. Niuafo'ou and Niuatoputapu are the most northerly islands of the Tongan arc. Most of the islands cluster in three groups. Vava'u is the most

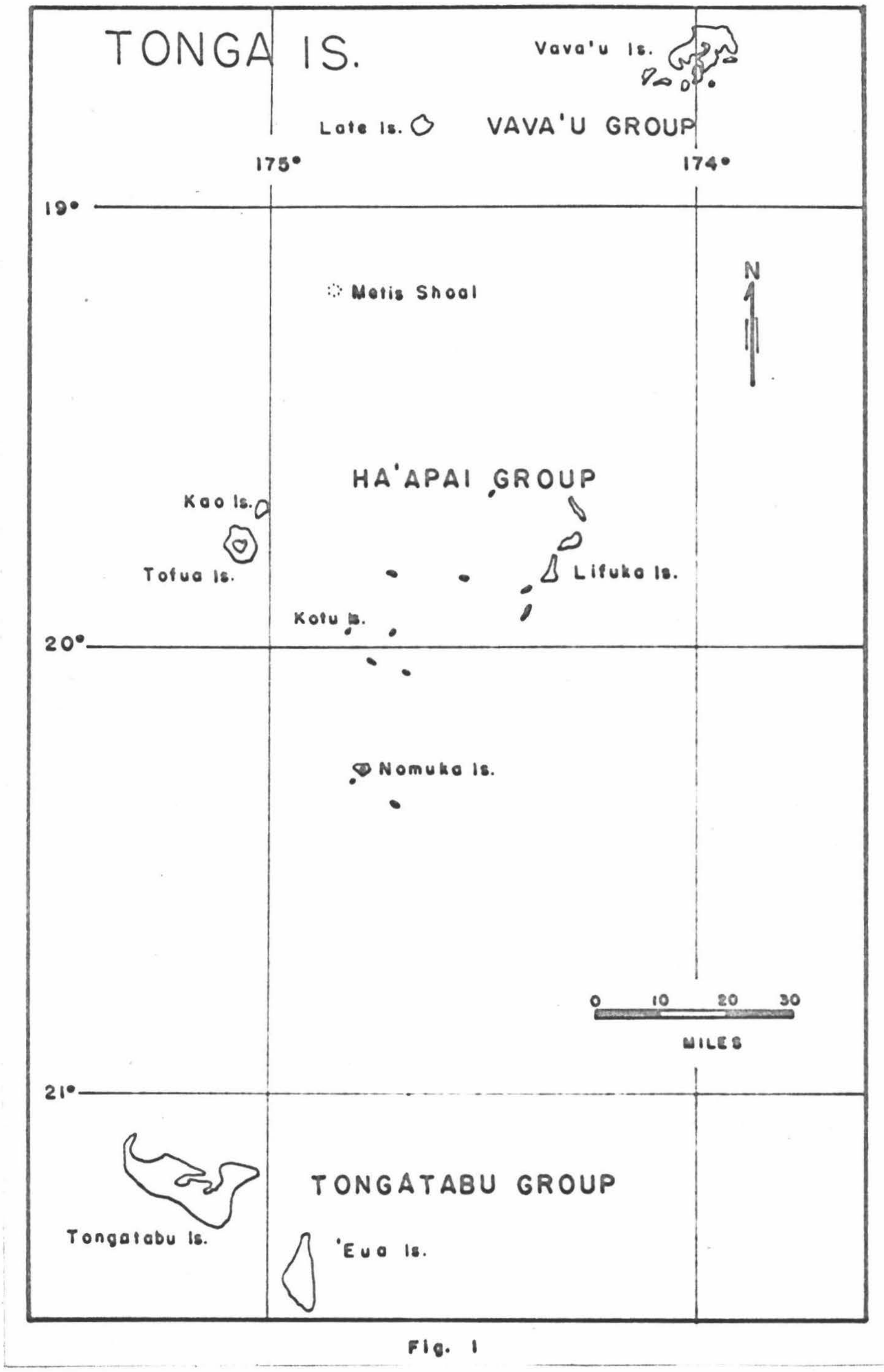


FIGURE 1. REGIONAL MAP OF TONGA

northerly group; about 70 miles south is the Ha'apai group, and the Tongatabu group is 90 miles south of Ha'apai. Tofua is one of the western outliers of the Ha'apai group (Figure 1).

In Tonga, coralline islands are found in north-south alignment on the seaward side of the archipelago just west of the Tonga Trench. The volcanic islands form a western, inner line parallel to the non-volcanic islands. 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 19°45' south latitude, 175°05' west longitude. It is 17 miles northwest of Kotu Island. Between Tofua and Kotu is the north-south trending Tofua trough. The volcanic cone of the island of Kao lies four miles to the north. Examination of the bathymetry shows that Tofua and Kao are joined by a submarine ridge.

In many ways the Tonga Archipelago is similar to other trench-island arc systems around the world. Macdonald (1949, p. 1590) gives the boundary between rocks which are nonorogenic-oceanic of the Pacific basin and those which are continental as the Tonga Trench. The rocks of Tofua are similar to continental orogenic andesites.

Acknowledgments

Without the hospitality and help of Maka Ifavalu and his family of Hokula, and Tulanga Vaea of Kolo, the field work on Tofua would have been virtually impossible.

The chemical analyses were made by the Japan Analytical Chemistry Research Institute in Tokyo.

GEOMORPHOLOGY

General Statement

Tofua Island is approximately five by six miles across and is oval in shape. The island is a single composite volcano, the summit of which has collapsed to form a caldera. The lower slopes rise rather steeply at an angle of 35°, though the slope lessens near the summit. When viewed from the sea, Tofua has an extremely regular profile. The caldera rim varies less than 300 feet in elevation, from 1400 to almost 1700 feet.

Features Associated with Volcanism

The caldera is subcircular, with an average diameter of two and a half miles. Half of its floor is occupied by a ~~crater~~ lake? of unknown depth, the surface of which is 79 feet above sea level. The walls of the caldera are extremely precipitous, but the southern, southwestern, and northern walls are less steep than the others. In some places a relief of over 1400 feet exists between the caldera rim and its floor; however, the mean relief is approximately 1100 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.

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

The formation of Tofua's caldera by collapse is being continued at present by relatively minor faulting on the northern, eastern, and southeastern rim. The faults have given this section of the rim a hummocky topography. Faulting has produced small grabens and steps with escarpments averaging from 50 to 100 feet high.

Drainage

Large stream valleys do not exist on Tofua; all the valleys are narrow and small, though some are deep. They are mostly on the south-eastern to southwestern flanks, the windward side. These steep-sided windward valleys do not extend 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 post-caldera 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 post-caldera age.

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

Sea Cliff

One of the more conspicuous geomorphic features is the wave-cut cliff that encircles most of Tofua. The average height of the cliff is 150 feet. In some places, especially where froth-lava is exposed, the cliff can be attributed to undercutting of the lower clinker zone of the flow with subsequent breaking of the overlying massive rock along joints.

STRATIGRAPHY

General Statement

The author recognized and mapped four different units: 1) Hamatua Formation; 2) Hokula Froth Lava; 3) Kolo Formation; 4) Lofia Formation. The sequence of the units was determined by superposition. Some rocks of the Kolo Formation were found to be contemporaneous with some of the rocks of the Lofia Formation, but their spatial distribution is different; therefore, they have been mapped separately.

Hamatua Formation

The rocks of the Hamatua Formation are those which were erupted before caldera collapse. They are the most voluminous rock unit, but outcrops occur only in limited areas. On the flanks of Tofua the Hamatua rocks outcrop in scattered patches, usually as rocky points around the island, or in stream valleys. On the southwest flank they are covered by soil, which is believed to have been derived from their weathering, but even there fresh outcrops of the Hamatua Formation are found in the seacliff.

The Hamatua Formation bears the name of the southeastern village. It occurs directly behind the village as a thick hypersthene-bearing augite dacite lava flow (chemical analysis 57) which forms an abrupt cliff 50 feet high. Below the village are rocky points of the Hamatua Formation.

The Hamatua Formation is best exposed in the walls of the caldera itself, where the flows attain a thickness of more than 1600 feet. The average thickness of individual flows is approximately 70 feet. Each flow consists of a thick and dense central portion, with relatively thin clinker zones above and below it. Poorly formed vertical joints are typical in the central mass. Columnar jointing was not seen. The flows appear to be of the block lava variety as described by Macdonald (1967, p. 23). The clinker fragments are less spinose than those of typical aa flows, and more rounded. In most cases they grade into the dense central portion of the flow.

The Hamatua rocks range in composition from basaltic andesites to hypersthene-bearing augite andesites, andesites, and hypersthene-bearing augite dacites. The rocks were classified by color index and the amount of free silica minerals present. All varieties usually contain plagioclase phenocrysts and microphenocrysts, which commonly are zoned from a calcic core to a more sodium-rich rim. The cores of plagioclase phenocrysts range from An_{90} to An_{51}. The more sodic plagioclase cores are found in the late flows of the Hamatua Formation which typically are basaltic andesite. Groundmass plagioclase feldspar is generally more sodic than the phenocrysts, and sometimes is normally zoned. Its average composition is about An_{45}. When hypersthene appears in the rock, 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 liquid, though in some thin sections slight embayment is observed. Groundmass pyroxene in the rocks 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 feldspar, augite, hypersthene and, in rare instances, pigeonite. Interspersed throughout the groundmass of the more silicic varieties of the pre-caldera, rocks are silica minerals which have been identified as quartz and tridymite. Neither alkali feldspar nor apatite were observed.

In the field, the rocks of the Hamatua Formation range from light to dark gray. Outcropping rocks of lighter color display conspicuous flow banding, with alternately light and dark bands. Some bands appear to have more ferromagnesian minerals and therefore to be slightly darker than those with fewer ferromagnesian minerals. On the average, the bands are two centimeters thick. Within the thicker ones, thin and less pronounced bands are sometimes seen. The bands are usually not horizontal, but form small folds due to deformation during flowage.

Characteristic of the Hamatua rocks is the superficial occurrence of a hematite-rich skin approximately one millimeter thick. Beneath this skin the rock is usually very fresh and difficult to break. In hand specimen the andesites and dacites often look vitreous. In thin section some are, though most are composed of crystallites of plagioclase feldspar, clinopyroxene, magnetite, silica minerals, and glass, and show a hyalopilitic texture. Intergranular and intersertal textures are also seen. The andesites sometimes exhibit subparallelism of the groundmass feldspar laths caused by viscous flowage. In thin section the basaltic andesites usually display intersertal to intergranular texture, though some are hyalophitic, with plagioclase surrounded by a matrix of tachylite glass.

Small inclusions of coaser grain rock are prevalent in the more siliceous rocks. These inclusions are angular in shape and consist of long rounded zones of coarser crystallinity which can be attributed to the local retention of volatiles during cooling. Quartz and tridymite are more abundant in these zones than in the rest of the rock.

A 400-foot type section of Hamatua Formation was measured just below the rim in the caldera wall between triangulation stations B and B1. The lower 350 feet consists of porphyritic hypersthene-bearing and augite andesites, and nonporphyritic andesites. These flows are very thick, the one at the bottom being nearly 80 feet. At the top of the section is a basaltic andesite flow containing relatively large crystals of pigeonite. It is not known, however, if the general trend of the Hamatua Formation is from acidic to basic going higher in the section. A hypersthene-bearing augite dacite sample was collected behind the village of Hamatua at an elevation of 500 feet.

Hokula Froth Lava

Directly overlying the Hamatua Formation by an erosional unconformity and forming a sea cliff on the northern and western shores of Tofua, is a rock group which in hand specimen appears tuffaceous. However, in outcrop it shows evidence of emplacement by flowage. It resembles rocks in other parts of the world that have been called "froth lava" (Locardi and Mittempergher, 1965).

The Hokula Froth Lava is overlain by rocks of the Kolo Formation and is only exposed in the sea cliff. Consequently, its width cannot be determined. The flow probably originated from the upper part of the mountain.

The type section of the froth lava flow is approximately 0.1 mile west of Hokula village. Here two separate flows of froth lava form a wave-cut cliff about 80 feet in height. The lower flow has been oxidized to a bright red color whereas the upper flow is gray to green. Structurally, both flows are identical, each consisting of three parts: a dense central portion grading into clinker zones above and below it. Generally the lower clinker layer is thicker, probably derived from the upper zone during emplacement (Macdonald, 1967, p. 18). The basal clinker of the lower flow is approximately five feet thick with cobble-size blocks that were slightly welded just after flowage. The denser central portion of the flow has an average thickness of 10 feet. Angular cobble size cognate xenoliths are common, though there are also rounded boulder-size inclusions in lesser abundance. They represent pre-caldera rocks brought to the surface by the rising magma. In addition, in the dense portion of the flow, there are lenticular masses that are lighter in color than the surrounding matrix, but composed of the same material. A thinner clinker deposit overlies the dense zone with a gradational contact, and its composition is the same as that of the basal one. The upper froth lava flow repeats the sequence described, the only difference being that it is thinner. The flow is about 15 feet thick.

The froth lava has rudimentary columnar jointing several feet across. The sea easily attacks the froth lava cutting out squarish caverns, which owe their shape to the joint pattern.

In thin-section, the rock shows a great many microvesicles which range in shape from round to angular. The rock is highly vitreous, containing small microlites of plagioclase feldspar and a green clinopyroxene in a matrix of glass. In the lower flow, red glass is due to the oxidation of iron minerals. Green-gray glass is present in the upper flow. Its color may be due to disseminated iron minerals which have not been oxidized.

Small amounts of clear glass are present in both flows. Its refractive index ranges from 1.552 to 1.535 $\pm$ 0.002. Using a graph compiled by George (1924, p. 365) of refractive index versus percentage of SiO_2, the froth lava rocks are of andesitic composition. Hypersthene, augite, and plagioclase feldspar commonly occur as phenocrysts. Tridymite has been identified in some of the samples and is usually seen in the vesicles as shards. Small included lithic fragments are also present. Under the microscope the lenticular bodies of lighter color are seen to be more vesicular than the surrounding matrix of the same composition.

Locardi and Mittempergher (1965, 1967) have described froth flows in Italy. They believe that froth lava or micro-vesiculated flows are the result of gas separation in a volatile-rich flow and represent a transition between ordinary lava flows and ignimbrites. That is, if vesiculation is extreme and the rock is disintegrated, then subsequently welded, it is ignimbritic. However, if vesiculation did not proceed far enough to cause disintegration and the rock is pumiceous, they consider it froth lava.

Lenticular pumice masses have also been described by Locardi and Mittempergher (1967, p. 133-134) within the dense zone of the Italian froth lavas. They believe the elongated masses of pumice are due to the destruction of certain bands where vesiculation was greatest. On Tofua Island, the lenticles of pumiceous material seem to demonstrate a preferred orientation. The longest axes of the lenses are nearly horizontal, parallel to the top of the flow. The lenses are randomly scattered throughout the central parts of the flows. The author believes that when movement stopped, masses of volatile-rich vesicular lava remained scattered throughout the central part of the flow. The elongation and flattening of these masses into lenses was due to the overburden. If the formation of these lenticles occurred during flowage, one would expect a lack of preferred orientation and more disorder due to turbulence in flowage.

Inclusions in Hokula Froth Lava

The inclusions in the Hokula Froth Lava flows are fragments of rocks of the Hamatua Formation, and 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 rocks predominating.

The fine-grained varieties are texturally and mineralogically similar to the rocks of the Hamatua Formation described above. The coarser-grained rocks, however, appear to have crystallized under plutonic 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 feldspar and greatly altered augite. Most of the augite has been altered to a low birefringent green mineral or mineraloid. Poor acute bisectrix figures were observed, definitely identifying the unaltered pyroxene as augite. One sample was stained for alkali feldspar with a negative result. The texture between the larger crystals is hypidiomorphic granular.

Some of the inclusions do not resemble the pre-caldera rocks in the nature of their pyroxenes. They frequently 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 are commonly coarser grained than the pre-caldera types, but are not typically plutonic. They may have been derived from shallow intrusive bodies. Whether or not these rocks are directly related to the Tofua volcano is not known.

The nature of the basement rock beneath Tofua cannot be stated from the existing data. It can only be said that Tofua may be underlain by continental plutonic rocks.

Kolo Formation

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

The lapilli-tuff-breccia member is an air-laid deposit, poorly sorted, with weakly developed bedding. It is composed of approximately 50 percent angular lapilli-size blocks and lapilli cinder, 40 percent ash, and 10 percent blocks larger than lapilli. Locally, however, the proportions change and zones of consolidated ash become abundant. Clasts of lapilli size and larger appear to have been derived from the Hamatua Formation. The ash and lapilli cinder are commonly vitreous and represent new magmatic material. The refractive index of the glass shows it to be basaltic. Within the lapilli-tuff-breccia are small rootless basaltic andesite flows (determined by color index). Microscopically these flows are similar to the andesitic lavas of the Hamatua Formation, though they are relatively devoid of phenocrysts. A flow near Hokula has been identified as hypersthene and augite-bearing basaltic andesite. The phenocrystic feldspar is bytownite, whereas 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 Formation. Near Hamatua village it grades into consolidated black ash. Here the ash attains a thickness of 200 feet, perhaps because it fills a valley. Near Hokula village an erosional unconformity exists between the underlying Hokula Froth Lava and the lapilli-tuff-breccia. Separating the two formations is a layer of consolidated ash. This unconformity can also be observed 0.25 mile west of triangulation station G. 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 (chemical analysis 50). The 70-foot-thick flow forms a rather broad plateau in the vicinity of triangulation station G. In thin section the groundmass texture is hyalopilitic with small crystals of labradorite, clinopyroxene, and magnetite. Hypersthene and augite phenocrysts appear ragged and have been embayed by groundmass material. Pyroxene phenocrysts usually form glomerocrysts. Pigeonite also forms phenocrysts.

Source vents of the consolidated lapilli-tuff-breccia dot the northeastern, eastern, and southern caldera rim. These vents are commonly shallow with gradually rising walls and thus give a maar-like appearance. Small craters 30 feet across and 50 feet deep are found on the north-eastern rim, but these are not common. Considering the number of blocks of the Hamatua Formation included in the tuff, in addition to the maar-like craters, it is probable that explosions took place near the surface, perhaps involving ground water.

The unconsolidated tephra of the Kolo Formation is younger than the lapilli-tuff-breccia. Unconsolidated tephra outcrops near triangulation station B1 and the southeastern rim of the caldera, which has been faulted down into a broad platform. In both places it overlies consolidated lapilli-tuff-breccia. 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, which now form talus debris in the caldera. Most of the fragments in the tephra are pumiceous lapilli cinder. Larger spindle bombs also are present. The refractive index of the glass in the cinder is 1.559 $\pm$ 0.002, indicating that it is basaltic.

The relationship of the Kolo Formation source vents on the caldera rim to the fault patterns is clear. Concentric faults formed during caldera collapse provided conduits for rising magma. However, it is unknown whether the thick andesite flow near triangulation station G originated from the caldera rim. Its source has been buried beneath later deposits of the lapilli-tuff-breccia and pyroclastics of the Lofia Formation.

Lofia Formation

Rocks of the Lofia Formation are confined mainly within the caldera, although they are continually exposed to an elevation of 950 feet on the northern flank of the volcano. Those outside of the caldera constitute only a thin veneer and were derived from the large spatter and cinder cones in the caldera. They overlie the rocks of the Kolo Formation, though near their gradational contact on the caldera rim there is some question as to whether rocks of both formations were erupted simultaneously. The Lofia Formation overlies pre-caldera rocks which have collapsed into the caldera during caldera development.

Lofia is the name given to the still active vent, hence the name Lofia Formation. Lofia cone exhibits almost all of the members of the Lofia Formation. Pyroclastics probably comprise 90 percent of the formation. The tephra member includes consolidated lapilli-tuff, tuff, spatter, and unconsolidated lapilli cinder interbedded with small basaltic-andesite and andesite lava flows. A separate unit is the ponded lava floor of Lofia's crater. The older eroded ash cone is composed mainly of weathered ash. Only one lava flow is large enough to be mapped separately. The flow is vesicular andesite.

The pyroclastic deposits are thinly bedded and friable. A rudimentary size sorting has taken place. Near the cinder cones lapilli tuffs predominate, whereas tuff with few lapilli mantles the walls of the caldera, suggesting that sorting was gravitational, with the larger fragments falling closer to the vent. However, cow-dung bombs, averaging 50 centimeters in diameter, and spatter are plastered against the eastern wall of the caldera, a half mile from their source. It is clear from their position that they originated from Lofia cone as a result of a directional blast.

The lapilli tuff of Lofia cone contains some angular blocks. A block selected at random is petrologically very similar to a small porphyritic basaltic-andesite lava flow interbedded with the lapilli tuff. Thin lava flows interspersed in spatter and tuff are exposed in the crater walls of Lofia cone and appear to be the same as the basaltic-andesite flow and block.

In thin section the porphyritic basaltic-andesite flow (chemical analysis 17) 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 xenocrystic augite is present. The olivine crystals do not have reaction rims, but are anhedral in shape. Labradorite and pigeonite are present in the groundmass. The texture is intersertal; groundmass minerals are surrounded by dark tachylitic glass. In hand specimen, small aggregates of olivine are present. Hypersthene is absent.

Refractive indices of glass from cinder samples ranged from 1.559 to 1.563 $\pm$ 0.002, indicating SiO_2 percentages of about 52 to 53, which are equivalent to basaltic andesite. The glass is both red and green-gray. The green-gray glass has partly devitrified to needles of green clinopyroxene and plagioclase. If the red glass is the result of ferric iron, then the green-gray glass may contain an abundance of ferrous iron which has not yet undergone oxidation.

All lava flows of the Lofia Formation are within the caldera, and all are relatively thin when compared to those of the Hamatua Formation. Most of them appear to be rootless. However, this is not certain, for the large volume of pyroclastics may cover their sources. Only one continuous lava flow can be seen. It is an aa flow, of andesitic composition, approximately 0.75 miles long and 0.25 mile wide, which poured out of the dormant southern vent and terminates at the crater lake.

GEOLOGIC STRUCTURE

Faults

The largest structural features on Tofua are faults associated with caldera collapse. These are classified into three main groups: 1) faults bounding the sunken block of the caldera; 2) faults related to the caldera-boundary faults which have been centers of volcanic eruption either during or after the collapse of the caldera to its present size; 3) faults on the rim of the caldera that do not have associated volcanism.

The author mapped the caldera-boundary faults at the base of the escarpment. Their maximum displacement is more than 1500 feet, since the base of the escarpment is sometimes buried by later volcanics. Even though parts of the caldera-boundary fault zone are buried, its trace can be seen because of recent escarpments in the later volcanics of the Lofia Formation.

Along the southern lake shore, the caldera-boundary fault zone consists of two major faults, between which is a large down-dropped portion of the rim. It takes the shape of a giant step. Its surface is a platform that slopes westward approximately 9°. On the east side of the platform the upper fault is a hinge fault along which cinder cones have erupted the unconsolidated tephra of the Kolo Formation.

Although the caldera-boundary faults appear as one continuous fault on the geologic map, in actuality the base of the caldera escarpment is probably a zone of many closely spaced fractures.

The faults of the second category are the most numerous. These faults are concentric to the caldera and are found on the northern, eastern, and southeastern rim of the caldera, and represent the outward migration of the caldera boundary. However, this is not the case at the western and southwestern rims, where there are no faults beyond the main caldera boundary.

Most of the faults along the eastern rim have acted as conduits for rising magma, and thus were the source vents for the pyroclastic eruptions of the Kolo Formation. Radiating fissure eruptions were not found on Tofua.

The two major vents within the caldera may lie on a single fissure. There is no direct evidence for this, except that the two cones appear to have been formed at or about the same time, although only one continues to be active.

Faults of the third variety are found on the eastern rim of the caldera and are high angle normal faults. Where these faults occur along with those with associated volcanism, they are typically on the caldera side of the rim, and thus are directly associated with caldera collapse. Commonly two or three faults are parallel to each other giving rise to step faulting and grabens. Vertical displacement on individual faults is as much as 50 feet, but averages 25 feet.

A few faults not associated with volcanism are found in the caldera north and east of Lofia cone. They are postulated to be part of the caldera-boundary fault zone.

<u>Tensional Cracks</u>

Tensional cracks extend along the southeastern rim of the caldera, but are not found anywhere else. Many are a few inches wide, although some are several feet 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 groups and it is inferred that the cracks may later develop into faults.

<u>Fold-like Structures</u>

Fold-like structures on Tofua were formed by mantling of preexisting topography by volcanic rocks. Near triangulation station F lapilli-tuff-breccia of the Kolo Formation has the appearance of a small anticline with dips of 20° on both sides of its crest. It was formed by the ash mantling the caldera rim. The same structure is found where pyroclastic rocks of the Lofia formation overlapped the northern caldera rim. Some good examples of structures resembling plunging synclines occur on the western coast, where froth lava followed valleys cut into the pre-caldera surface. At the end of the froth lava eruption the fluid lava drained away, thus lowering the center of the flow. The resulting lava sheet resembles a syncline. Folds of compressional origin were not found on Tofua.

PETROGRAPHY

General Statement

Ninety-eight thin sections were examined in detail. It was necessary to cut two or more sections of many of the rock specimens when undesirable mineral orientations were obtained with the first section.

Rocks were classified by color index and the amount of free silica present as observed silica minerals. However, the latter method is not always dependable, as 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.

Plagioclase Feldspar

Plagioclase feldspar is by far the most abundant mineral present. Most of the rocks contain phenocrysts of plagioclase; all have plagioclase in the groundmass. Even vitreous cinder exhibits fine needles of feldspar. These needles are probably plates seen on edge.

Plagioclase is typically lath shaped in thin section, showing a subhedral crystal habit. A few phenocrysts are euhedral, and may be situated near a phenocryst of the same composition that is deeply embayed by the groundmass. Similarly, a single rock specimen sometimes contains phenocrysts of widely varying compositions. Phenocrysts of plagioclase range in size from 2.0 to 0.3 mm long. Groundmass laths are from 0.5 to 0.08 mm. The smaller laths are abundant in the andesites.

In the andesite and dacite of the Hamatua Formation, plagioclase phenocrysts often form glomerocrysts, either with themselves or with other minerals. Feldspar laths in the groundmass are usually in a hyalopilitic textural relationship with the other minerals and interstitial glass. Intersertal and intergranular textures are seen in the basaltic andesites of the Hamatua Formation and those of the Lofia Formation.

Whether as phenocrysts or in the groundmass, plagioclase laths are often normally zoned, though in some crystals reverse zoning is also present. Normal oscillatory zoning is common, and is probably due simply to falling temperature. Vance (1962, p. 751) proposes that oscillatory zoning is due to a fluctuation of supersaturation and undersaturation between the plagioclase crystals and the adjacent melt. Reverse zoning, when present, is found only locally in a crystal.

Rittmann's zonal method was used with a four-axis universal stage to determine the composition of zoned plagioclase (Emmons, 1943, p. 115-133). The combined albite-Carlsbad twin law method was used to determine composition of unzoned plagioclase following the graph in Heinrich (1965, p. 365). Where microlites of plagioclase were in the groundmass, 12 extinction angle measurements were taken; the largest extinction angle was applied to a graph in Heinrich (1965, p. 364).

Very commonly in the zoned phenocrysts, the cores are rounded. Composition of the cores range from An_{90} to An_{40}, whereas the rims range 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}.

Twinning is very common, with albite, Carlsbad, and combined albite-Carlsbad twins. Pericline twinning is present but to a lesser degree. In the Hamatua and Lofia Formations, where plagioclase forms glomerocrysts more complicated twin laws are sometimes represented.

The rocks of Tofua contain a high percentage of labradorite-bytownite feldspar, whether the rocks contain free silica minerals or not.

Inclusions in Plagioclase

Some of the plagioclase phenocrysts and larger groundmass laths contain inclusions of glass, magnetite dust, and microlites of clino-pyroxene. Similar inclusions have been reported by Kuno (1950, p. 968-969), Swanson (1966, p. 1303), and Macdonald and Katsura (1965, p. 475-482). 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 feldspar crystal. When found in glomerocrysts of plagioclase, the inclusions tend to form in zones of rounded blebs, giving the appearance of embayment, with subsequent growth of the feldspar aggregate. 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 assumes a triangular shape.

This suggests that melting may have taken place along inherent crystal weaknesses.

In some cases, almost all of the plagioclase crystal is crowded with dark blebs. It is more common, however, to find inclusions in only about 25 percent of the lath.

Kuno (1950, p. 967-968) explains the occurrence of these inclusions by remelting of the host crystal along its crystal faces, when enclosed by a magma that is in equilibrium with a more calcic plagioclase. He considers the plagioclase grains to be xenocrysts. Rapid crystal growth could explain the inclusion of liquid and mineral grains within the plagioclase.

Most of the feldspar phenocrysts in the basaltic andesite lava flow of the Lofia Formation are crowded with glassy inclusions. The more acidic rocks of the pre-caldera flows contain only small amounts of this type of plagioclase. The coarse-grained cognate xenolith found in the froth lava flow does not show any glassy blebs in the feldspar.

Pigeonite

Pigeonite is the most abundant pyroxene found in the Tofua rocks. It is found in all of the rock types. It is typically a groundmass pyroxene, present as subhedral to anhedral grains though sometimes forming slender needles of low birefringence. The mineral is green to gray-green in thin section. Usually the grains average 0.1 mm long. Optic figures could only be obtained on grains larger than 0.3 mm. Pigeonite also occurs as phenocrysts in some basaltic andesites and rarely in andesites. Large pigeonite grains are usually rounded and embayed, though subhedral laths are found 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.

Pigeonite was identified mainly by its small optic angle. $2V_z$ is usually close to zero, but in some rocks it ranges from 10° to 20°. Its low birefringence, for a monoclinic pyroxene, aided in its identification. The optic plane of the pigeonite is parallel to (010), indicating that it is Ca-rich (Tröger, 1959, p.57).

The N_y refractive index averages 1.710 ± 0.005. This, with $2V_z$ equal to 0°, indicates an average weight percent composition of $Mg_{45}\ Fe_{45}\ Ca_{10}$ (Heinrich, 1965, p. 219).

Pigeonitic Augite

Pigeonitic augite is a common groundmass clinopyoxene, though it occurs rarely as phenocrysts. As a groundmass constituent, it is typically anhedral, and is distinguished from pigeonite by a larger 2V, which averages about 35°.

Pigeonitic augite probably forms reaction rims around hypersthene phenocrysts, though it is often difficult to distinguish it when it forms aggregates of tiny grains around the hypersthene.

Phenocrysts of pigeonitic augite may have pigeonite cores. When such is the case, the $2V_z$ of the pigeonitic augite tends to be small. If pigeonite is not present, the $2V_z$ approaches that of augite (40°). Pigeonitic augite phenocrysts are typical of the basaltic andesites.

Augite

Augite is the commonest phenocryst in Tofua rocks. It is also found in the groundmass, but is not as plentiful there as pigeonite and pigeonitic augite. As a phenocryst it is often a single crystal lath, though it sometimes is 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. Euhedral grains are not uncommon. Deeply embayed anhedral 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 pigeonite. In the augite andesites of the Hamatua Formation, the phenocrysts are relatively uniform in size throughout the whole rock. There is a greater size variance in the more basic rocks.

Some augites are slightly pleochroic with X = green, Y = green, and Z = gray green. However, pleochroism is not common; crystals are usually gray-green in thin section. The optic axial angle is usually from 44^{o} to 47^{o}. An augite phenocryst with $2V_z = 60^{o}$ was found in the thick porphyritic augite-hypersthene andesite flow in the Kolo Formation. Extinction angles measured from flash figures show $Z \wedge C = 44^{o}$. Refractive index of N_y averages 1.692 ± 0.002. Hence, the average weight percent composition of augite is $Mg_{47}\ Fe_{28}\ Ca_{25}$ (Heinrich, 1965, p. 219).

Twinning is very common in augite phenocrysts, especially those in the basaltic andesites. Orientations of the twins were not determined. The twins are rather broad; fine multiple twinning was not observed.

In some instances, augite phenocrysts have overgrowths of higher birefringent augite in the same crystallographic orientation, indicating an enrichment of either calcium or iron or both in the outer layer.

Small inclusions of other pyroxenes of lower birefringence, presumably pigeonitic (no optic figures were found), or blebs of magnetite, are sometimes observed in the augite. Sometimes both occur in the same crystal.

Hypersthene

Hypersthene is the least abundant pyroxene in Tofua rocks. It has been identified only as phenocrysts. It almost always forms subhedral laths from approximately 1.0 to 0.5 mm in length. It is found alone or in glomerocrysts with augite and/or pigeonite, plagioclase feldspar, and magnetite. As mentioned above, hypersthene always has a rim of either pigeonite or pigeonitic augite.

Hypersthene is usually present in the augite andesites and augite dacites of the Hamatua Formation. It has not been found in basaltic andesites in the Hamatua rocks, Kolo Formation, and Lofia Formation.

The $2V_x$ of hypersthene ranges from 50° to almost 90° and averages 65°. Because of the relative scarcity of hypersthene, refractive index measurements were not made.

Pleochroism is slight. Most hypersthene crystals appear green in thin section, though in some orientations they are pale rose in color.

Olivine

Olivine was found only in the basaltic andesite lava flow of the Lofia Formation. The olivine forms both small dunite inclusions and large individual grains. In thin section they are seen to be somewhat rounded, but show no reaction rims.

The olivine has $2V_x$ of almost 90°. Refractive indices show $N_x = 1.655 \pm 0.002$, $N_y = 1.673 \pm 0.002$, and $N_z = 1.690 \pm 0.002$. The composition of the olivine 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 found in the Hokula Froth Lava.

Quartz was identified by its uniaxial interference figure. Tridymite was much harder to find, because of its extremely low birefringence. Very faint acute bisectrix figures were observed in some grains. Its refractive indices are much lower than that of Canada balsam. Quartz and tridymite are always anhedral and appear moth-eaten.

Quartz and tridymite commonly line vesicles or occur as micro-veinlets showing micropegmatitic intergrowth relationships with plagioclase feldspar. This intergrowth is quite apparent due to the increase in the size of the minerals involved when compared with the surrounding rock. It is postulated that volatiles retained in the lava after the end of the main period of crystallization caused an increase of grain size.

Ore Minerals

Magnetite is the most common ore mineral. Ilmenite is also present. Magnetite often forms euhedral to subhedral grains averaging 0.05 mm across. Sometimes anhedral herring-bone magnetite is found, though it is rare. It represents late crystallization of magnetite and forms between groundmass feldspar crystals.

In a pyroxene dacite flow, large octahedra of magnetite are seen in glomerocrysts of plagioclase, augite, and hypersthene. Crystallization of magnetite continued throughout the solidification of the rock.

As mentioned above, magnetite dust is very abundant in blebs of glass that are included in some plagioclase feldspars, and in some augite phenocrysts.

Glass

Glass is a common groundmass constituent in all of the Tofua rocks. In the andesites and dacites glass is typically in either hyalopilitic or hyalophitic textural relationship with groundmass minerals. In the basaltic andesites, glass is tachylite and occurs intersertally between plagioclase and clinopyroxene crystals.

It has been postulated that the absence of silica minerals in the more acidic rocks is due to the fact that silica remains in the glass. Measurements on glass from rocks of the Hamatua Formation show that the refractive index ranges from about 1.550 to 1.530, indicating that the glass is siliceous (George, 1924, p. 365). Tachylite from the basaltic andesites has a SiO_2 content similar to that of the entire rock.

Cumuloporphyry

Glomerocrysts are quite common. The constituents are plagioclase, augite, hypersthene, rarely pigeonite and pigeonitic augite, and rarely magnetite. These minerals may appear alone or in combinations of two or three.

According to Vance and Gilreath (1967, p. 529) cumuloporphyry implies the early formation and drifting together of crystals in a fluid medium. This means that crystals of plagioclase, hypersthene, and augite all were present at an early stage, perhaps while there was still a large proportion of fluid magma. Magnetite, when in glomerocrysts, also crystallized early.

Crystallization Sequence

The existence of plagioclase, hypersthene, and augite as glomerocrysts argues for early simultaneous crystallization of these three components.

There is a continuous reaction in the feldspar from anorthitic bytownite to andesine. The early-formed plagioclase phenocrysts generally are calcic, whereas groundmass plagioclase is richer in sodium.

In most instances augite and hypersthene crystallize together. Pigeonite and pigeonitic augite occur as reaction rims around hypersthene and as groundmass pyroxene, thus arguing for a late crystallization at temperatures above the inversion temperature of pigeonite. The existence of pigeonite phenocrysts and augite phenocrysts with pigeonite cores presents problems. The presence of pigeonite may mean the surrounding lava cooled too rapidly for unmixing of the pigeonite to take place.

As mentioned above, magnetite may form early, but typically it crystallizes side-by-side with the groundmass pyroxene and feldspar. The groundmass feldspar sometimes crystallizes prior to magnetite, as shown by the herring-bone structure of magnetite found in some rocks.

If the flows chill quickly, or are poor in volatile components, quartz and tridymite do not form, and interstitial glass forms instead. Thus, the last-formed minerals are quartz and tridymite, except for much later minerals formed by devitrification of glass.

CHEMISTRY

The Chemical Analyses

Seven rocks from Tofua were analyzed chemically. The analyses, with their respective CIPW norms, are shown in Table I. Tofua samples 32, 33, and 57 represent the Hamatua Formation; Tofua 4, and 68 are inclusions from the Hokula Froth Lava; Tofua 50 is from the thick porphyritic hypersthene-augite andesite flow of the Kolo Formation; and Tofua 17 represents the porphyritic augite basaltic andesite flow of the Lofia Formation. The Hokula Froth Lava was not analyzed due to its high degree of oxidation.

Discussion of the Analyses and Norms

The composition of the Tofua rocks in Table I are similar to those reported from other parts of the Circum-Pacific region, that is Japan, Kurile Islands, and the Cascade Province of the United States (Kuno, 1950, p. 1004, 1967, p. 647-8; Coats, 1967, p. 694-717). Rocks of the Pacific region commonly contain higher percentage of CaO than those of other parts of the world. Table II shows the average compositions of orogenic andesite and related rock from Japan (Kuno, 1967, p. 647-8), for comparison with the Tofua analyses.

Kuno (1950, 1967), working with andesites and related rocks in the Izu-Hakone region of Japan, divided them into two suites, the hypersthenic and pigeonitic. The pigeonitic suite contains pigeonite in the groundmass, whereas the hypersthenic suite is oversaturated with silica and thus contains hypersthene in the groundmass. According to Kuno (1950, 1959) the hypersthenic suite represents contamination of the magma by a sialic crust, whereas pigeonitic group is not contaminated. Later, Kuno (1965, 1967), following Osborn (1962, p. 211-26), suggested that the hypersthenic or orogenic suite can be derived from tholeiitic, high alumina, and alkalic magmas by an increase in the partial pressure of oxygen in the magma, resulting in early crystallization of magnetite.

As seen in Figure 2, the CaO content of the rocks of Tofua is higher than in either the average hypersthenic or pigeonitic rock types of Japan. There is a nearly linear decrease of CaO with increasing silica. The high CaO content is reflected in the norm calculations of the plagioclase feldspars. Every rock, except Tofua 57, contains normative labradorite to bytownite. The high amount of CaO also

TABLE I. CHEMICAL ANALYSES OF ROCKS FROM TOFUA

	Tofua 4	Tofua 17	Tofua 32	Tofua 33	Tofua 50	Tofua 57	Tofua 68
SiO_2	56.03	53.80	57.13	56.04	54.42	65.86	55.93
Al_2O_3	15.83	14.47	14.59	15.38	16.56	13.27	16.59
Fe_2O_3	3.47	2.71	2.58	3.63	4.65	1.83	6.25
FeO	7.32	7.07	8.43	6.92	5.32	6.12	4.41
TiO_2	0.77	0.49	0.74	0.71	0.64	0.67	0.73
CaO	9.95	11.92	9.17	9.86	10.89	6.01	10.03
MgO	3.61	7.34	4.22	4.46	4.71	1.84	3.15
Na_2O	2.29	1.48	2.23	2.07	2.00	3.13	1.98
K_2O	0.52	0.33	0.53	0.49	0.40	0.88	0.54
MnO	0.16	0.17	0.18	0.17	0.16	0.16	0.16
$H_2O(+)$	0.48	0.51	0.62	0.61	0.64	0.53	0.50
$H_2O(-)$	0.15	0.29	0.24	0.27	0.25	0.24	0.21
P_2O_5	0.14	0.09	0.15	0.14	0.12	0.23	0.15
TOTAL	100.72	100.67	100.81	100.75	100.76	100.77	100.63
Total Fe as FeO	10.44	9.51	10.75	10.19	9.50	7.77	10.03

Analyst: Shiro Imai

TABLE I. (Continued) CHEMICAL ANALYSES
OF ROCKS FROM TOFUA
NORMS (CIPW)

		Tofua 4	Tofua 17	Tofua 32	Tofua 33	Tofua 50	Tofua 57	Tofua 68
q		13.56	10.64	14.22	14.16	13.02	27.72	18.60
or		3.34	2.22	3.34	2.78	2.22	5.00	3.34
ab		19.39	12.58	18.86	17.29	16.77	26.20	16.77
an		31.14	31.69	28.08	31.41	35.03	19.74	34.75
di	wo	7.31	11.14	6.96	6.96	7.54	3.36	5.92
	en	3.50	6.70	3.60	3.80	4.90	1.00	4.30
	fs	3.70	3.83	3.17	2.90	2.11	2.51	1.06
hy	en	5.50	11.70	7.00	7.40	6.90	3.60	3.60
	fs	5.51	6.34	9.37	5.81	3.04	6.47	0.92
mt		5.10	3.94	1.37	5.34	6.73	2.55	9.05
il		1.52	0.91	3.71	1.37	1.22	1.22	1.37
ap		0.34	0.34	0.34	0.34	0.34	0.67	0.34
		$Ab_{38}An_{62}$	$Ab_{28}An_{72}$	$Ab_{40}An_{60}$	$Ab_{36}An_{64}$	$Ab_{32}An_{68}$	$Ab_{57}An_{43}$	$Ab_{33}An_{67}$

TABLE I. (Continued) CHEMICAL ANALYSES OF ROCKS FROM TOFUA

Tofua 4: Inclusion of medium grained hypidiomorphic-granular labradorite augite diorite in the Hokula Froth Lava on the beach beneath Hokula village.

Tofua 17: Porphyritic augite basaltic andesite or (quartz basalt in Rittmann's nomenclature) from a small lava flow on the southern flank of Lofia cone.

Tofua 32: 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 B1.

Tofua 33: Aphanitic hypersthene-bearing augite andesite (labradorite dacite in Rittmann's nomenclature) from a 30-foot-thick lava flow of the Hamatua Formation, 300 feet below the caldera rim between triangulation stations B and B1.

Tofua 50: Porphyritic hypersthene-augite andesite (quartz-bearing labradorite andesite in Rittmann's nomenclature) collected from a 70-foot-thick lava flow of the Kolo Formation from triangulation station G.

Tofua 57: Microporphyritic hypersthene-bearing augite dacite (dacite in Rittmann's nomenclature) collected from the Hamatua Formation behind Hamatua village at an elevation of 500 feet.

Tofua 68: A labradorite andesite (labradorite dacite in Rittmann's nomenclature) collected 0.1 mile northwest of Hokula village as an inclusion in the Hokula Froth Lava.

TABLE II. AVERAGE CHEMICAL ANALYSES OF ROCKS FROM IZU-HAKONE REGION, JAPAN
(From Kuno, 1967, p. 647-48)

	1J	2J	3J	4J	5J	6J	7J
SiO_2	50.34	53.09	58.98	71.37	53.81	55.55	66.55
Al_2O_3	15.72	15.44	14.96	13.59	17.79	17.24	15.35
Fe_2O_3	2.80	4.02	3.29	1.89	2.44	3.68	2.21
FeO	8.96	9.01	7.59	2.94	6.60	5.96	3.19
TiO_2	0.81	1.17	1.06	0.48	0.95	0.83	0.68
CaO	11.93	9.68	7.30	3.44	8.79	8.40	5.11
MgO	7.40	4.66	2.74	0.66	5.87	4.42	1.74
Na_2O	1.37	2.12	3.03	3.84	2.76	2.92	3.66
K_2O	0.27	0.45	0.69	1.42	0.62	0.68	1.17
MnO	0.31	0.23	0.19	0.18	0.19	0.18	0.15
P_2O_5	0.09	0.12	0.15	0.19	0.19	0.13	0.19
TOTAL	100.00	99.99	99.98	100.00	100.01	99.99	100.00

1) Average basalt of the pigeonitic series, 5 analyses

2) Average basaltic andesite of the pigeonitic series, 53 analyses

3) Average andesite of the pigeonitic series, 4 analyses

4) Average dacite of the pigeonitic series, 8 analyses

5) Average basaltic andesite of the hypersthenic series, 8 analyses

6) Average andesite of the hypersthenic series, 13 analyses

7) Average andesite-dacite of the hypersthenic series, 9 analyses

TABLE II. (Continued) AVERAGE CHEMICAL ANALYSES
OF ROCKS FROM IZU-HAKONE REGION, JAPAN
NORMS
(From Kuno, 1967, p. 647-48)

	1J	2J	3J	4J	5J	6J	7J
q	3.79	9.80	17.09	34.24	6.02	10.55	26.75
or	1.61	2.67	4.06	8.36	3.67	4.01	6.90
ab	11.58	17.93	25.64	32.45	23.33	24.69	30.93
an	35.94	31.29	25.20	15.66	34.29	31.93	22.03
wo	9.49	6.67	4.22	0.13	3.42	3.76	0.93
en	18.42	11.60	6.83	1.65	14.62	11.00	4.34
fs	13.39	11.72	9.83	3.38	8.89	6.86	3.20
mt	4.06	5.84	4.77	2.74	3.54	5.35	3.20
il	1.54	2.21	2.02	0.91	1.81	1.58	1.29
ap	0.20	0.91	0.37	0.45	0.44	0.30	0.44

explains the calcic nature of the plagioclase feldspars 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 the crystallization of Ca-rich clinopyroxenes. Augite and pigeonite are very abundant, whereas non-calcic pyroxene (hypersthene) is sparse.

The alkali:silica diagram at the bottom of Figure 2 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 apparent parallel trends between the suites. K_2O content is nearly the same in the two regions. Dickinson (1968, p. 2261-67) notes that K_2O is normally low in andesites which are erupted near the trench side of the island arc-trench systems.

When total iron is plotted against SiO_2, as in the upper diagram of Figure 2, the iron content of the Tofua rocks falls in between those of the two Japanese suites when the SiO_2 percentage is less than 58, though it is greater than that in the Japanese rocks at higher contents of SiO_2. The A-F-M diagram, Figure 3, in which A is total alkalies, F is total iron as FeO, and M is MgO, reiterates Figure 2 by showing that the general trend of the Tofua lava suite is iron enrichment with regard to magnesium and alkalies. The most siliceous sample, Tofua 57, does not display a large increase in the alkalies, as do the average pigeonitic and hypersthenic dacites of Japan.

In the A-F-M diagram, iron enrichment of the pigeonitic suite is similar to that in the rocks of Tofua. However, examination of Figure 2 shows that in the pigeonitic series of Japan, iron enrichment takes place at a lower SiO_2 percentage than in the Tofua rocks.

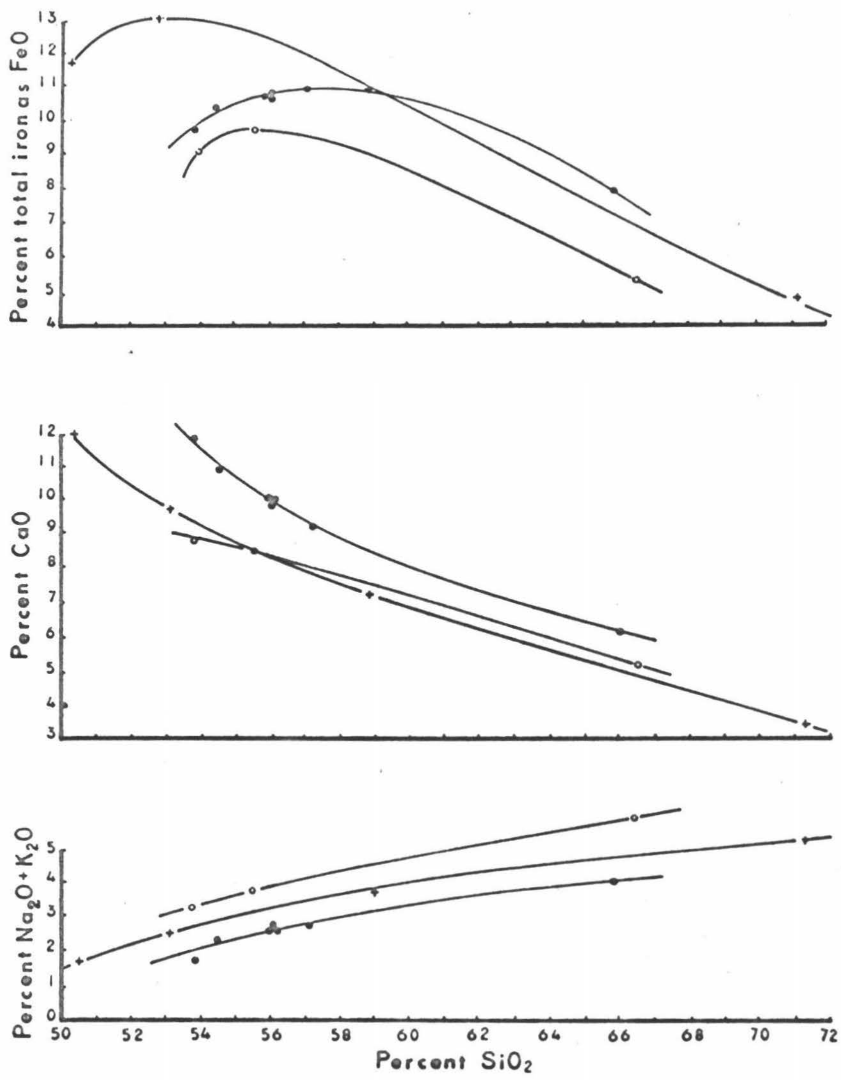


FIGURE 2. VARIATION DIAGRAMS

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

Examination of Table I shows that P_2O_5 content generally increases with greater silica percentages, and hence with increasing total alkalies. Apatite was not observed in the mode.

Normative orthoclase in the Tofua rocks ranges from 2.22 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 to that in the Izu-Hakone rocks. Normative quartz tends to be more abundant in the Tofua rocks than in the Japanese rocks. The average dacite of the hypersthenic suite has a normative quartz value comparable to that of Tofua 57.

Comparison of the Mode to the Norm

Table III represents 1000-point-count modal analyses of the chemically analyzed rocks from Tofua. When compared to the CIPW Norms shown in Table II, there are obvious discrepancies.

Quartz (silica minerals) is considerably less in the mode than the norm. Silica is present but as a component in the glass of the quickly chilled aphanitic andesites. Most quartz did not have time to crystallize. Table III shows that the rocks lowest in modal silica minerals contain the greatest amount of glass. Tofua 4, a medium grain labradorite-augite diorite, does not have glass in the mode, and the rock shows good correspondence between modal and normative quartz.

Plagioclase feldspar is generally less in the mode than in the norm. This can also be attributed to the large glass content in the rocks. For example, Tofua 33 contains abundant glass in the mode, and

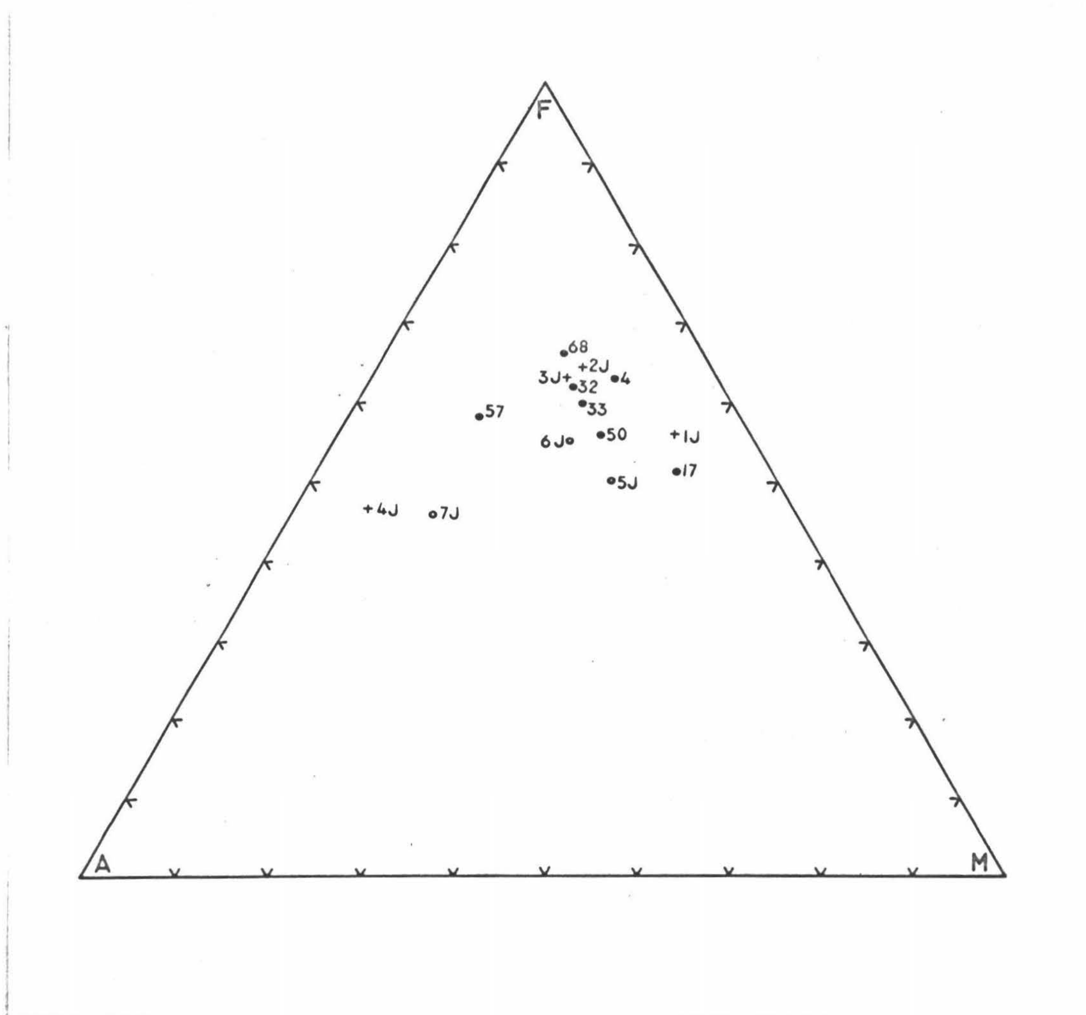


FIGURE 3. A-F-M DIAGRAM

is correspondingly poor in plagioclase feldspar and silica minerals.

In Tofua 57, the most siliceous rock analyzed, normative quartz is nearly 28 percent, whereas modal silica minerals are only six percent. The modal and normative feldspar content are almost the same. Although glass is present, it is not enough to make up for the small amount of quartz in the mode. However, clinopyroxene is approximately five times greater in the mode than in the norm, thus reducing the amount of free silica.

Tofua 17 contains abundant enstatite-rich normative hypersthene though no hypersthene was observed in thin section. Modal olivine undoubtedly contains some of the Mg of the normative hypersthene, but only a trace of olivine is present. The rest of the components of the normative hypersthene must have entered into the modal clinopyroxene.

GEOLOGIC HISTORY

The early geologic history of the Tonga Archipelago is unknown. The coralline islands of Tonga are primarily composed of Eocene limestone. Possibly during the late Pleistocene epoch the eruption of the pre-caldera lavas of Tofua took place. In the type-section of the Hamatua Formation, the rocks appear to become more basic upward.

A period of quiesence followed, which allowed deep valleys to be incised into the pre-caldera surface. It is unknown if the eruption of the Hokula Froth Lava took place just before, during, or after the initial collapse of the caldera. The field and petrographic evidence indicate that the froth lava contained a large amount of volatiles. It is possible that during quiesence, these volatiles were concentrated in the magma

TABLE III. MODAL ANALYSES OF CHEMICALLY ANALYZED ROCKS FROM TOFUA

Sample	Fpr	Cpx	Opx	S M*	Ore	Ol	Glass	Ves
Tofua 4	39.4	39.2	----	12.4	9.4	----	----	----
Tofua 17	29.8	29.8	----	5.4	9.0	tr.	9.0	14.0
Tofua 32	21.4	33.2	----	3.6	15.6	----	25.8	0.4
Tofua 33	17.0	17.6	----	4.0	13.6	----	42.0	3.8
Tofua 50	12.2	6.8	2.6	----	13.4	----	28.6	36.4
Tofua 57	42.4	30.0	0.8	6.1	9.2	----	9.8	1.6
Tofua 68	58.8	19.2	0.4	8.6	8.2	----	----	4.8

*silica minerals (quartz and tridymite)

chamber, and that the eruption of the froth lava initiated caldera collapse. It is believed that most of the froth lava has either been eroded away or flowed into the sea during emplacement, because of the small volume seen at the present time. If so, a larger amount existed at the time of eruption. It should be noted that the froth lava only crops out on the northern and western shores of Tofua; therefore, its source must be from the northern sector of the caldera, which is the site of present volcanism.

Following its eruption, streams attacked the Hokula Froth Lava cutting deep valleys. Tensional cracks and normal faults associated with the ever-enlarging caldera created conduits for rising magma which erupted as a series of ash and cinder cones on the caldera rim, thus creating the tephra members of the Kolo Formation. By then, the composition of the magma had become more basic, although periodic eruptions of andesite lava flows continued.

Within the caldera itself, rocks of the Lofia Formation were erupted. Undoubtedly, rocks of the Lofia and Kolo Formations were erupted concurrently, as seen by gradational contact relationships between the two formations. In historic time, frequent eruptions of Lofia cone have been reported. The last was in 1959 (Richards, 1962, p. 16).

FIGURE 4. PANORAMIC VIEW OF THE TOFUA CALDERA.

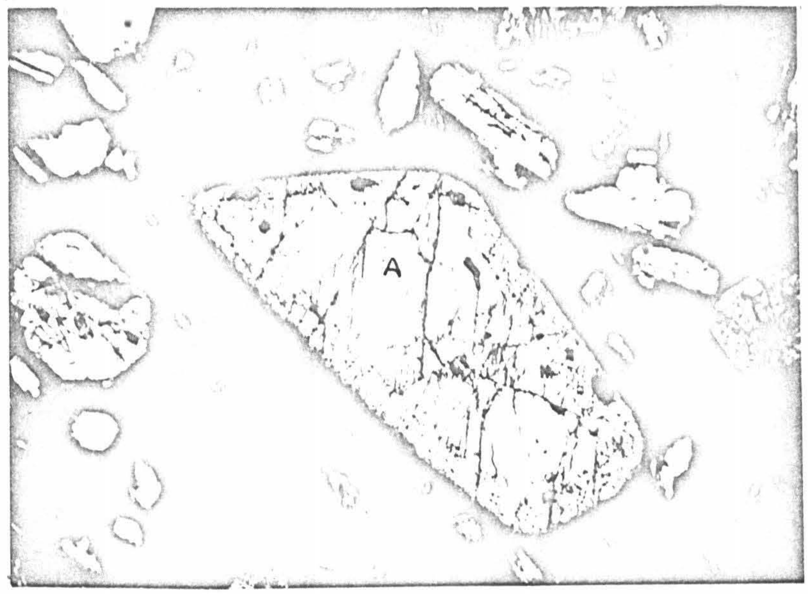


FIGURE 5. PHOTOMICROGRAPH OF XENOCRYSTIC AUGITE (A) IN TOFUA 17. NOTE REACTION RIM AND ROUNDING. CRYSTAL IS 1.7 mm LONG. CROSSED NICOLS.

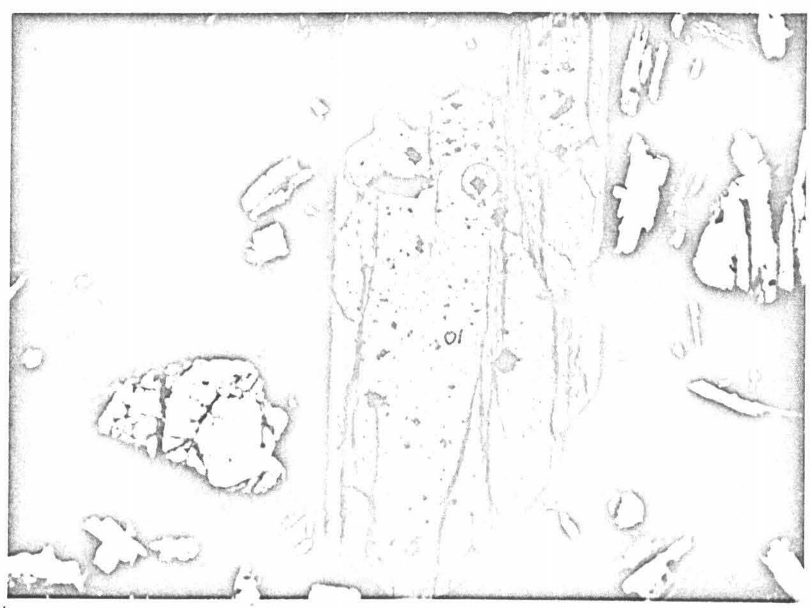


FIGURE 6. PHOTOMICROGRAPH OF OLIVINE (01) PHENOCRYST IN TOFUA 17. CRYSTAL IS 2.1 mm. CROSSED NICOLS.

FIGURE 7. PHOTOMICROGRAPH OF PLAGIOCLASE FELDSPAR GLOMEROCRYST 2.3 mm ACROSS IN TOFUA 17. NOTE INCLUSIONS OF GLASS AND MAGNETITE DUST FORMING ZONE AROUND ENTIRE CRYSTAL WITH SUBSEQUENT GROWTH. CROSSED NICOLS.

FIGURE 8. PHOTOMICROGRAPH OF PHENOCRYST OF PIGEONITIC AUGITE (PA) WITH PIGEONITE CORE (P) IN TOFUA 17. CRYSTAL IS .42 mm LONG. TWINNED EUHEDRAL AUGITE TO THE LEFT. CROSSED NICOLS.

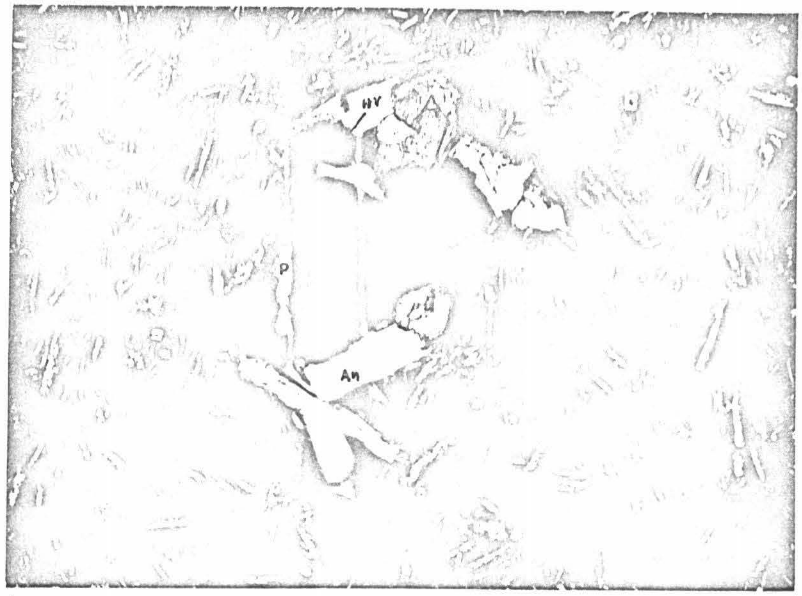


FIGURE 9. PHOTOMICROGRAPH OF GLOMEROCRYST OF HYPERSTHENE (Hy), PLAGIOCLASE (An), AND AUGITE (A) IN TOFUA 57. THE HYPERSTHENE GRAIN IS .35 mm LONG. NOTE PIGEONITE (P) RIM AROUND HYPERSTHENE. CROSSED NICOLS.

FIGURE 10. PHOTOMICROGRAPH OF ZONED PLAGIOCLASE MICROPHENOCRYST .25 mm ACROSS IN TOFUA 57. NOTE OSCILLATORY ZONING. CROSSED NICOLS.

BIBLIOGRAPHY

Bloss, F. D., 1961, An Introduction to the Methods of Optical Crystallography, Holt, Rinehart, and Winston, San Francisco, 294 p.

Coats, R. R., 1967, Basaltic Andesites, p. 689-736, in Basalts, A. Poldervaart and H. H. Hess, eds., Interscience, New York, v. 2, 379 p.

Cook, James, and George Forster, 1777, A Voyage Round the World Performed in His Majesty's Ships the Resolution and Adventure, in the Years 1772, 1773, 1774, 1775, v. IV, Dublin, 518 p.

Daly, R. A., 1916, Petrography of the Pacific Islands, Bull. Geol. Soc. Amer., v. 27, p. 325-344.

Dalyell, Sir John, 1812, Shipwrecks and Disasters at Sea, George Ramsay and Co., Dublin, v. III, 515 p.

Dickinson, W. R., 1968, Circum-Pacific andesite types, Jour. Geophys. Res., v. 73, p. 2261-2269.

Emmons, R. C., 1943, The universal stage, Geol. Soc. Amer. Mem. 8, 205 p.

George, W. O., 1924, The relation of the physical properties of natural glasses to their chemical composition, Jour. Geology, v. 32, p. 353-372.

Harker, Alfred, 1891, Notes on a collection of rocks from the Tongan Islands, Geol. Mag., v. 8, p. 250-258.

Heinrich, E. W., 1965, Microscopic Identification of Minerals, McGraw-Hill, San Francisco, 414 p.

Hoffmeister, J. E., 1932, Geology of Eua, Tonga, B. P. Bishop Mus. Bull., no. 96, 93 p.

Johannsen, Albert, 1931, A Descriptive Petrography of the Igneous Rocks, v. 1, Univ. of Chicago Press, Chicago, 267 p.

Kuno, Hisashi, 1950, Petrology of Hakone volcano and adjacent areas, Japan, Bull. Geol. Soc. Amer., v. 61, p. 957-1020.

________, 1959, Origin of Cenozoic petrographic provinces of Japan and surrounding areas, Bull. Volcan., v. 20, p. 37-76.

________, 1965, Origin of calc-alkaline rock series, Geol. Soc. Amer. Spec. Paper 82, p. 116.

________, 1967, Differentiation of basalt magmas, p. 623-688, in Basalts, A. Poldervaart and H. Hess, eds., Interscience, New York, v. 2, 379 p.

Lahee, Frederick, 1961, Field Geology, 6th ed., McGraw-Hill, New York, 926 p.

Lister, J. J., 1891, Notes on the geology of the Tongan Islands, Quart. Jour. Geol. Soc. of London, v. 47, p. 590-617.

Locardi, E., and Mario Mittempergher, 1965, Study of an uncommon lava sheet in the Bolsena District (Central Italy), Bull. Volcan., v. 28, p. 75-84.

_______, and _______, 1967, On the genesis of ignimbrites, how ignimbrites and other pyroclastic products originate from a flowing melt, Full. Volcan., v. 31, p. 131-152.

Macdonald, G. A., 1949, Hawaiian petrographic province, Bull. Geol. Soc. Amer., v. 60, p. 1540-1596.

_______, 1967, Forms and structures of extrusive basaltic rocks, p. 1-61, in Basalts, A. Poldervaart and H. H. Hess, eds., Interscience, New York, v. 1, 482 p.

_______, and Takashi Katsura, 1965, Eruption of Lassen Peak, Cascade Range, California, in 1915: example of mixed magmas, Bull. Geol. Soc. Amer., v. 76, p. 475-482.

Marshall, Patrick, 1916, Oceania, handbuch der regionalen geologie hrsg. von prof. dr. G. Steinmann und prof. dr. O. Wilckens, Heidelberg, v. II, p. 1-36.

Osborn, E. F., 1962, Reaction series for subalkaline rocks based on different oxygen pressures, Am. Mineralogist, v. 47, p. 211-226.

Peacock, M. A., 1931, Classification of igneous rocks, Jour. Geology, v. 39, p. 54-67.

Richard, J. J., 1962, Catalogue of the active volcanoes of the world including solfatara fields, Part XIII Kermadec, Tonga, and Samoa, Internat. Assoc. Volcanolog., Napoli, 38 p.

Rittmann, Alfred, 1952, Nomenclature of volcanic rocks, Bull. Volcan., v. 12, p. 75-102.

Tröger, W. E., 1959, Optische Bestimmung der Gesteinsbildenden Minerale, E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 147 p.

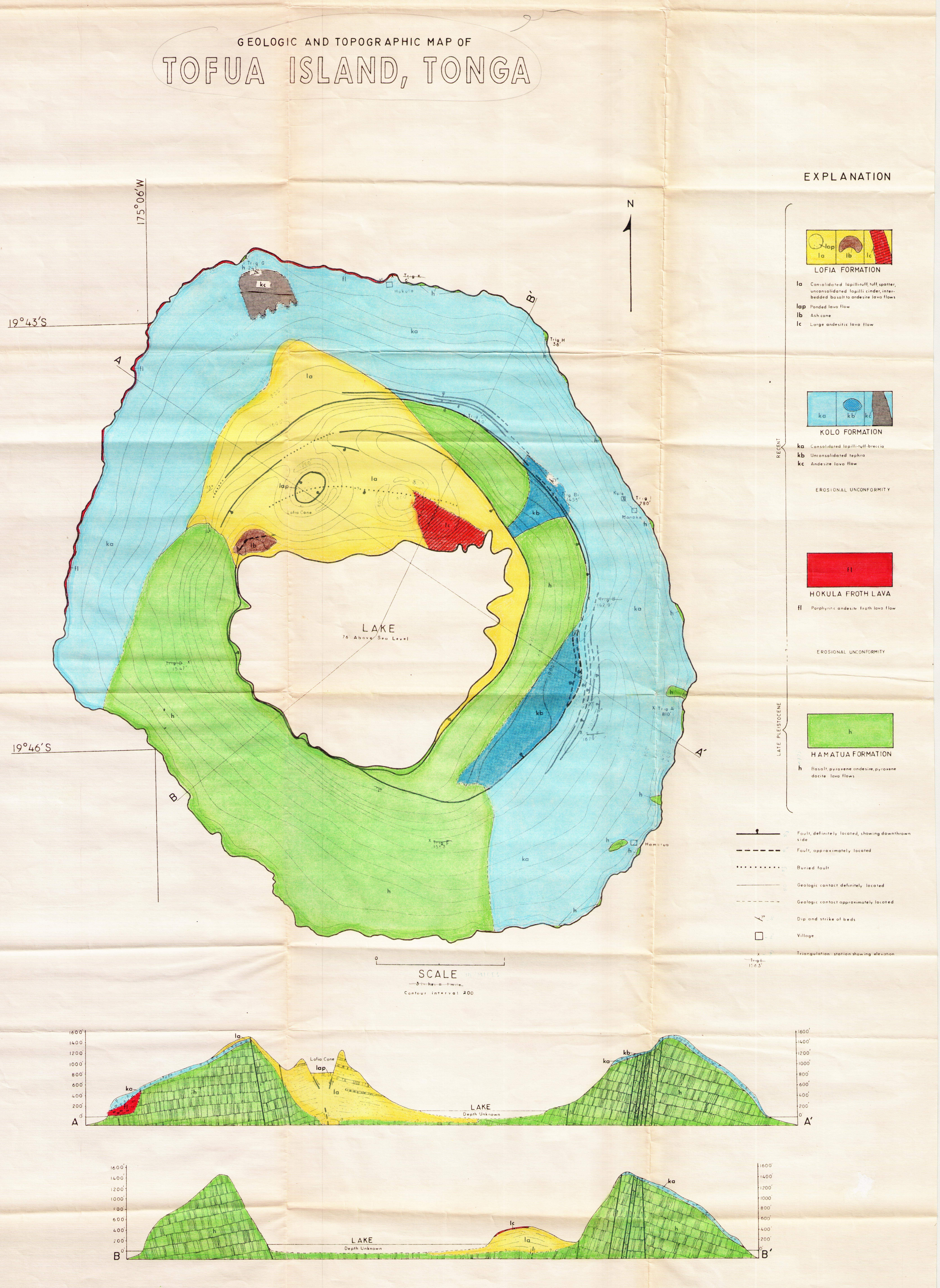
Turner, F. J., and John Verhoogen, 1960, Igneous and Metamorphic Petrology, 3rd ed., McGraw-Hill, New York, 694 p.

Vance, J. A., 1962, Zoning in igneous plagioclase: normal and oscillatory zoning, Amer. Jour. Sci., v. 260, p. 746-760.

_______, and John Gilreath, 1967, The effect of synneusis on phenocryst distribution patterns in some porphyritic igeneous rocks, Amer. Mineral., v. 52, no. 3 & 4, p. 529-536.

Williams, Howel, F. J. Turner, and C. M. Gilbert, 1954, Petrography, An Introduction to the Study of Rocks in Thin Sections, W. H. Freeman and Co., San Francisco, 406 p.

Woide, Charles, 1776, trans., Abel Tasman's 1643 Journal, microfilm copy 1205, University of Hawaii.


GEOLOGIC AND TOPOGRAPHIC MAP OF
TOFUA ISLAND, TONGA
175°06'W
19°43'S
19°46'S
N
LAKE
76' Above Sea Level
Lofia Cone
Hokula
Manaka
Hamatua
SCALE
Contour interval 200
EXPLANATION
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
KOLO FORMATION
ka Consolidated lapilli-tuff-breccia
kb Unconsolidated tephra
kc Andesite lava flow
EROSIONAL UNCONFORMITY
HOKULA FROTH LAVA
fl Porphyritic andesite froth lava flow
EROSIONAL UNCONFORMITY
HAMATUA FORMATION
h Basalt, pyroxene andesite, pyroxene dacite lava flows
RECENT
LATE PLEISTOCENE
Fault, definitely located, showing downthrown side
Fault, approximately located
Buried fault
Geologic contact definitely located
Geologic contact approximately located
Dip and strike of beds
Village
Triangulation station showing elevation
A
A'
B
B'
LAKE
Depth Unknown