SMITHSONIAN CONTRIBUTIONS TO THE
EARTH SCIENCES

NUMBER 4

William G. Melson,
Eugene Jarosewich,
and Charles A. Lundquist

Volcanic Eruption at Metis Shoal, Tonga, 1967–1968: Description and Petrology

SMITHSONIAN INSTITUTION PRESS
CITY OF WASHINGTON
1970

ABSTRACT

Melson, William G.; Jarosewich, Eugene; and Lundquist, Charles A. Eruption of Metis Shoal, Tonga, 1967–1968: Description and Petrology. *Smithsonian Contributions to the Earth Sciences,* 4: 1–18, 1970.—The 1967–1968 eruption of Metis Shoal, Tonga, was evidentially similar to the frequent shallow submarine eruptions of the inner island arc of Tonga. The eruption began about 10 December 1967, and an island eventually emerged; by 19 February 1968, the island had been eroded to beneath wave base. The eruptions were characterized by explosions of steam and ash which hurled bombs a few to several hundred feet into the air. The rocks ejected are pumiceous dacites which, for their silica content, have unusually low alkali contents and rare earth-element contents. The chemical characteristics of the dacite are hard to account for by partial melting of an ocean-ridge basalt parent. The peculiar properties of the dacite appear to characterize other Tongan lavas and support the idea that Tonga is part of a distinct petrographic province.

Official publication date is handstamped in a limited number of initial copies and is recorded in the Institution's annual report, Smithsonian Year.

UNITED STATES GOVERNMENT PRINTING OFFICE
WASHINGTON : 1970

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 30 cents

William G. Melson,
Eugene Jarosewich,
and Charles A. Lundquist

Volcanic Eruption at Metis Shoal, Tonga, 1967–1968: Description and Petrology

Introduction

In late December 1967, we were informed by the Smithsonian Center for Short-lived Phenomena that a volcanic eruption was under way in the Tonga Islands. The early reports indicated that a submarine eruption had resulted in creation of a new island. In February 1968, Charles A. Lundquist, on a previously planned trip to Australia, managed to detour and visit the site. At that time, the volcanic island had been eroded away, and only shoals remained; however, samples were obtained by diving. The petrology of these samples and the description of the eruption, obtained from photographs and from other documentation of the eruption obtained by correspondence and by interviews with eye witnesses, are the subject of this paper. Background information is summarized on the probable relationships between volcanism and seismicity in this island-arc environment.

Geologic Setting of Tonga

The Tonga Islands have long been known as sites of frequent earthquakes and volcanic eruptions. The volcanic activity is restricted to the western islands; the eastern islands, including Tongatapu, long inactive volcanically, are capped by coral reefs and seldom have exposures of volcanic rocks.

Figure 1 shows that the western Tonga Islands lie on a line that, with but slight bending, can be extended to include the volcanic Kermadec Islands, and the volcanic and hydrothermal regions of North Island, New Zealand.

There are 10 active volcanoes in western Tonga (Richards, 1962). Of these, only Tofua, Late, and Fonualei have remained above sea level throughout historic times. The remaining seven volcanoes are submarine. Of these seven, only Falcon Island, Metis Shoal, and Home Reef have reached above sea level during eruptions, and, at present, even these three have been eroded to below sea level. The most active shoal volcano appears to be the one which periodically builds Falcon Island. In all, nine separate eruptions have been reported. Perhaps because of their transitory existence, very little is known about the petrology of these "jack-in-the-box" islands.

One of the few generalizations about the petrology of the Tonga Islands was made many years ago by Alfred Harker (1891), after examination of a suite of Tongan rocks:

> With the exception of the Falcon Island rocks, all those [rocks] examined from the Tonga Islands ap-

---

William G. Melson and Eugene Jarosewich, Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, D.C. 20560. Charles A. Lundquist, Smithsonian Astrophysical Observatory, Cambridge, Massachusetts 02138.

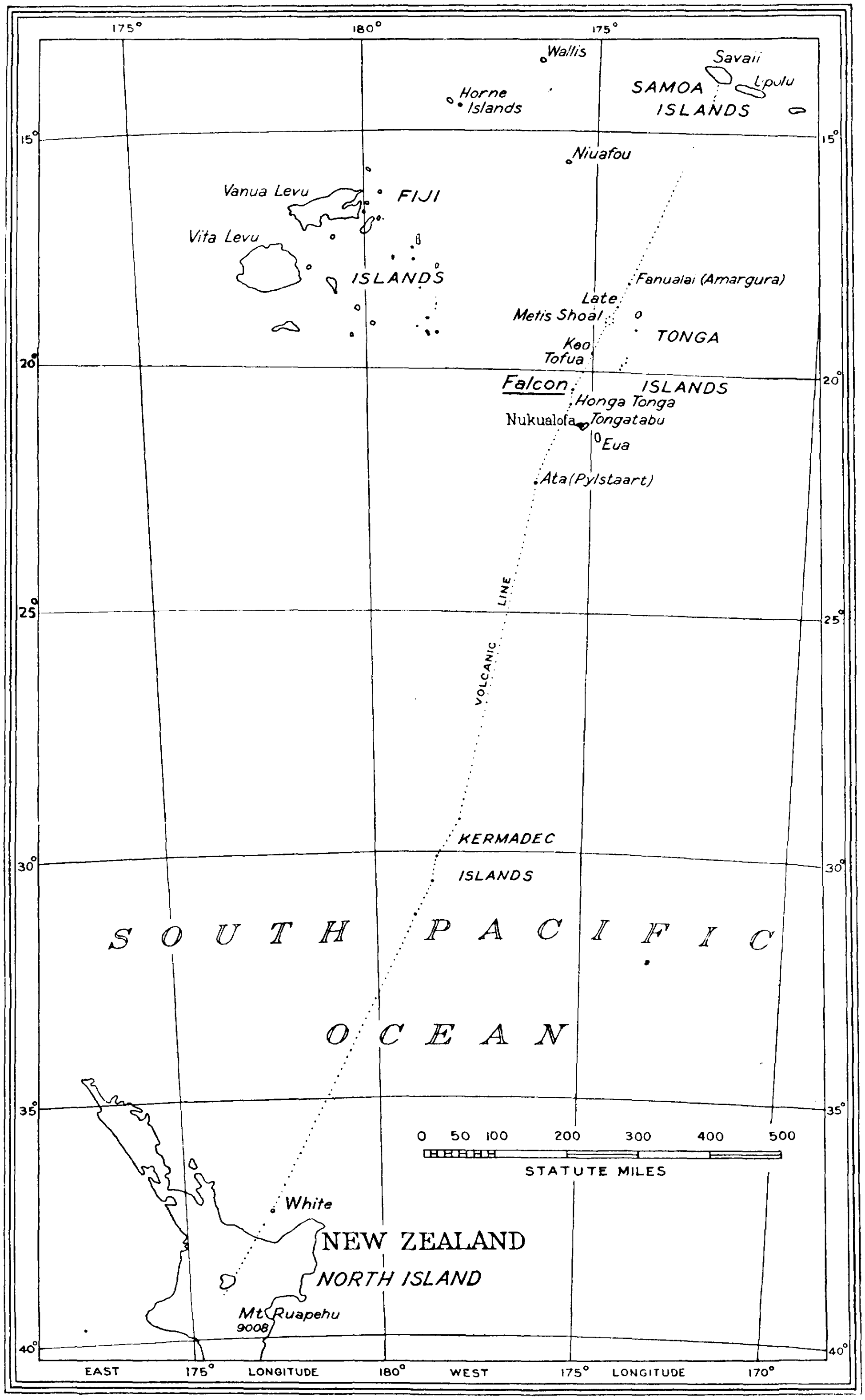

FIGURE 1.—Location of Tonga and Metis Shoal.

pear to be of submarine formation. The absence or presence in different strata of any sensible proportion of calcareous matter and organic remains is perhaps related to the more or less rapid rate of accumulation at different epochs of eruption. The volcanic material ejected seems to have been almost exclusively of fragmental character, and in some cases there are indications of violent explosive action. This is quite in accord with the andesitic nature of the materials thrown out, which are the types common in the Pacific region.

Harker evidently did not examine samples of lavas, which do make up parts of Tofua and other active subaerial Tongan volcanoes.

Bryan (1969) drew attention to certain chemical peculiarities of Tongan volcanic rocks—unusually low alkalies and high iron with high silica contents. He notes that this tendency applies not only to the dacites, but to the basalts from Late and Tofua as well. This peculiarity is true of our Metis Shoal's samples, and bears out the distinctive chemistry of Tongan lavas.

RELATION BETWEEN VOLCANISM AND SEISMOLOGY.—Tonga is along the junction of two of the six major tectonic blocks of the earth's crust (Figure 2). The contact between these blocks is normally an oceanic trench, oceanic ridge, or a fracture zone (transform fault zone, Figure 3). At oceanic trenches, the thick lithosphere, estimated to be around 100 kilometers thick, is believed to move downward. Along its upper surface, numerous earthquakes occur, defining a narrow belt. Rocks of the lithosphere, as they descend, are envisioned as becoming hot enough to undergo partial melting. Where tensional fractures occur along the lithosphere, melts so generated move upward, giving rise to the volcanism that characterizes most island arcs (Figure 4).

The Tonga-Kermadec region is one of the world's most active seismic belts (Isacks et al., 1969). Figure

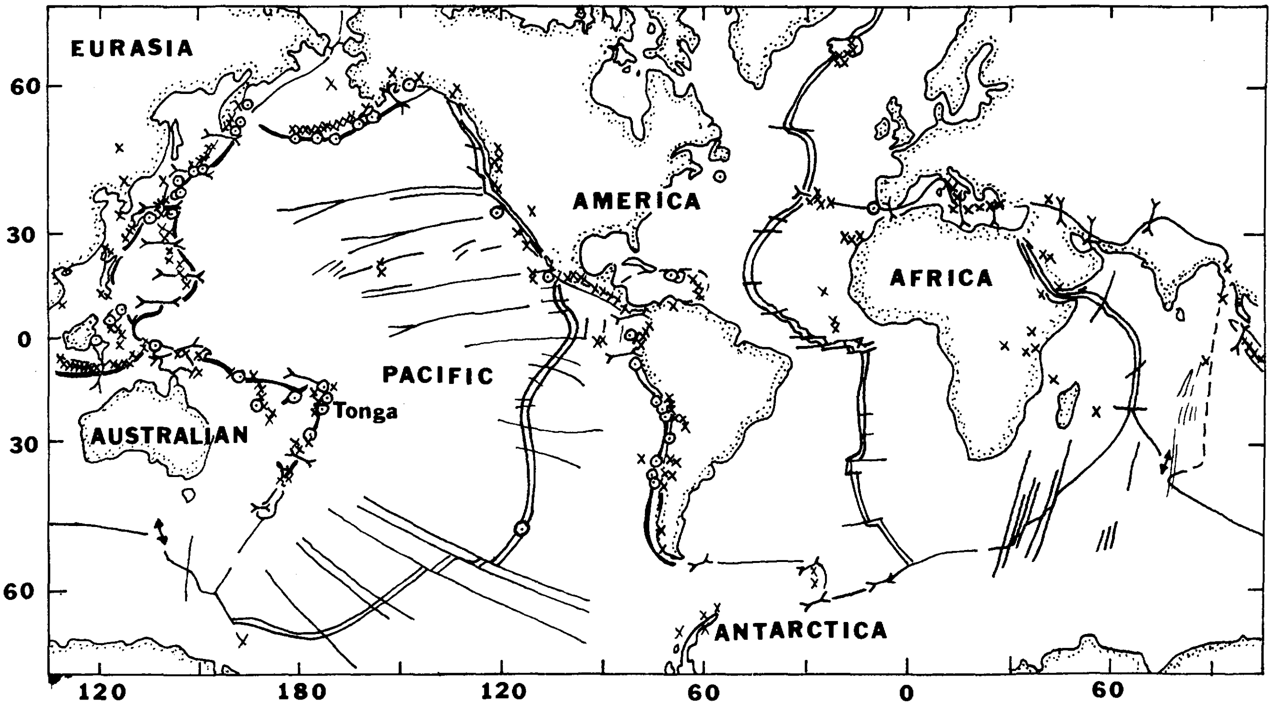

FIGURE 2.—Location of Tonga in regard to the large tectonic blocks of the new global tectonics. Heavy lines are island arcs or arc-like features. Tensional (divergent arrows) and compressional (convergent arrows) indicate relative movements at margins of blocks; length of arrows is roughly proportional to rate of relative movements. Some historically active volcanoes are indicated by X. Open circles represent earthquakes that generated tsunamis (seismic sea waves) detected at distances of 1,000 or more kilometers from their source. The six major tectonic blocks are shown (America, Africa, Eurasia, Antarctica, Pacific, and Australian). Modified from Isacks, Oliver, and Sykes (1968).

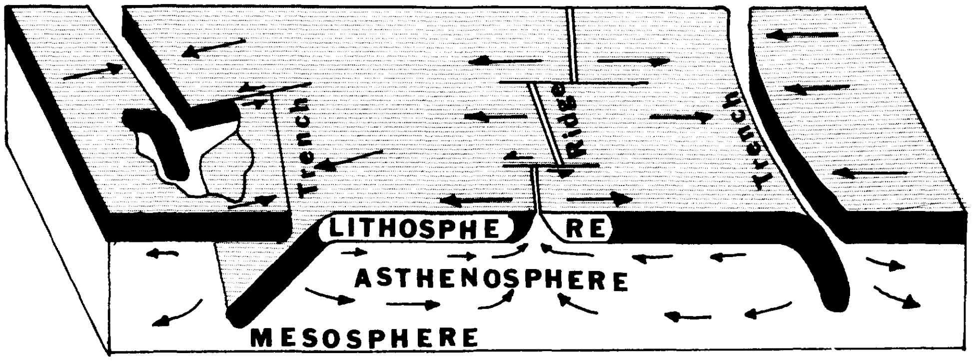

FIGURE 3.—Idealized block section showing probable nature of contacts between the tectonic blocks (Figure 2). Contacts are trenches, ridges, and fracture zones (transform faults). Modified from Isacks, Oliver, and Sykes (1968). Arrow indicates relative movements. The lithosphere moves under at oceanic trenches and is generated by igneous activity at mid-ocean ridges in the now widely accepted models of the new global tectonics. The contact between the lithosphere and asthenosphere is not the contact between the crust and mantle, but is at the much greater depth of about one-hundred kilometers.

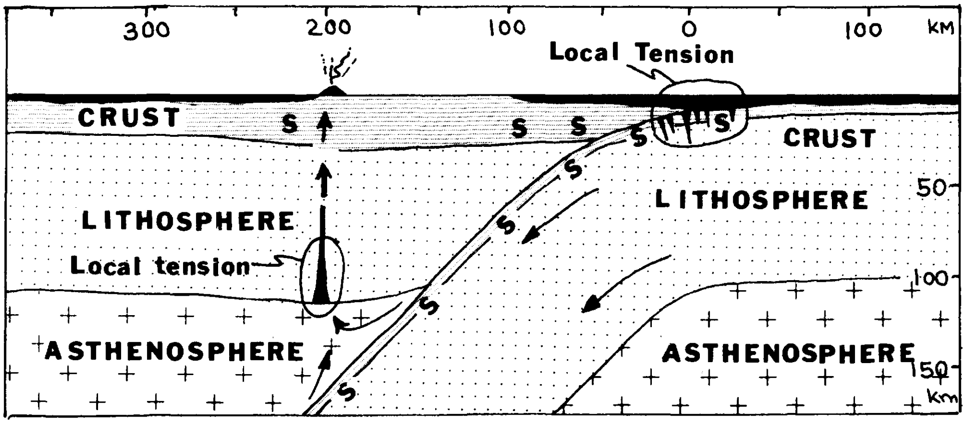

FIGURE 4.—Hypothetical section through an island arc. Down-going slab of lithosphere, seismic zone (S) near surface of slab and in adjacent crust, tensional features beneath ocean deep where slab bends abruptly and surface slab is still open are shown. Island-arc magmas move upward along tension fractures developed near the base of the astheosphere. Modified from Isacks, Oliver, and Sykes (1968).

5 shows epicenter locations through a portion of Tonga during a single year. The large number of events and their clear-cut restriction to a relatively narrow zone (the Benioff Zone) is characteristic of other island arcs. It is along this zone that the upper surface of the lithosphere is believed to be descending (Figure 4). It is also thought that the lavas of island arcs originate along this zone. A correlation between lava chemical composition and the depth below the eruption site to the Benioff Zone has been found. Specifically, the potassium content has been found to increase with increasing depth to this zone (Hatherton and Dickinson, 1969). At present, there is insufficient data on Tongan lavas to adequately test for such a relation. The presence of such a relation does indicate that the depth of magma generation is either at the Benioff Zone or directly related to the depth of this zone.

Course of the Eruption

On 11 December 1967 (Greenwich Time), volcanic activity in the Metis Shoal region of the Tonga Islands was noted by the crews of several ships and by passengers on a Polynesian Airlines flight from Samoa to

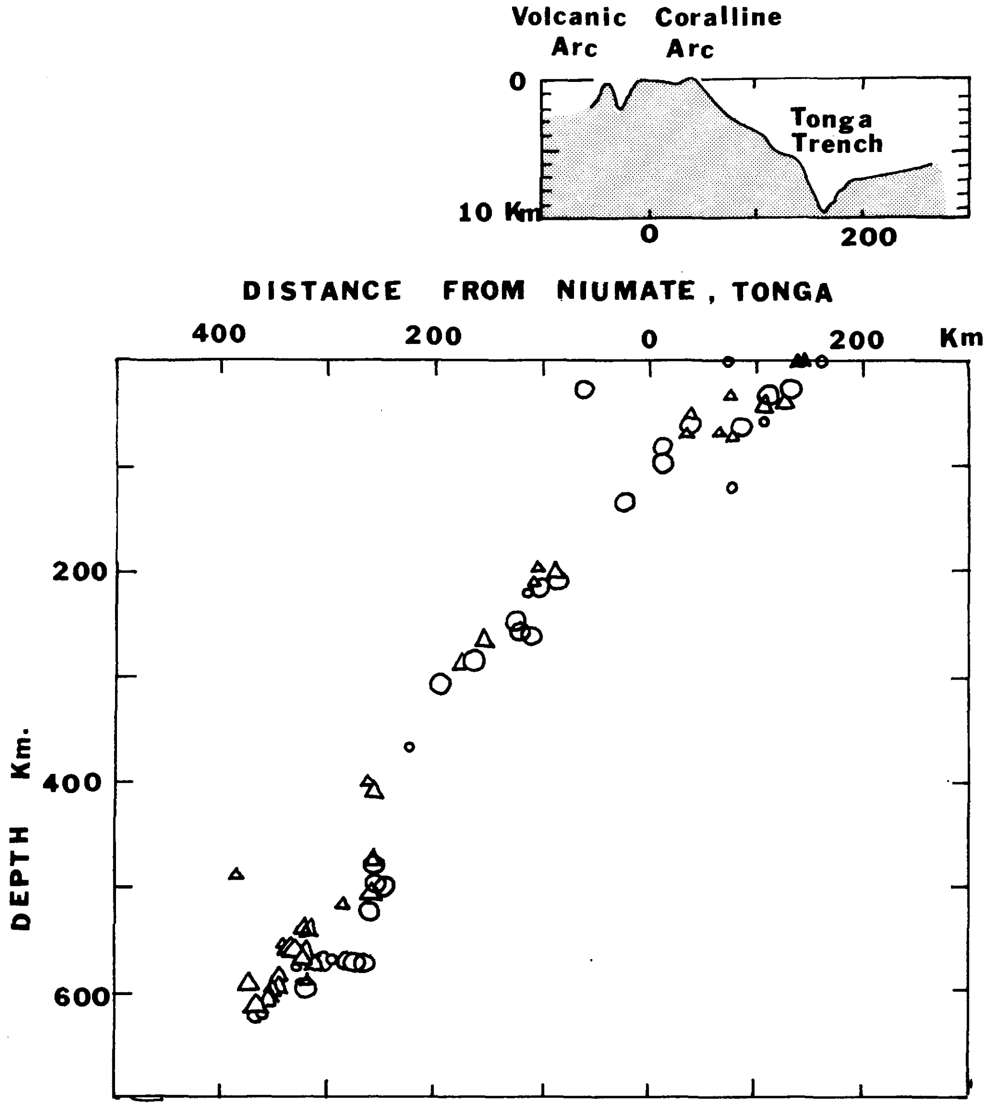

FIGURE 5.—Location of earthquake epicenters beneath Tonga during 1965. Vertical section through Niumate, Tonga. Triangles represent events projected from within 0–150 km south of the section; circles represent events projected from within 0–150 km north of the section. A vertical exaggeration of about 31 : 1 is used for the topographic section. Modified from Isacks, Oliver, and Sykes (1968).

Tonga. Volcanic activity was last reported from this region in 1876 (Phillips, 1899), and accounts exist for still earlier events (Richards, 1962).

The United States Navy Hydrographic Office map [1] of the Tonga Islands indicates three shallow areas in the region, of which the most southerly is designated Metis Shoal. Each area is shown with a diameter of about 0.5′. The approximate coordinates of these areas are:

Metis Shoal	19°10.8′S	174°51.8′W
northwestern shoal	19°9.8′S	174°52.6′W
northeastern shoal	19°9.5′S	174°51.1′W

The United States destroyer Fox, the first ship to sight the 1967 eruption, reported the site to be 0.7 nautical miles north of Metis Shoal, which puts the eruption approximately at the center of the three areas

---

[1] Map number 2016, Tonga Islands. 3d edition, 1947. Hydrographic Office, Washington, D.C.

in the Hydrographic Office chart. After its visit to the site on 13 February 1968, the Soviet research vessel Vityaz reported coordinates (Bezrukov et al., 1968):

19°09′06″S 174°51.1′W.[2]

These are nearest to the coordinates of the northeastern shoal. The *Alaimoana,* en route from Nuku'alofa, on 19 February 1968, passed near one shoal south of the eruptive site where specimens were collected. Hence, it appears that recent volcanic activity was north of a more southerly shoal. No other reports reaching us mention positions of the recent eruption relative to other shoals, nor do we know how many shoals might have been present at this time. On the basis of sea discoloration, there may be some possibility that the southerly shoal, observed at a distance from the *Alaimoana,* also had volcanic activity.

One observation on 11 December was from the *Tofua.* Captain Peter Bennett reported:

> At the closest approach of 9 miles the volcanic eruption had the appearance of an incandescent island about ½ mile long and 150 feet high, glowing cherry red at constant intensity. Above this island a dense pillar of steam and smoke ascended to 3000 feet and at approximately 1 minute intervals molten lava or boulders in parabolic arcs were observed being ejected to a height of 1000 feet.[3]

His Majesty, King Taufa'ahau Tupou IV of Tonga and his party obtained early photographic records of the events during a charter flight to the volcano on 14 December. At this time, rocks projected an estimated 50 feet above the sea as shown in Figure 6, and the island was some 100 to 200 yards across.[4]

On 14 December, two Orion Aircraft of No. 5 Squadron, Royal New Zealand Air Force, flew around the volcano for approximately 30 minutes. Flight Lieutenant P. K. Simpson reported:

> At the site of the eruption an island had formed and it was variously estimated to be 20 to 40 feet high and as much as 150 to 300 yards long. At the eastern (upwind) extremity of the island was a crater guessed to be 10 to 20 yards across. Its shape was circular with dark grey lips. Inside, the grey soon changed to a dark cherry red becoming brighter and more orange with increasing depth. These details were observed only momentarily when for a few seconds the smoke cleared about the crater. . . .
>
> Lumps of dark colored matter were being flung several hundred feet into the air. They seemed to be ejected at intervals of 10 to 20 seconds and they splashed into the sea in all directions out to a distance of 250 yards. This matter was clearly visible from ½ to 1 mile away. Occasionally a much larger piece (perhaps 2 or 3 feet across) would be seen to rise to a height of 100 to 200 feet.
>
> The sea water around the volcano was colored an emerald green streaked with brown. This discoloration extended several hundred yards upwind and 7 nautical miles on a bearing of 240° T from the island.[5]

Five days later, on 19 December, Captain C. H. Hill-Willis of the motor vessel *Aonui* observed the island from a distance of 4 miles. He noted: "the island was one third of a mile long and approximately 80 feet high. It was erupting from a single cone at intervals of roughly 3 minutes, with steam vapour rising to some 8,000 feet." [6]

Particularly informative observations were provided by Captain Thomas M. Holmes of Polynesian Airlines, who flew over the site repeatedly. Figures 7 and 8 were taken by him on 31 December. He relates that:

> The island, generally kidney-shaped at its best, lay with its longitudinal axis approximately E–W. Steam clouds on that day, 31 December, were blowing in a direction of about 200 degrees true, the surface wind was from the N.N.E.[7]

Concerning volcanic activity, Captain Holmes

---

[2] P. L. Bezrukov, J. O. Murdmaa, N. G. Prokoptsev, M. A. Repechka, Preliminary results of geological investigations at Metis Shoal Area, Tonga Islands. 1968. Enclosure with letter of 6 May 1968 from P. L. Bezrukov to C. A. Lundquist.

[3] Letter from Captain P. Bennett, *Tofua,* Union Steam Ship Company of New Zealand Limited, to C. A. Lundquist, 9 April 1968.

[4] Volcanic eruptions produces new "Jack-in-the-Box" island. Article in *The Chronicle,* Nuku'alofa, Tonga Islands (J. Reichelmann, editor), 15 December 1967, page 1. Also, private communication and 8-mm motion-picture film from J. J. Furniss, aviation adviser, Office of H. B. M. Commissioner and Consul, Tonga, to R. Citron in 1968.

[5] Royal New Zealand Air Force report on flight to Metis Shoal, 14 December 1967. Enclosure with letter from D. Rishworth, New Zealand Department of Scientific and Industrial Research, Geological Survey Office, to R. Citron, 8 May 1968.

[6] Letter from Captain C. H. Hill-Willis of the motor vessel *Aonui* Nuku'alofa, Tonga Islands, to C. A. Lundquist, 10 April 1968.

[7] Letter from Captain T. M. Holmes, Polynesian Airlines Limited, to R. Citron, 10 April 1968.

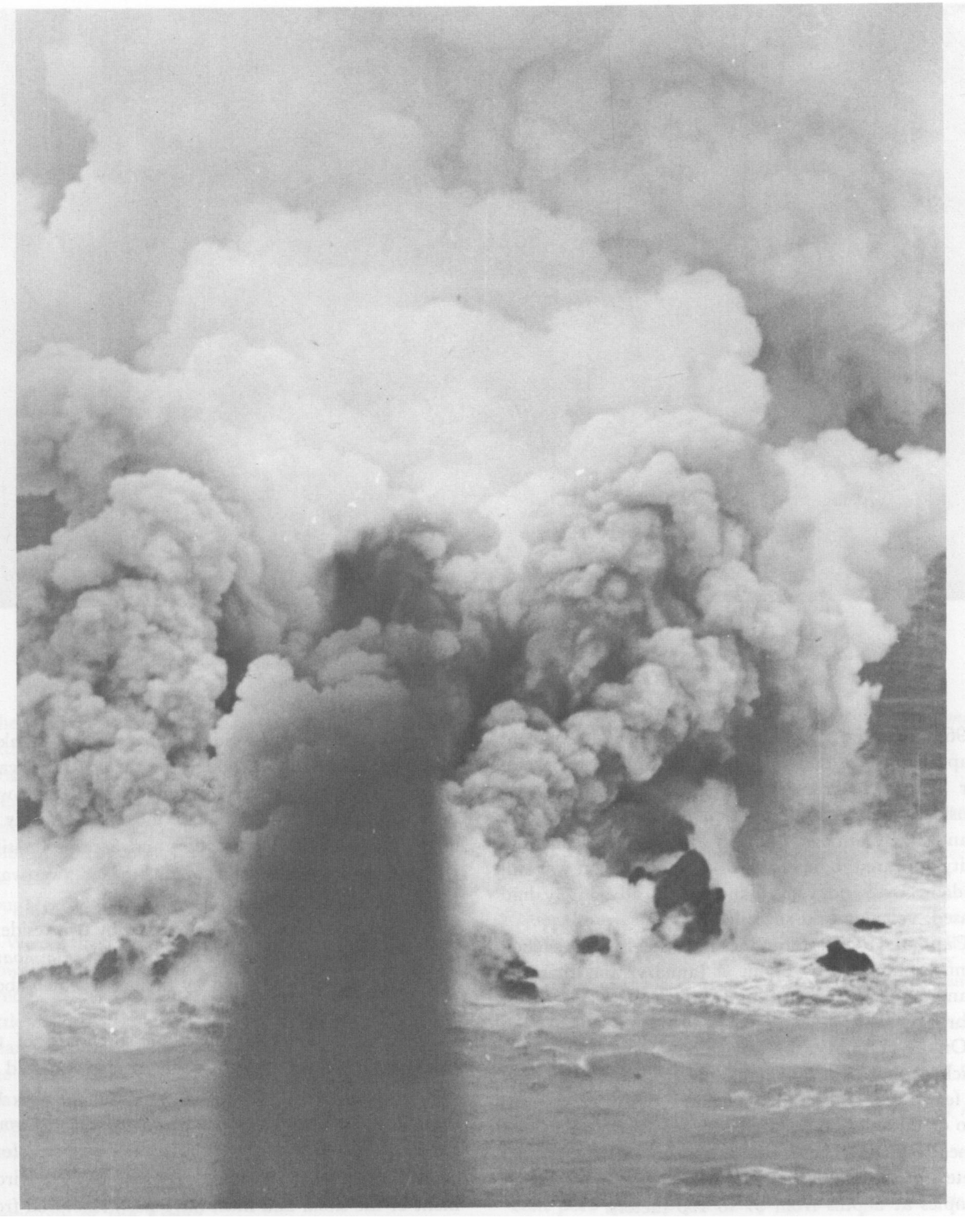

FIGURE 6.—Metis Shoal eruption. Steam and ash clouds with projecting blocks at base of cloud. Rocks projected an estimated fifty feet above sea surface at this time. (*Photograph courtesy of Mr. J. Reichelmann.*)

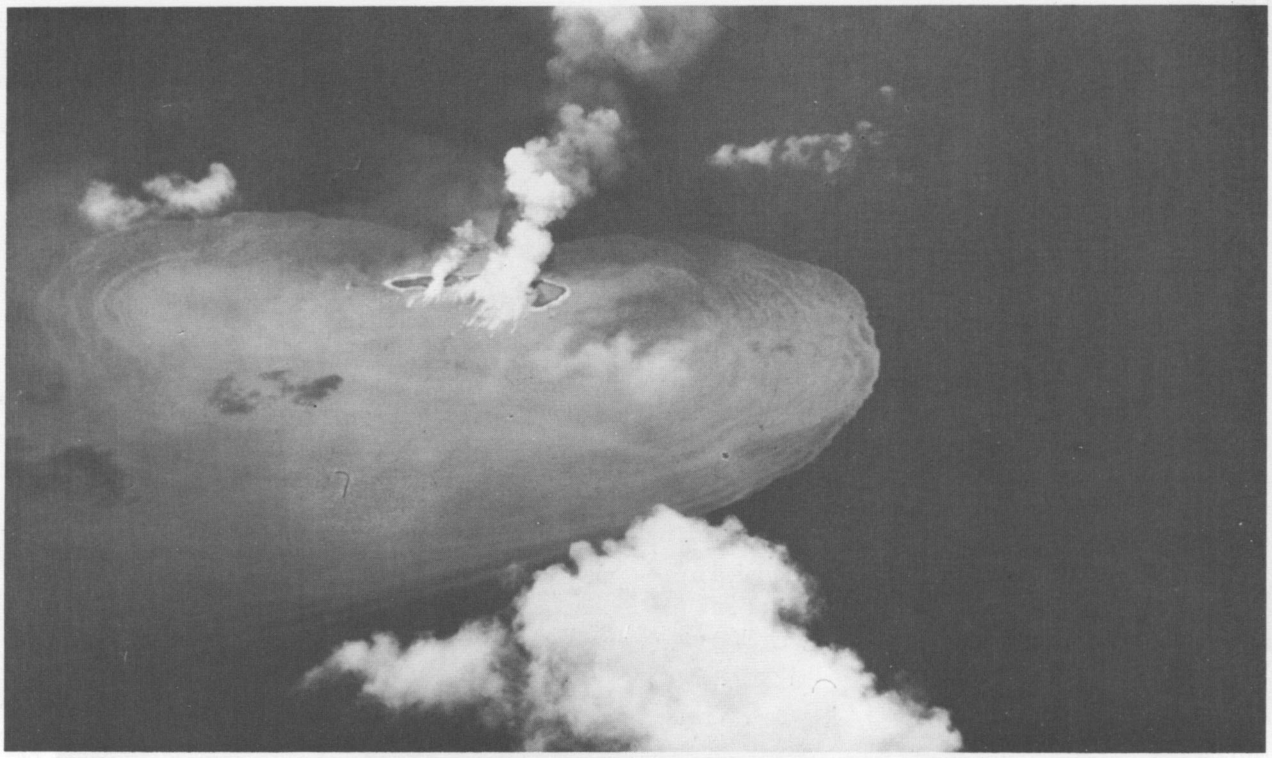

FIGURE 7.—Metis Shoal, 31 December 1967. Island has its long axis oriented about east-west. Steam clouds are blowing to 200° true; surface winds are blowing from approximately N.N.E. (*Photograph courtesy of Mr. T. M. Holmes.*)

(1968) reported: "On Sunday December 24th, violent eruptions were taking place. By Sunday, December 31st, these eruptions appeared to have reduced considerably, although still actively steaming [Figures 7 and 8]. By Sunday, January 7th, 1968, volcanic activity appeared to have ceased although steam was still evident. By Sunday, 31 January 68, all activity had ceased, volcanic and steaming." [6]

Captain Holmes estimates that the island reached a maximum size by about 7 January, and that the island disappeared in the first or second week of February.

On 13 February, the Soviet research vessel *Vityaz* reached the site [2] (Bezrukov et al. 1968). They found no features of continuing volcanic activity. There were two or three low rocks above the sea level and a shoal beneath them. They approached to within 200–300 meters of the rocks, and used a grab to obtain bottom samples at depths from 37 to 190 meters.

The site was visited on 19 February by Charles A. Lundquist in a small motorboat, the *Alaimoana,* chartered from Nuku'alofa. Only an occasional point of rock could be glimpsed in the towering breakers that were present even though the sea was quite calm (Figure 9). A linear shoal extended roughly east-west from the breakers. The shoal increased sharply in depth in the eastward direction and became invisible within a few hundred meters of the breakers; westward, the shoal increased in depth more gradually.

A dugout outrigger canoe, manned by two residents of Matuku Island, was launched from the *Alaimoana,* and samples were obtained by diving in water about 1.5 meters deep.

An immediate examination on shipboard of the specimens revealed delicate fibers of glass exposed on the surface, indicating only slight erosion; also, the rocks were easily broken manually. This evidence would seem to indicate that the rocks in their collected form could not have been exposed very long to the environment of the shoal and must have been fractured from larger objects shortly before their collection.

A final report by Captain Holmes describes the site on 21 April 1968:

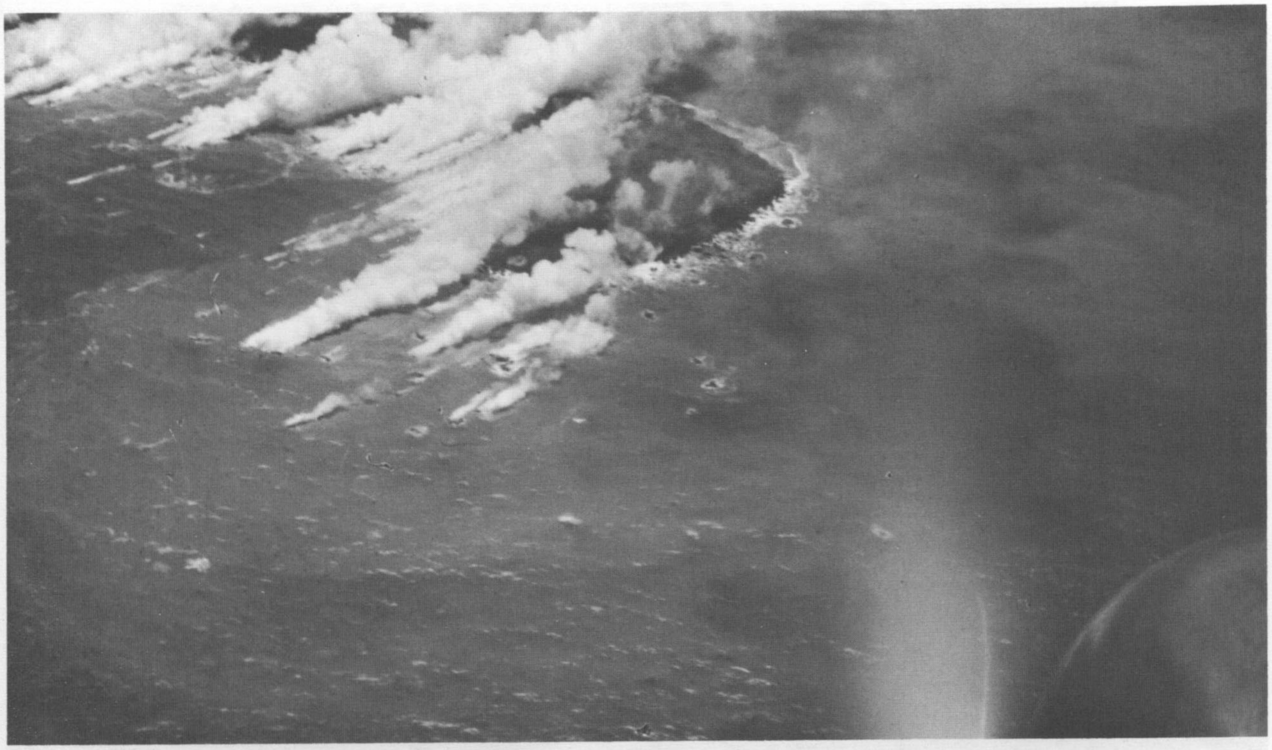

FIGURE 8.—Metis Shoal, 31 December 1967. Details are the same as for Figure 7, but viewed from much closer. (*Photograph courtesy of Mr. T. M. Holmes.*)

The sea was calm and the island completely covered without any appearance of breaking waves. The color looked more like yellow sand as opposed to black sand, mentioned earlier. The water around about had a definite yellow tinge, suggesting a sulphur content. The coloring effect gave an impression of a discharge in the sea. The size of the island (beneath the sea) was roughly 100 yards across and circular in form.

We obtained no information on the volume of ejecta; however, Murdmaa and others (1969) carried out a dredging survey around the volcano and found very little new debris on the sea floor. In many places, even near the summit, there was no volcanic debris. Instead, the area consisted of old ejecta encrusted with various marine organisms. From this, Murdmaa and his colleagues (1969) concluded that the total volume of ejecta was small.

TABLE 1.—*Chronology of events, Metis Shoal, Tonga Islands*

1. Submarine eruption begins—unknown
2. Island emerges, subaerial eruptions—probably not earlier than 10 December 1967
3. First observation and report of supermarine eruption—11 December 1967
4. Activity reached peak sometime in 31 December 1967 and apparently ended by 7–8 January 1968
5. Maximum length, 700 meters; width, 100 meters; height, 15 meters ($\pm 50\%$)—reached on or about 7 January 1968
6. Erosion of island down to "rocky outcrops"—25 January 1968
7. Island only "jagged rocks and water washing across"—1 February 1968
8. Island submerged, very high breakers on subsurface rock: 19 February 1968
9. Shoal completely beneath water with no breakers—1 April 1968

Petrology of the Ejecta

DESCRIPTION.—The blocks, collected by diving, are pumiceous dacites with about 43 percent glass, 37 percent pore space, 9 percent plagioclase phenocrysts, 11 percent pyroxene phenocrysts (augite>hypersthene), and 0.3 percent magnetite. In order of abundance, the phenocrysts are bytownite, augite, hypersthene, and

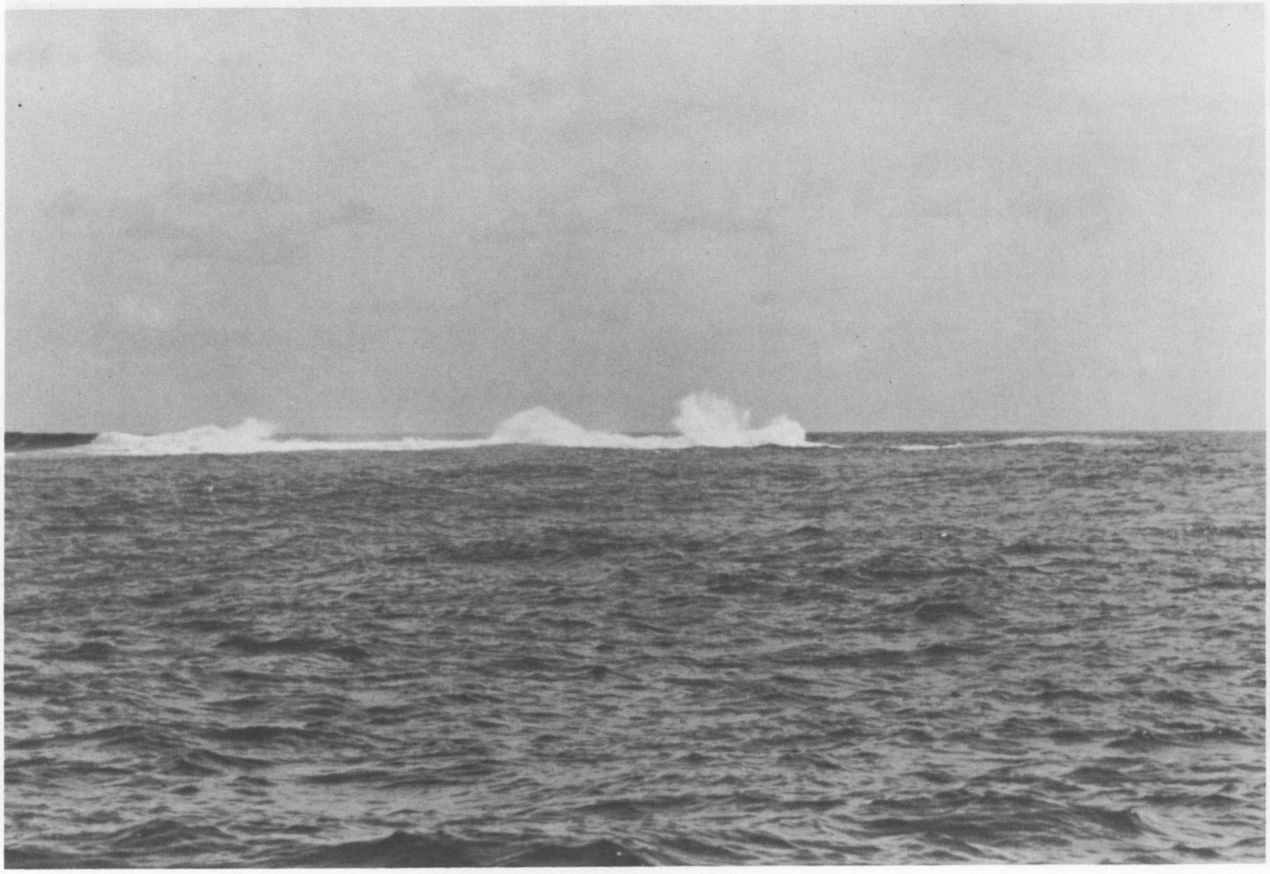

FIGURE 9.—Only shoals remained at the eruption site on 19 February 1968. (*Photographed by Charles A. Lundquist.*)

titanmagnetite. The phenocrysts commonly occur in clusters (Figure 10a) and bytownite phenocrysts are up to 5 mm long. Critical features of the glass and minerals follow:

Glass: The glass is colorless in thin section, has a refractive index of 1.502, and has the following approximate composition measured on the electron microprobe: $SiO_2 = 72.0 \pm 4.0$ (ranges slightly from spot to spot); $Al_2O_3 = 13.7 \pm 1.0$; $TiO_2 = 0.3 \pm 0.1$; $Fe = 3.4 \pm 0.2$; $MgO = 1.1 \pm 0.1$; $CaO = 3.4 \pm 0.2$; $Na_2O = 2.7 \pm 0.2$; and $K_2O = 2.1 \pm 0.2$. The glass has a silica content comparable to that of rhyolites, although the Na_2O and K_2O contents of the glass are lower than the contents of these elements in typical rhyolites. A separate of glass was prepared and analyzed by traditional wet chemical analysis (Table 2). This analysis confirmed the compositional pecularities indicated by the microprobe analysis. The glass contains abundant flattened vesicles (Figure 11) and but few microlites.

Plagioclase: The plagioclase phenocrysts are remarkably calcic (An_{83}–An_{87}). One might expect oligoclase, and perhaps even sanidine, in a volcanic rock so rich in silica. The pronounced oscillatory zoning in the plagioclase reflects a remarkably small variation in composition. On the basis of microprobe traverses, the maximum range on a single phenocryst is probably no greater than 4-mole percent anorthite molecule. The larger plagoclase phenocrysts commonly consist of complex multiple intergrown crystals. Some of the smaller phenocrysts are untwinned, or have only a single twin plane. These might be mistaken for phenocrysts of alkali feldspar; their high index of refraction, and composition given by microprobe analyses show decisively that they are not alkali feldspar.

Augite: the augite phenocrysts are light green and weakly pleochroic and have a composition around $En_{42}Fs_{17}Wo_{41}$. Zoning is readily visible in thin section, but compositional variations across phenocrysts are

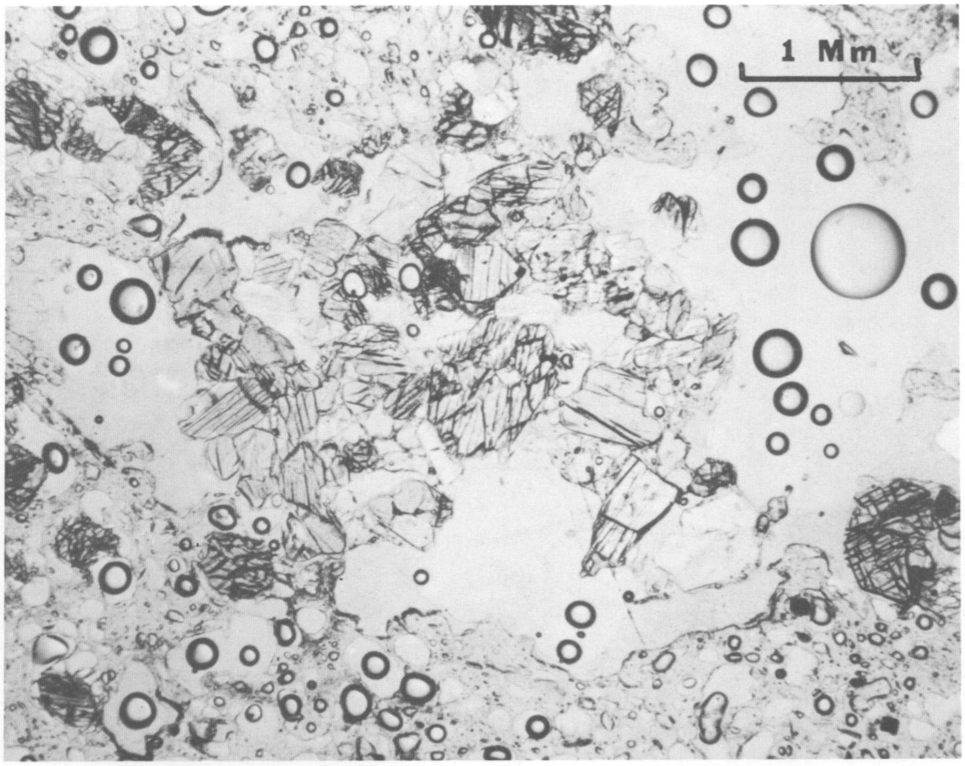

FIGURE 10.—Phenocrysts of augite, hypersthene, and calcic bytownite in individual crystals and groupings (conglomerporphyritic clots).

small, amounting to less than 0.2% Fe variation. The augite contains around 1.3±0.2% Al_2O_3, and only traces of Na_2O and TiO_2.

Hypersthene: Hypersthene occurs as pleochroic light-green to light-pink phenocrysts, and has a composition around $En_{63}Fs_{34}Wo_{3.0}$. The hypersthene is only chromian spinel occur in the olivine phenocryst (Fig- and only traces of other elements.

Titan-magnetite: There are octahedral opaque phenocrysts of a magnetic spinel-group mineral containing about 4.4% Ti and 2.6% Mg (only these two elements were determined).

Olivine: One partly resorbed olivine crystal rimmed by hypersthene granules was noted in one of four thin sections (Figures 12 and 13). One would expect it to be iron-rich in such a high silica rock. Surprisingly, it is Fo_{93}, and thus even more forsteritic than is typical of most basaltic olivines.

Chromite(?): Octahedra of a brown translucent chromian spinel occur in the olivine phenocryst (Figure 13).

CLASSIFICATION.—Tongan volcanic rocks seem to fit roughly into the basalt-andesite-rhyolite association of Turner and Verhoogen (1960), an association common in areas of crustal deformation and most typically developed in connection with orogenic movements along the margins of the Pacific. Many data are available on this association because the basalt-rhyolite series has been erupted in numerous places along the chains of active and recently active volcanoes that form the island arcs of the Pacific border.

This association shows the average plagioclase composition to be increasingly sodic along the general series of basalt—andesite—quartz latite—rhyolite, but the composition of plagioclase phenocrysts shows little relation to the bulk chemical composition of the rocks in which they occur; the range for rhyolitic quartz latites being about An_{12} to An_{55}.

The pumiceous Metis Shoal's rocks are difficult to classify precisely because of their chemical and mineralogic peculiarities. They are different from most dacites in their low total alkali content, and in their mineralogy. Typical dacites contain around five percent total alkalies, and K_2O typically is more abundant than

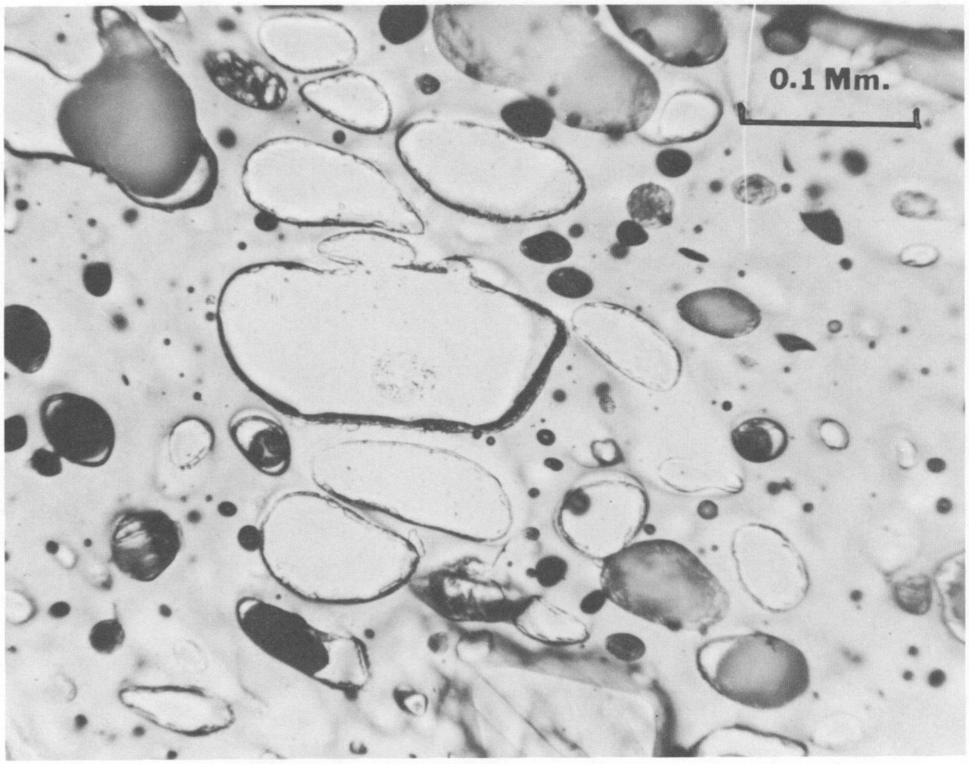

FIGURE 11.—Details of the glassy matrix. The glass was analyzed by electron probe (see text) and by classical methods (Table II).

Na_2O. For example, the type dacite (Tröger, 1935, p. 75) has $Na_2O=3.02$ percent, and $K_2O=2.51$ percent, although its silica content (66.76 percent) is quite like that of the Metis Shoal's rocks (64.01 percent). Mineralogic peculiarities, which in part reflect the compositional peculiarities, include the presence of forsteritic olivine and associated chromite, and the abundance of bytownite phenocrysts. Dacites are typically porphyritic, but more sodic plagioclase phenocrysts, as well as phenocrysts of sanidine and quartz, are common phenocryst minerals.

RELATION TO TEKTITES.—The Metis Shoal's glass is compositionally similar to certain tektites. Tektite chemistry typically differs from that of most volcanic glasses in a high silica content and low total alkali content, a feature of the Metis Shoal's glass. Some caution should thus be used in judging that "microtektites," small glass spheres found in certain deep sea cores, are extraterrestrial based on chemistry alone.

The Metis Shoal's glass differs, however, from tektites compositionally in that Na_2O is higher than K_2O, and petrographically in its pumiceous texture (Figure 11), compositional homogeneity (only slight compositional differences—mainly in SiO_2 were noted), and in presence of scattered microlites of hypersthene, plagioclase, and possibly other minerals. Also, the porphyritic texture of the bulk sample (glass + phenocrysts) clearly is not a feature of tektites.

PETROGENESIS.—The Metis Shoal rocks present some difficult problems of origin. Crustal crystal-liquid fractionation of a basaltic liquid can generate higher silica liquids, but, along with silica, the alkalies are highly enriched in residual liquids. For example, residual glasses in a tholeiitic basalt from the prehistoric Makaopuhi lava lake, Hawaii, have $SiO_2=75\%–78\%$ and total alkali contents typically about 8.6%, with $K_2O=0.41$ in the uppermost analyzed sample, and an SiO_2 content of about 50 percent in the parent basalt (Evans and Moore, 1968). It is thus clear that a single-stage low pressure differentiation of basalt could not have produced the Metis Shoal's rocks.

The presence of forsteritic olivine and associated chromite octahedra is anomalous in a rock with such high silica. Clearly the olivine was not in equilibrium

TABLE 2.—*Chemical composition of whole rock (column 1) and separated glass (column 2) from Metis Shoal's 1968 eruption. These samples have been entered into the petrology collections of the United States National Museum (USNM 111108).*

	1	2
SiO_2	64. 01	73. 38
Al_2O_3	12. 95	12. 66
Fe_2O_3	1. 51	1. 11
FeO	5. 43	2. 84
MnO	0. 13	0. 06
MgO	5. 47	0. 84
CaO	7. 51	3. 79
Na_2O	1. 83	3. 09
K_2O	0. 95	1. 52
H_2O+	0. 00	$<$0. 13
H_2O-	0. 00	0. 03
TiO_2	0. 32	0. 45
P_2O_5	0. 06	0. 00
	100. 17	99. 77
CIPW Norm:		
Q	24. 52	39. 11
OR	5. 61	8. 98
AB	15. 49	26. 15
AN	24. 32	16. 19
DI	10. 23	2. 21
HY	17. 07	4. 64
MT	2. 19	1. 61
IL	0. 61	0. 85
AP	0. 14	0. 03
	100. 18	99. 77

Analyst: Eugene Jarosewich, Smithsonian Institution

with the liquid during the final phase of phenocryst crystallization. This is shown by the jacketing of the olivine by hypersthene granules (Figure 12). The incongruent melting (and hence crystallization) of hypersthene might conceivably lead to first crystallization of olivine in a high silica magma, but probably not in a magma as high in silica as that of Metis Shoal, nor, even if olivine did crystallize, would one expect it to be so forsteritic and associated with chromite. It is much more likely that the olivine and chromite are xenocrysts, or reflect mixing and hybridization of already partially crystallized basaltic magma with some other more siliceous magma.

At the present time, we can think of no plausible scheme of partial melting or other processes which could account for all the compositional and mineralogic peculiarities of the Metis Shoal lava.

TABLE 3.—*Rocks from Tonga chemically similar to Metis Shoal's bulk docite and glass (Table 1).*

	1	2	3	4	5	6
SiO_2	73. 50	67. 20	64. 82	65. 84	65. 98	65. 23
Al_2O_3	11. 90	12. 13	11. 95	12. 02	11. 43	12. 59
Fe_2O_3	0. 76	0. 52	1. 53	1. 05	2. 38	1. 24
FeO	4. 84	8. 47	8. 16	8. 25	5. 86	6. 80
MnO	....	0. 13	0. 15	0. 13	1. 80	1. 68
MgO	0. 63	1. 30	1. 19	1. 29	1. 10	1. 42
CaO	3. 80	5. 60	6. 54	6. 22	5. 20	5. 80
Na_2O	2. 81	2. 62	2. 64	2. 66	2. 77	2. 88
K_2O	0. 75	0. 63	0. 85	0. 77	1. 09	1. 00
H_2O+	0. 46	0. 34	1. 16	0. 84	0. 56	0. 24
H_2O-	....	....	0. 20	0. 16	0. 10	0. 14
TiO_2	0. 58	0. 62	0. 78	0. 76	0. 91	0. 88
P_2O_5	0. 09	0. 16	Tr.	Tr.	0. 23	0. 21
	100. 12	99. 72	99. 97	99. 99	99. 41	100. 11
CIPW Norms:						
Q	42. 25	31. 07	27. 70	28. 78	30. 61	26. 64
Or	4. 43	3. 72	5. 02	4. 55	6. 44	5. 91
Ab	23. 78	22. 17	22. 34	22. 51	23. 44	24. 37
An	17. 64	19. 48	18. 25	18. 58	15. 54	18. 47
Di	0. 58	6. 38	12. 28	10. 61	7. 56	7. 70
Hy	8. 57	14. 28	9. 32	11. 00	9. 48	12. 70
Mt	1. 10	0. 75	2. 22	1. 52	3. 45	1. 80
IL	1. 10	1. 18	1. 48	1. 44	1. 73	1. 67
AP	0. 20	0. 35	....	....	0. 53	0. 49
H_2O	0. 46	0. 34	1. 36	1. 00	0. 66	0. 34
	100. 11	99. 72	99. 97	99. 99	99. 44	100. 09

1. Herald Cays, light pumice, L. J. Sutherland, analyst (Bryan, 1968).
2. Herald Cays, dark pumice, L. J. Sutherland, analyst (Bryan 1968).
3 and 4. Falcon Island, Tonga, Pumice from 1928 eruption (Lacroix, 1939).
5 and 6. Fonualei, Tonga, dacite, (Richard, 1962).

Dr. Norman Hubbard of the Lamont-Doharty Geological Observatory is carrying out an investigation of the contents of the lanthanide elements in various Tongan lavas. He performed an analysis for these elements in the pumiceous dacite described in this paper (Table 2, whole rock analysis). He kindly allowed us to give the results of that analysis in this paper. He obtained, via neutron activation analysis, the following values (given in parts per million): lanthanum, 2.70; cerium, 7.31; niobium, 5.17; samar-

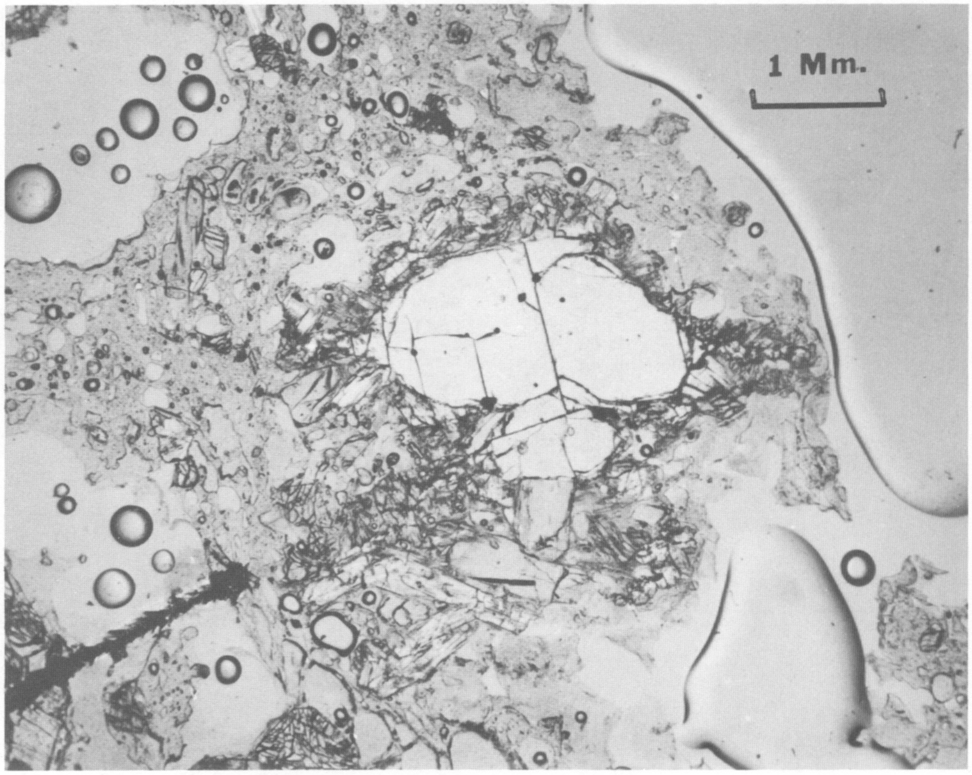

Figure 12.—Large, rounded olivine crystals (xenocryst) rimmed by hypersthene. Olivine composition around Fo_{93}.

ium, 1.56; gadolinium, 1.98; europium, 0.452; dysprosium, 2.51; erbium, 1.68; and ytterbium, 2.19. Dr. Hubbard also reports a barium content of 334 parts per million.

Normally, higher silica lavas, like dacites and andesites, are higher in the lanthanide elements than are the lower silica lavas, like basalts. Remarkably, however, the Metis Shoal dacite is lower in the lanthanide elements than most basalts, particularly those from the ocean-ridge system. Although lower in lanthanides than the ocean-ridge basalts, the Metis Shoal sample has the same "primitive" lanthanide abundance ratios compared to chondritic meteorites as have the ocean-ridge basalts. Thus, any scheme of partial fusion or fractional crystallization of a basaltic parent must provide for depletion of the lanthanide elements but at the same time give high silica.

Comparisons of the Metis Shoal lava with mid-ocean ridge basalts are appropriate. Most models of sea-floor spreading and island arc development envision the oceanic crust as moving beneath island arcs (Figure 4). Island arcs represent the place where oceanic crust is destroyed either by addition to continental margins or by movement downward into the mantle. In those models where ocean-ridge basalts are envisioned as moving downward into the mantle, partial melting might occur as the basaltic rocks descend deeper into the mantle, where they eventually transform into eclogites. The partial melting of oceanic-ridge basalts is thus a plausible and often considered mechanism for generating island-arc lavas, such as those of Tonga. If partial melting of ocean-ridge basalts is giving rise to the Tongan lavas, however, the process must involve separation of crystals which are higher in the lanthanide elements and lower in silica than are those of the ocean-ridge basalts. If this were not the case, the Metis Shoal lava would not be depleted in rare earth elements and would be higher in silica than ocean-ridge basalts. Dr. Hubbard (personal communication) has stated that separation of a sizable amount of hornblende from a basaltic parent might account for the peculiarities of the Metis Shoal sample. This process would require that the ocean-ridge basalts undergo partial fusion at high

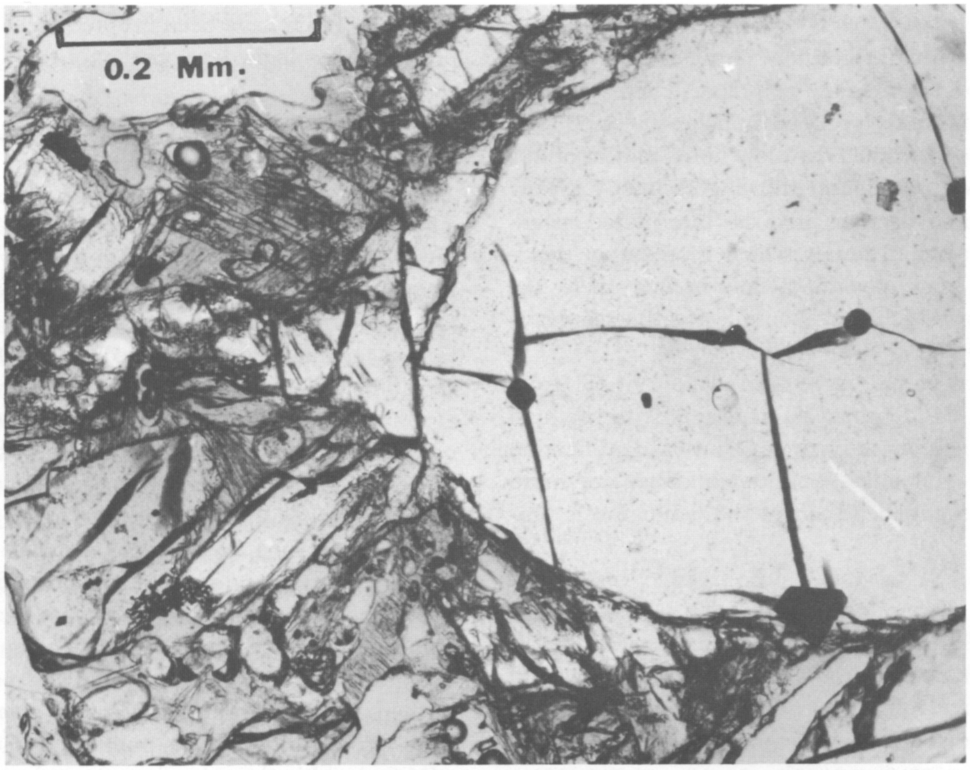

FIGURE 13.—Detail of margin of olivine xenocryst showing chromite inclusions and hypersthene rims.

water pressures. Liquids generated under such high water pressures, which may be on the order of a few kilobars, would be expected to be high in dissolved water. The absence of hydrous phases in the Metis Shoal dacite indicates that lava was not high in water. This may mean that the above outlined explanation for the silica and lanthanide contents is not correct, or that the lava lost water by much degassing prior to the crystallization of its phenocrysts minerals, or that ocean-ridge basalts are not the parent material of the Metis Shoal lava.

Comparison With Eruptions at Falcon Island

The nearest historic volcanism occurred on Falcon Island (now only shoals remain), which is about 60 miles south of Metis Shoal. An account of the eruption of 1927 is given by Hoffmeister, Ladd, and Alling (1929). Beginning on 4 October 1927, and ending sometime in the spring of 1928, the eruption built an island about 2 miles in diameter, and more than 1.2×10^{10} ft^3 of fragmental volcanic debris were ejected. No lava was erupted; the island was composed entirely of pyroclastic material ejected as agglomerate, a mixture of brownish-gray ash, scoria, pumice, and blocks of solid lava. Most of the material, except on the beaches, was poorly sorted.

No bulk nor mineral chemical analyses are available of the erupted materials; however, Alling (Hoffmeister, et al. 1929) gives a brief petrographic description of the rocks:

> A study of several thin sections of samples collected on Falcon shows that the rock is a basic one of basaltic affinities, its textural relations suggesting a diabasic pyroclastic. It is composed in large part of a nearly opaque brown glass, the small amount of crystalline matter present being very fine-grained and profoundly stained with oxides of iron.
>
> Rods or lath-shaped crystals of plagioclase feldspar are strikingly embedded in the glass. Many present a zonal structure and when not actually concentrically grown show an undulatory extinction. Extinction angles point to a labradorite of bytownite composition

but it seems highly probable that the composition is not uniform but varies. Absolutely untwinned crystals of plagioclase are surprisingly common. These rods are arranged in curiously grouped bunches in some portions of a slide, controlled by blow holes, and in others exhibit a crude parallelism showing distinctly a flow structure. These portions may be interpreted as inclusions of volcanic matter which represent a previously formed rock, possibly a flow broken up by the recent activity which is responsible for the reappearance of the island.

Stout grains of pale green pyroxene, not far from diopside, can be identified by exploring with the high power. Olivine is probably present but its identification is uncertain. Magnetite, apatite, ilmenite, are more definitely determined. Much of the magnetite is titanium bearing.

Alling believed the rocks to be basaltic, but on the basis of his petrographic description, there is little justification for this view. The index of refraction of the glass for Falcon Island was not given. This would have been a good guide to the SiO_2 content of the glass, which in turn would allow determination of the actual nature of the erupted materials.

The Falcon Island volcanic rocks of the 1927 eruption differ from those from Metis Shoal. The large and abundant phenocrysts in the latter obviously were not present in equal abundance in the described Falcon Island ejecta, nor is it likely that they would have been missed during the sampling of the island, as they are readily visible.

The Falcon Island eruptives of 1885 consisted in part of pumiceous blocks, containing bytownite and augite phenocrysts (Harker, 1891), but lacking hypersthene. Harker's description of the phenocrysts shows them to be remarkably like those from Metis Shoal: Some of the larger (augite) crystals are so associated with the porphyritic feldspars as to prove that they belong to an early phase of consolidation, but the bulk of the minerals occur in ill-shaped idiomorphic crystals scattered through the ground.

Harker's (1891) descriptions of glassy ash from other of the Tonga Islands commonly mention crystals of plagioclase, clinopyroxene (presumably augite), and rhombic pyroxene (presumably hypersthene). It thus appears that ash and pumiceous lava blocks, such as those erupted at Metis Shoal recently, and at Falcon Island in 1885, have been erupted at numerous times during the geologic development of the Tonga Islands.

Relation Between the Pumiceous Blocks and the Nature of the Metis Shoal Eruption

The generation of pumice from lava implies release of pressure on lava containing dissolved volcanic gases, perhaps during ascent of the lava from depth, or due to the sudden explosive release of pressure on a near-surface magma chamber due to failure of the chamber's roof. The vesiculation process, combined with injection of the vesiculating lava into cold, water-saturated older volcanic debris, would lead to explosive steam generation and further shattering of the injected materials. These materials would contribute to the formation of a pyroclastic cone, containing very little massive, unvesiculated rock, and no extrusive flows. Such an eruptive scheme appears to fit the events recorded during the eruptions at Metis Shoal and Falcon Island.

Figure 6 shows very large, angular blocks in the sea at the base of the eruption cloud. It seems likely that these large, undoubtedly pumiceous blocks actually solidified within the volcanic cone, and were then forcefully pushed upward as solid masses during continued injection of new pumice-forming lava at shallow depth. Wave erosion and further shattering of these blocks during intense steam eruptions would rapidly reduce these blocks to fine materials, which eventually form the surficial materials of the cone. These pyroclastic cones are readily reduced to below sea level once the eruption ceases. Wave erosion is the dominant process of reduction (Hoffmeister et al., 1929); postulation of some sort of volcanism-related subsidence to account for the rapid disappearance of these islands appears to be unnecessary.

The high silica content of the Metis Shoal volcanic glass suggests a highly viscous lava, compared, for example, to basaltic lava. Such high viscosity characterizes volcanic rocks that typically are violently erupted in the Pacific region, and much less frequently form flows.

Should an unusually voluminous eruption eventually occur, a more permanent island may form at Metis Shoal. Petrologically it may be much like Fonualei, an active Tongan volcanic island containing dacitic eruptives.

Suggestions for Additional Studies

Further data on the Metis Shoal pumiceous blocks are needed. High-temperature experimental studies would help to determine the origin of the phenocrysts in the blocks. The preliminary petrographic and microprobe data appear to point to derivation of the bytownite phenocrysts by direct crystallization from a magma with the composition of the pumiceous blocks; mixing of genetically unrelated materials seems more likely to account for the presence of olivine. If the phenocrysts did, in fact, crystallize from a magma of the bulk composition of the blocks, this could be demonstrated under experimental conditions; the possible role of water and high total pressures may complicate the experimental approach. Nonetheless, one-atmosphere anhydrous experiments would be initially useful. These experiments would also provide some idea of the rocks' eruption temperature. Further useful data include trace elements and radiogenic isotopic ratios. All these data are pertinent to the further characterization of the eruptives of the western arc of Tonga, and hence to the possible nature of partial melting and subsequent evolution of magmas in the upper mantle and crust beneath an active inner-island arc.

Careful monitoring of the volcanic eruptions of Tonga should begin. Such monitoring should yield the rate at which materials are being emitted in the region, the dynamics involved in shallow submarine eruptions and in the construction and destruction of volcanic islands. Bathymetric surveys are needed in particular before, during, and after eruptions to at least roughly gauge volumes of eruptions. Early detection of eruptions and possible locations of as yet undiscovered active Tongan submarine volcanoes may be possible by the acoustic means which recently located active submarine volcanoes just north of New Zealand (Kibblewhite, 1966). This would require new listening stations near Tonga.

Acknowledgments

We wish to thank all those who provided the information on the eruption, and who are noted in the referenced sources. In addition, we acknowledge the helpful assistance provided by Mr. J. Riechelmann and other members of the Tonga government, the British Council in Nuku'alofa, Captain William Stanley of the ship *Alaimoana,* and 'Aplipate and Penisimani Tupouniua of Nuku'alofa. Mr. Robert Citron, Smithsonian Center for Short-lived Phenomena, provided helpful assistance in communications with Tonga throughout the course of the eruption.

Literature Cited

Bryan, W.
1969. Low-potash Drift Pumice from the Coral Sea. *Geological Magazine,* 105(5): 431–539.

Evans, B. W., and Moore, J. G.
1968. Mineralogy as a Function of Depth in the Prehistoric Makaopuhi Tholeiitic Lava Lake, Hawaii. *Contributions to Mineralogy and Petrology,* 17: 85–115.

Harker, A.
1891. Notes on a Collection of Rocks from Tonga. *Geological Magazine,* 8: 257–258.

Hatherton, T., and Dickinson, W. R.
1969. The Relationship Between Andesitic Volcanism and Seismicity in Indonesia, the Lesser Antilles, and other Island Arcs. *Journal of Geophysical Research,* 75: 5301–10.

Hoffmeister, J. E.; Ladd, H. S.; and Alling, H. L.
1929. Falcon Island. *American Journal of Science,* 18: 461–71.

Isacks, B.; Sykes, L. R.; and Oliver, J.
1969. Focal Mechanisms of Deep and Shallow Earthquakes in the Tonga-Kermadec Region and the Tectonics of Island Arcs. *Bulletin of the Geological Society of America,* 80: 1443–70.

Isacks, B.; Oliver, J.; and Sykes, L. R.
1968. Seismology and the new Global Tectonics. *Journal of Geophysical Research,* 73: 5855–99.

Kibblewhite, A. C.
1966. The Acoustic Detection and Location of an Underwater Volcano. *New Zealand Journal of Science,* 9: 178–99.

Lacroix, A.
1939. Composition mineralogique et chimique des lavée des volcans des îles de l'ocean Pacifique situées entre l'Equataur et le tropique du Capricarne, le 175° de longitude ouest et le 165° de longitude est. *Mémories de l'Académie des Sciences,* Paris, 63 :1–97.

Murdmaa, I. O.; Bezruko, P. L.; Zenkevich, N. L.; Prokoptsev, N. G.; and Repechka, M. A.
1969. Eruption of the Submarine Volcano Metis in the Tongan Archipelago and its Effect on Sedimentation. *Akademiia Nauk, SSSR, Doklady,* 185(5): 1149–52. (In Russian.)

Phillips, C.
1899. On the Volcanoes of the New Zealand–Tonga

Volcanic Zones. *Transactions and Proceedings of the New Zealand Institute,* 31: 510–51.

Richards, J. J.
1962. *Catalogue of the Active Volcanoes of the World.* Part 8: Kermadec, Tonga, and Samoa. International Association of Volcanology, Rome. 38 pages.

Tröger, W. E.
1935. Spezielle Petrographie der Eruptivgesteine. *Deutschen Mineralogischen Gesellschaft,* Berlin. 360 pages.

Turner, F. J., and Verhoogen, J.
1960. *Igneous and Metamorphic Petrology.* McGraw-Hill Book Company. 694 pages.

U.S. GOVERNMENT PRINTING OFFICE:1970 O—381-735