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U.S. GEOLOGICAL SURVEY BULLETIN 1663

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By JAMES G. MOORE, DANIEL J. FORNARI, and DAVID A. CLAGUE

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DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE : 1985

For sale by the
Distribution Branch, Text Products Section
U.S. Geological Survey
604 South Pickett St.
Alexandria, VA 22304

Library of Congress Cataloging-in-Publication Data

Moore, James Gregory, 1930-
Basalts from the 1877 submarine eruption of Mauna Loa, Hawaii: New data on the variation of palagonitization rate with temperature.

(U.S. Geological Survey Bulletin 1663)
Bibliography: p. 9–10
Supt. of Doc. No.: I 19.3:1663
1. Basalt—Hawaii—Kealakekua Bay region. 2. Mauna Loa (Hawaii Island, Hawaii)—Eruption. 3. Palagonite—Hawaii—Kealakekua Bay region. I. Fornari, Daniel J. II. Clague, David A. III. Title. IV. Series: United States. Geological Survey. Bulletin 1663.

QE75.B9 no.1663 557.3s 85–600163
[QE462.B3] [552'.22]

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Basalts from the 1877 Submarine Eruption of Mauna Loa, Hawaii: New Data on the Variation of Palagonitization Rate with Temperature

By James G. Moore, Daniel J. Fornari[1], *and* David A. Clague

Abstract

The well-documented 1877 submarine eruption of Mauna Loa volcano occurred offshore from Kealakekua Bay, west Hawaii. The three vents active during the eruption are aligned parallel to the Kealakekua fault, which apparently bounds the north side of a large slump structure of Mauna Loa volcano. Samples of 1877 glassy basaltic lava were collected by submersible from these eruption sites, at water depths from about 100 m to greater than 1000 m. Because their age, depths, and ambient ocean temperatures are known, these samples of basalt permit determination of palagonitization rates at different temperatures. The rate is found to increase 1.8 times for each 10 ^{o}C of temperature increase. At 4-5 ^{o}C (the prevailing water temperature on much of the ocean floor) the rate is 0.003-0.03 μm per year, and the extrapolated rate at 300 ^{o}C (the temperature at some hot springs on ridges) is 0.27-2.7 mm per day. These samples and others from nearby subaerially erupted lavas that flowed into the sea allow determination of vesicularity at different water depths. The data indicate that the decrease in vesicularity of subaerial lava flows that cross a shoreline and flow into increasingly deeper water is largely explicable by the pressure effect, and hence the vesicularity of such flows can provide information on the depth of cooling of ancient lava. However, vesicle volume and size are slightly smaller than expected, probably because of re-solution of volatiles back into the melt as pressure increases.

INTRODUCTION

A short-lived submarine eruption occurred on February 24, 1877, within one mile of shore in Kealakekua Bay on the west side of the island of Hawaii (fig. 1). This activity followed a brief summit eruption of Mauna Loa on February 14, yet it occurred 35 km west of the summit of the volcano in a region remote from any known rift zone. Most of the reports about this eruption appear to be derived from an excellent descriptive article which appeared in the February 28, 1877, issue of the Hawaiian Gazette published in Honolulu. The complete text of that article, written by a passenger of the interisland steamer Kilauea as it steamed into the bay on the morning of February 24, appears in the appendix.

The eruption was first observed at 3 a.m. when red, green, and blue lights appeared about a mile offshore. Daylight disclosed steam and lava blocks at the water surface along a west-northwest-trending line that extended as far as 1.6 km offshore (fig. 2), where water depths were 37-110 m. The sea surface in the most active area appeared agitated as though boiling, and many blocks of solid lava as large as 60 cm rose from below. The lava blocks floated readily while hot and emitted sulfurous gases, but they sank after cooling. Numerous fish were killed by the activity. A severe earthquake, felt during the night of the eruption, may have signaled movement on the Kealakekua fault (fig. 2) that allowed magma to enter subsidiary fractures and erupt on the sea floor.

Submarine explorations since 1975 have located three vent areas inferred to be related to this 1877 eruption, and samples of basaltic lava have been collected at these sites. The purpose of this paper is to describe these samples and to examine implications of their characteristics for (1) the extent and source of the 1877 eruption, (2) the relation of vesicularity to water depth, and (3) the relation of palagonitization rate to temperature.

Acknowledgements.—Collection of samples from the submersible Makali'i was skillfully conducted by the Hawaii Undersea Research Laboratory (HURL) technical team; costs for both submersible and support ship were funded by NOAA's National Undersea Research Program at the University of Hawaii. Support for Fornari was provided by the Office of Naval Research contract N00014-80-0098Scmm to the Lamont-Doherty Geological Observatory. Lee Tepley collected samples by SCUBA diving off Palemano Point. William Loskutoff made modal analyses and vesicle measurements on basalt samples. Robert Tilling and Roy Bailey reviewed the manuscript. The help of these individuals and groups is appreciated.

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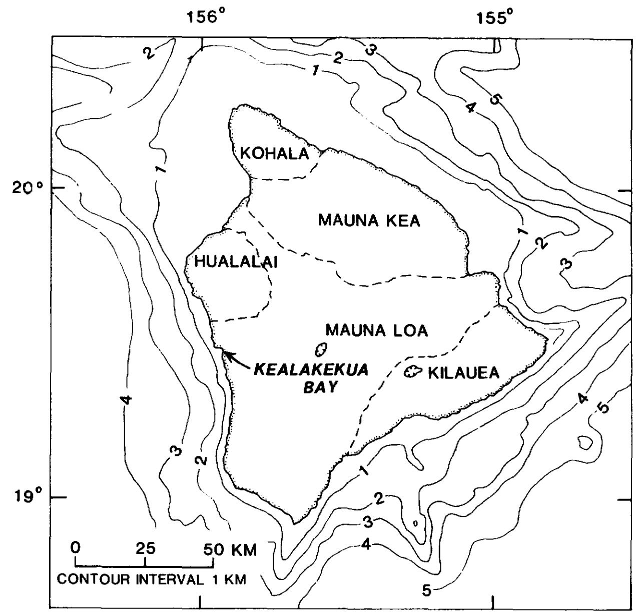

Figure 1. The island of Hawaii and location of Kealakekua Bay. Dashed lines are boundaries between volcanoes.

SUBMARINE GEOLOGY AT KEALAKEKUA BAY

Fifteen submersible dives, utilizing the U.S. Navy's deep-diving submersible Sea Cliff, were made off the west side of the island of Hawaii (fig. 1) in the summer of 1975. These dives fortuitously discovered several extremely young volcanic vents west of Kealakekua Bay at depths between 690 and 1050 m (Fornari and others, 1980). Because of this discovery and the historical documentation (appendix) of the submarine eruption inshore from this locality in 1877, a detailed bathymetric and acoustic survey was made of the Kealakekua Bay region in 1976 (Normark and others, 1978). Submersible navigation had been imprecise during the 1975 diving program, but better estimation of the position of bottom tracks and submarine vents became possible when the new bathymetry was available (See fig. 4 of Normark and others, 1978). On subsequent dives with Sea Cliff in 1979 and Turtle in 1983 (D. J. Fornari, unpub. data) utilizing an improved navigation system, these relatively deep-water young vents and the lava flows which issued from them were more precisely located (fig. 2).

During the summer of 1982 a SCUBA-diving program was undertaken inshore from these deep-water vents seeking any evidence of the reported 1877 eruption. This work revealed a submarine lava delta offshore from the prehistoric Palemano Point lava flow (fig. 2) Observations were limited to depths less than 65 m, and no evidence of the submarine volcanic vent was found (Lee Tepley, written commun., 1982).

During the summer of 1983, ten dives were made with the submersible Makali'i, a two-man vehicle with a depth limit of 380 m, operated by the Hawaii Undersea Research Laboratory (HURL). The position of the support ship was fixed during the dive program by a radio navigation system (Motorola MiniRanger[1]) utilizing two shore stations. Such ship-position determinations were made every few minutes and, combined with ranges and bearings from ship to submersible based on an acoustic navigation system (EDO-Western[1]), provided locations of the submersible on the bottom generally accurate to within 50 m.

Five of the Makali'i dives explored a terrace at 150-m depth, whose outer edge proved to be a major submerged reef built of coralline limestone that yielded an average ^{14}C age of 13,250 years B.P. (Moore and Fornari, 1984). The other five dives were inshore from the shelf break in the general area of the reported 1877 eruption and also to the north. No evidence of the 1877 eruptive vent was observed; we suspect this vent is now covered by drifting calcareous sand. These dives did, however, recover two samples of rock, described herein, that we have determined to be 1877 lava.

The two offshore vents and associated lava flows west of Kealakekua Bay (fig. 2A) have been observed, mapped, and sampled by submersibles . The location and extent of the shallower (eastern) of these vents were determined accurately during the diving programs in 1979 and 1983. The deeper (western) vent area remains known only from imprecisely navigated dives (Normark and others, 1978; Fornari and others, 1980). The two deep vents and the 1877 shallow disturbed area are all aligned in an east-west zone that is generally parallel to, and 2 km south of, the surface trace of the Kealakekua fault (fig. 2A). The Kealakekua fault appears to form the northern boundary of a region that has undergone massive gravitational slumping (Normark and others, 1979). Presumably the dislocation zone of this slump margin is profound enough to have tapped the magma conduit system of Mauna Loa volcano and brought about these submarine eruptions a century ago.

The eastern vent constructed a discontinuous low ridge of shelly pillow lava that interrupts the regional southwest-facing slope. This vent ridge is generally about 3-5 m high, and most of the lava that issued from it flowed southwest, down the regional slope; some lava, however, flowed northeast into a narrow trench that formed between the vent ridge and the regional slope. The well-pillowed lava flows that issued from these vents are increasingly cavernous and shelly toward the vent ridges (figs. 3 and 4 of Fornari and others, 1980). Samples of hollow, shelly pillows from near the crest of the vent ridges display well-preserved spreading cracks, important in the formation of pillow crust (Moore and Lockwood, 1978).

STUDIES OF BASALT SAMPLES

Petrology

Thirty-six lava samples, collected in 1983 by the submersible Makali'i, were compared with nine

[1] Any use of trade names and trademarks is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

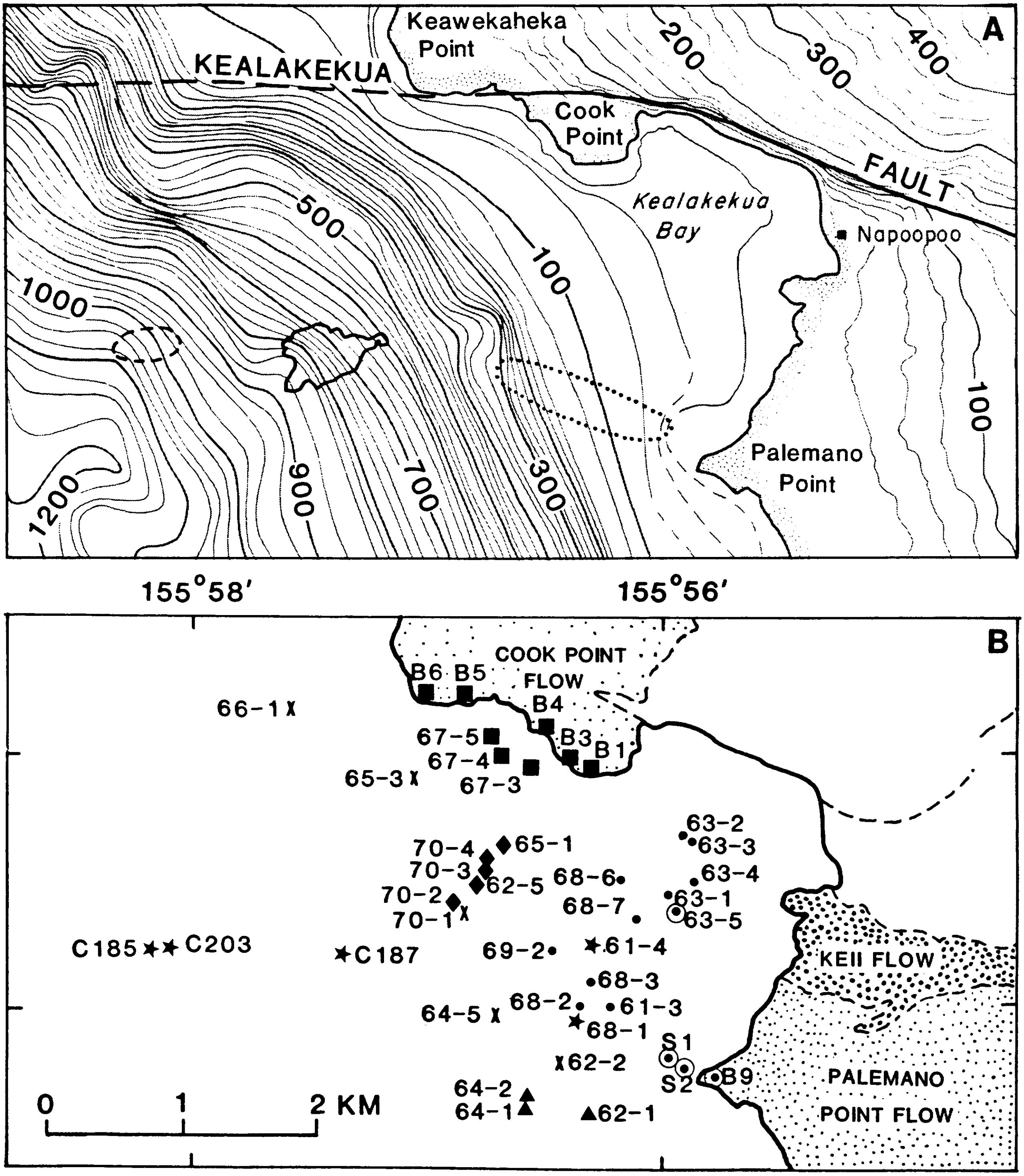

Figure 2. Maps of Kealakekua Bay region. A, Location of features associated with the 1877 eruption of Mauna Loa. Depth contours in meters. The shallow-water disturbed area of 1877 (dotted) is based on contemporary accounts (see appendix); the position of the eastern deep-water lava flows (solid line) has been refined as a result of the dives of 1979 and 1983; the western deep-water lava (dashed) remains poorly located. B, Location of submarine and subaerial basaltic lava samples (see tables 1 and 2). Stars, 1877 basalt; squares, Cook Point flow; circled dots, Palemano Point flow; dots, Keei flow; triangles, picritic basalt; diamonds, hypersthene-bearing basalt; crosses, unassigned basalt. Unplotted samples 68-4, -5 and -8, and 69-3 and -4 are close to 61-4. Dashed lines on land bound major lava flows including the Cook Point, Keei, and Palemano Point flows.

samples collected on land and with two recovered by SCUBA divers from lavas that flowed into the sea (table 1). Most of the submersible-collected samples can be assigned to one of the following major lava flows: (1) Palemano Point lava flow, (2) Keei lava flow, (3) Cook Point lava flow, (4) a submerged hypersthene-bearing porphyritic lava flow, (5) a submerged picritic lava flow, and (6) the 1877 lava flows.

The Palemano Point pahoehoe lava flow crosses the coastline in the vicinity of Palemano Point. It contains many distinctive, elongate olivine phenocrysts as much as 2 mm long, as well as phenocrysts of plagioclase and subordinate clinopyroxene (fig. 3; table 1). This lava is distinctive in containing abundant millimeter-size clots of clinopyroxene and plagioclase crystals.

The Keei aa lava flow, which overlies the Palemano Point flow on the north, is about one-half kilometer wide and can be traced more than a kilometer offshore, where it curves to the south. The petrology of this aa flow is similar to that of the Palemano Point flow, except that it is somewhat richer in both plagioclase and pyroxene phenocrysts (fig. 3). Below sea level the flow occurs as branching rounded lobes several meters wide and a meter or two high that are partly buried by carbonate sand. These flow lobes are fissured by deep, irregular breadcrust-like cracks.

The Cook Point lava flow drapes the west end of the Kealakekua fault scarp on land and forms a distinct steep-fronted delta extending toward the south. The subaerial part of this delta forms a flat lobate pahoehoe plain, which was formerly occupied by Kaawaloa, the large native village where Captain Cook was killed near the shoreline in 1779. The Cook Point lava flow extends west to Keawekaheka Point, and the Cook Point delta has been traced about 0.5 km offshore to depths of about 180 m (fig. 2). The Cook Point lava flow is moderately rich in plagioclase (fig. 3).

Three samples of an olivine-rich lava flow were collected in the southern part of the study area. This picrite flow forms thin draperies that cover the face of the submerged reef and are consequently less than 13,000 years old. The flow has not been identified on land, where it is apparently covered by the Palemano Point lava flow.

Five samples were collected from a hypersthene-bearing porphyritic lava flow that likewise drapes the coral-reef face near the middle of the study area, but this lava flow has also not been identified on land.

Two samples of vesicular lava (61-4 and 68-1) were collected close to the reported area of the sea-surface disturbance associated with the 1877 eruption. Though from the outer part of the Palemano Point lava delta, they are petrographically distinct from Palemano Point lava. In contrast to other major units of the dive area, these samples are notably rich in pyroxene phenocrysts (fig 3). The phenocrysts are orthopyroxene, commonly overgrown with a thin rim of clinopyroxene, and similar pyroxene phenocrysts occur in the pillow lavas collected farther offshore from the deep-water vents. Such orthopyroxene phenocrysts mantled by clinopyroxene are not common in Mauna Loa lavas. Their presence in the nearshore vesicular blocks and also in lava associated with the deep-water vents, suggests that both were erupted in the same volcanic episode. The nearshore vesicular blocks were found adjacent to the area reported to be active in 1877, and we infer that these occurrences of lavas with mantled pyroxene were products of the 1877 eruption.

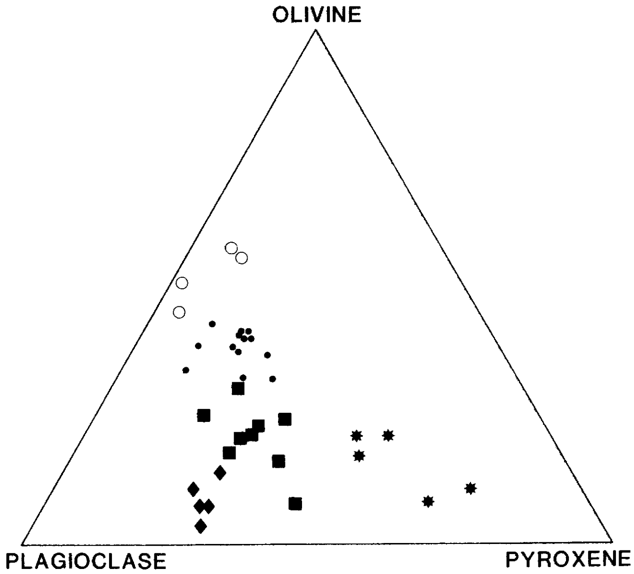

Figure 3. Modal proportions of phenocrysts in basalt samples from Kealakekua Bay region. Stars, 1877 basalt; squares, Cook Point flow; circles, Palemano Point flow; dots, Keei flow; diamonds, hypersthene-bearing basalt.

Vesicle content

The vesicularity of lava erupted under water is related to the water depth. One of the shallowest sample sets of submarine basalt is that collected from the crest of the Reykjanes Ridge south of Iceland (Moore and Schilling, 1973). Those rocks become systematically less vesicular with increasing depth of eruption (fig. 4) because (1) the exsolved gas occupies a smaller volume at greater depth and pressure, and (2) less gas exsolves at greater depth because higher pressure inhibits exsolution.

For subaerially erupted lava that has flowed into the sea, the relationship between vesicularity and the water depth at cooling defines an entirely different trend from that for suaqueously erupted lava. Subaerially erupted lava loses most of its volatiles by exsolution and bubbling while the lava is fountaining and flowing on the surface at one atmosphere of pressure. When a lava flow crosses the shoreline and descends below sea level, however, the pressure then increases one atmosphere for each 10 m of water depth, and the vesicles are increasingly compressed in accordance with Boyle's law. Samples from the submarine parts of the Palemano Point, Keei, Cook Point, and hypersthene-bearing basalt flows fall generally on the trend

Table 1. Modal analyses of basalt samples from the Kealakekua Bay region

[Sample number prefixes indicate: B, collected on land; S, collected by SCUBA diving; C, collected by submersible Sea Cliff; sample numbers beginning with a 6 or 7, collected by submersible Makali'i (dive number is first two digits plus 100). Types of pyroxene: +, orthopyroxene; *, orthopyroxene mantled by clinopyroxene; others all clinopyroxene]

Sample number	Water depth (m)	Phenocrysts (volume percent calculated vesicle-free)				Vesicles (volume percent)	Vesicles/rock (volume ratio)	Specific gravity
		Olivine	Pyroxene	Plagioclase	Glass			
				Lava of 1877 submarine eruption				
61-4	113	2.6	16.9*	4.4	76.1	50.1	1.01	1.94
68-1	122	2.2	16.9*	7.0	73.9	35.5	.55	2.28
C187	691	3.3	7.1*	5.0	84.6	11.1	.125	
C203	993	3.2	8.7*	6.1	82.0	4.7	.049	
C185	1017	3.8	9.2*	4.8	82.2	4.5	.047	2.75
				Palemano Point flow				
B-7	0	5.6	0.70	3.4	90.3	41.0	0.69	2.20
B-8	0	5.7	1.0	3.5	89.9	40.2	.67	2.20
B-9	0	6.3	.22	5.8	87.6	43.3	.76	1.85
S-2	23	7.5	.84	4.6	87.0	9.2	.10	2.63
S-1	38-52	13.1	.75	5.6	81.0	3.8	.040	2.77
63-4	41	8.6	3.7	10.0	77.7	3.9	.041	2.68
63-3	42	9.7	3.3	9.4	77.5	5.3	.056	2.70
63-5	46	8.1	.7	8.9	82.3	4.3	.045	2.72
63-2	49	8.4	5.3	9.0	76.8	4.3	.045	2.72
63-1	70	7.5	6.1	9.7	76.7	2.6	.027	2.67
				Keei flow				
68-7	85	8.2	2.5	13.1	76.3	2.4	0.025	2.82
68-4	99	9.5	2.6	12.3	75.6	2.1	.021	2.84
68-5	104	10.3	4.8	10.5	74.5	2.4	.024	2.74
68-6	104	9.3	2.3	9.9	78.5	2.5	.025	2.80
68-3	113	8.0	3.3	7.8	80.8	1.6	.017	2.84
68-8	117	6.8	3.0	7.1	83.0	1.2	.012	2.82
61-3	119	9.5	3.8	9.5	77.2	1.7	.017	2.66
69-4	123	7.3	4.8	10.3	77.5	2.0	.021	2.86
68-2	125	7.2	3.4	8.4	80.5	1.5	.016	2.83
69-2	130	7.3	3.0	7.6	82.1	1.4	.014	2.85
				Cook Point flow				
B-1	0	4.2	2.8	6.5	86.5	41.7	0.72	2.26
B-2	0	3.2	6.9	9.7	94.1	41.4	.71	2.18
B-3	0	3.7	2.6	8.5	85.2	32.2	.48	2.23
B-4	0	4.0	5.9	12.7	77.3	31.0	.45	2.46
B-5	0	2.1	11.9	14.1	71.9	40.1	.67	2.36
B-6	0	4.0	5.0	9.8	80.4	29.5	.42	2.27
67-4	79	5.5	7.3	10.3	75.0	1.4	.014	2.79
67-3	81	5.5	7.2	13.4	71.6	2.2	.022	2.77
67-5	85	6.0	7.0	12.7	72.9	1.2	.012	2.74
				Picritic (olivine-rich) flow				
62-1	180	18.3	1.9	0.52	79.3	2.1	0.021	2.85
64-1	346	22.2	.81	4.5	76.6	3.0	.031	2.91
64-2	369	23.2	.41	0	76.4	2.0	.021	2.89
				Hypersthene-rich flow				
65-1	130	0.5	1.1+	3.0	95.4	1.6	0.017	2.79
70-4	130	.78	2.8+	6.7	89.7	2.1	.022	2.82
70-3	137	.44	3.3+	8.0	88.2	1.5	.015	2.83
62-5	207	1.1	2.0+	4.6	92.3	.16	.0016	2.85
70-2	262	1.1	3.9+	9.5	85.5	.9	.0094	2.80
				Unassigned flows				
65-3	178	3.0	8.0	12.2	76.8	1.6	0.016	2.85
62-2	186	7.4	3.9	10.4	78.3	15.8	.19	2.50
66-1	227	7.5	3.3	5.1	84.1	2.0	.020	2.83
70-1	319	1.3	7.8	10.1	80.7	1.5	.015	2.85
64-5	365	1.3	3.0	7.8	87.9	.4	.0039	

expected for subaerially degassed lavas subjected to increasing submarine pressure. The vesicularity of these lavas is only about one-fortieth that of subaqueously erupted lavas quenched at the same depth (fig. 4).

As expected, the samples from the deep offshore vents fall on the curve for subaqueously erupted lava. The two petrographically similar shallow samples, collected from depths of 113 and 122 m near the 1877 disturbed area, also fall on this curve. Their vesicularity therefore supports our interpretation that these shallow samples were erupted from a submarine vent, most likely in 1877.

Examination of the vesicularity-depth variation indicates that Boyle's-law compression of vesicles is largely responsible for lower vesicularity with increasing depth. However, the available data show a tendency toward an even lower proportion of vesicles with increasing depth than would be predicted from Boyle's law (fig. 4). The same tendency is apparent in vesicle size. About 30 vesicles were measured in each sample, and the median diameter was plotted against depth (or pressure). The median vesicle diameter shows a greater decrease with depth than would be expected from the pressure effect alone (fig. 5). We suspect that the gas within the vesicles was not only compressed with increasing pressure, but also was redissolved back into the basalt melt.

This variation in vesicularity with depth may have utility as a gauge of the depth of cooling of subaerially erupted submarine lavas. Subaerially erupted lavas can be distinguished from lavas erupted under the sea by their low sulfur content (see table 2). The water depth at cooling could be estimated with some confidence if the slope and position of the depth-vesicularity curve could be determined by measurement of several samples from the same flow. Such estimates would only be feasible to a depth of about 200 m, however, because of the rapid decrease of vesicularity with depth (fig. 4).

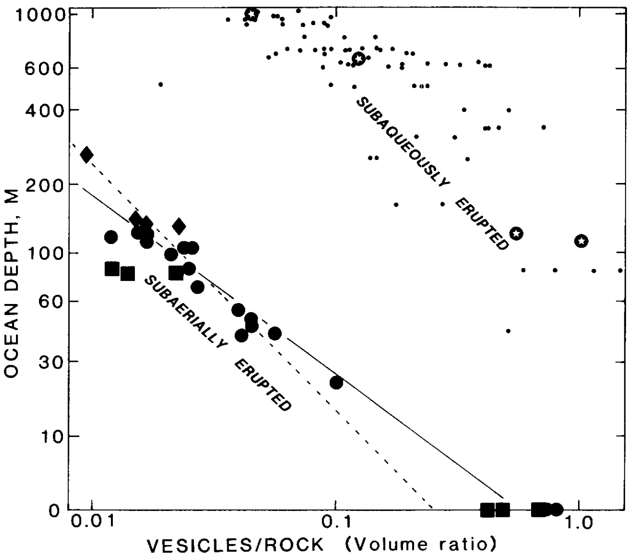

Figure 4. Vesicularity of subaerially erupted and subaqueously erupted basaltic lava samples as a function of depth of collection (see table 1). Lava flows that were erupted on land and flowed into the sea are on lower left: large dots, Keei flow; squares, Cook Point flow; diamonds, hypersthene-bearing basalt. Lavas erupted from submarine vents are on upper right: stars, Kealakekua Bay 1877 submarine vents; small dots, Reykjanes Ridge (Moore and Schilling, 1973). Lava collected above sea level is plotted at zero depth. Solid line is estimated data trend line; dashed line indicates calculated Boyle's law slope.

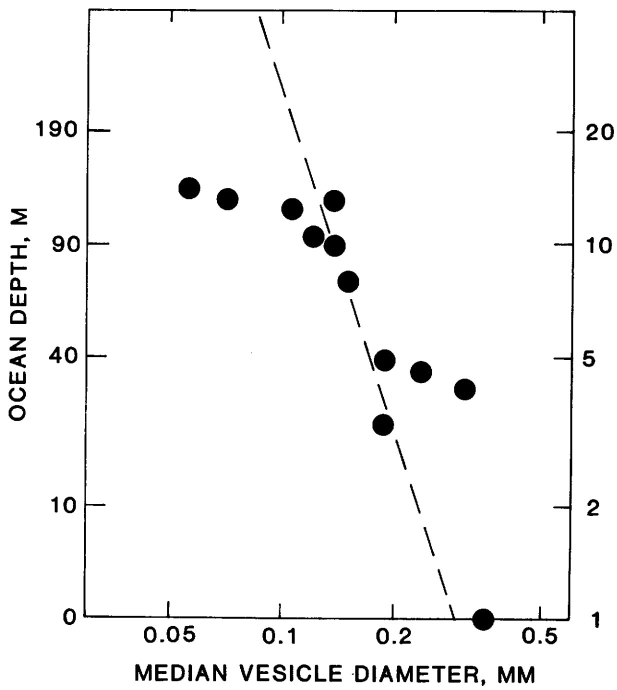

Figure 5. Median diameter of vesicles in lava samples (plotted on logarithmic scale) as a function of depth of collection and ambient pressure. Dashed line indicates calculated Boyle's law slope.

Chemistry

Electron microprobe analyses of glass in four samples of lava from the deep-water vents and two samples of vesicular lava from the shallow-water area associated with the reported 1877 eruption are shown in table 2. The analyses indicate that these glasses are virtually identical and represent material from the same eruption. For comparison, glass from the Cook Point lava flow was also analyzed by microprobe; it is chemically distinct, especially in its higher TiO_2 and K_2O contents (table 2).

The sulfur content of glass from the deep-water 1877 vents (table 2) averages about 0.12 percent, in good agreement with the normal sulfur content of undegassed submarine lava (Moore and Schilling, 1973). The glass from the shallow 1877 vent area (depths 113-122 m) averages about 0.042 percent sulfur, and it has therefore lost, relative to the deep lava, more than half the sulfur during shallow submarine venting. The high vesicularity of these samples and the reported odor of sulfur during the 1877 activity attest to the loss of sulfur. Glass from the Cook Point subaerially erupted lava that flowed into

Table 2. Microprobe analyses of glass from submarine lavas, Kealakekua Bay

[All figures in weight percent]

	Submarine eruption of 1877						Cook Point flow
	Deep vents				Shallow vent area		
Sample---	C185	C187	C203-1	C203-2	61-4	68-1	67-4
Na_2O-----	2.42	2.45	2.38	2.43	2.51	2.49	2.52
MgO------	5.75	5.48	5.77	5.72	5.58	5.51	5.31
Al_2O_3----	13.26	13.64	13.74	13.47	13.10	13.32	12.90
SiO_2-----	52.21	52.10	52.15	51.52	53.09	52.23	52.15
P_2O_5-----	0.29	0.30	0.33	0.31	0.33	0.30	0.39
S--------	0.12	0.10	0.12	0.12	0.040	0.044	0.016
K_2O------	0.47	0.47	0.45	0.46	0.48	0.47	0.58
CaO------	10.12	9.99	10.13	10.21	9.92	10.00	9.86
TiO_2-----	2.50	2.50	2.45	2.44	2.51	2.52	2.72
MnO------	0.20	0.21	0.19	0.19	0.19	0.19	0.20
FeO------	11.83	12.14	11.76	11.81	11.96	12.13	12.09
Total---	99.34	99.54	99.66	98.87	99.76	99.28	98.76

the sea contains 0.016 percent sulfur and is typical of degassed subaerial lavas (Fornari and others, 1979).

Palagonitization rates

Palagonite is an alteration product of basaltic glass (sideromelane) that replaces the glass inward from a surface exposed to water or air. Palagonitization is primarily a hydration process in which most of the elements in the glass are partly replaced by water. TiO_2 and FeO are apparently the principal major elements not removed and hence are passively enriched during removal of the remaining cations (Staudigel and Hart, 1983). The rate of palagonitization of basalt, like that of the hydration of rhyolitic glass or obsidian (Friedman and Smith, 1960), is dependent on the ambient temperature. Estimates of the palagonitization rate at different temperatures are available from laboratory experiments and from measurements of palagonite thicknesses on historical lava flows and on lavas dated by other means.

Basaltic glass (Moore, 1965, table 2, sample 6) was crushed, screened to a size range of 0.5-1 mm, and immersed in sea water held close to 100 °C in a steam bath for one year. Palagonite rims 3-6 μm thick are visible on the glass clasts in thin sections of this material, indicating that the palagonitization rate at 100 °C is 3-6 μm per year.

In another experiment, artificial basaltic glass of various compositions, made by melting and quenching basalt samples in a furnace, was cast into disks that were immersed in water at known temperatures for various lengths of time (Furnas, 1975). Measurements of the thickness of palagonite visible in thin sections of these disks indicate palagonitization rates much higher than those found by other workers. Perhaps this anomaly results from the use of remelted and artifically quenched samples.

The oldest historical subaqueous lava flow sampled in connection with this problem is the basalt flow that flowed into Lake Motosu on the flank of Mt. Fuji, Japan, in 864 A.D. (Moore, 1966). The measured summer temperature of the water at 9-m depth, at the site of sample collection by divers, was 17.5 °C. The estimated year-round average temperature in this lake, which is frozen several months per year, is 10±5 °C. Palagonite rims measured in 1965, after 1101 years, are 7-9 μm thick. The apparent rate of palagonitization is 0.0064-0.0082 μm per year.

The 1381 lava flow of Mount Etna volcano in eastern Sicily flowed 8 km into the Ionian Sea north of Catania. This alkali basalt lava flow was sampled by divers in 1970 (Moore and others, 1971). The average temperature of near-surface waters at the site of collection is 23-24 °C. Measured palagonite thickness after 589 years is 9-16 μm, indicating a rate of 0.015-0.027 μm per year (table 3).

Samples from four historical lava flows of known age have been collected by SCUBA divers offshore the island of Hawaii. These lava flows were erupted subaerially from Hualalai and Mauna Loa volcanoes and subsequently flowed into the sea. The palagonite rimming the glass crust was measured in thin sections cut perpendicular to the outer lava surface and shows a linear increase in thickness with age for samples from similar water depths (table 3). This demonstrates that the rate of hydration of basaltic glass, at constant temperature, is directly proportional to time, as suggested by Morgenstein and Riley (1975), and is not proportional to the square root of time, as is the hydration rate of rhyolitic glass (Friedman and Smith, 1960). The measured rate of palagonitization in Hawaiian marine waters at depths of 10-35 m and temperatures of 25-26 °C is 0.07±0.01 μm per year (fig. 6).

A 150-m-deep drill hole on the island of Surtsey,

Table 3. Palagonite on historical lava flows

Volcano	Year of eruption	Water depth (m)	Year collected	Age (years)	Temperature (°C)	Palagonite thickness (µm)
Surtsey	1963	0	1979	15.4	100	30
Mauna Loa	1919	23	1969	50	25	3-5
	1887	21	1969	82	25	5-6.5
	1877	113-122	1983	106	23-24	4-9
		691-1017	1983	106	4-6	0.5-1
	1868	23	1969	101	25	5.4-8.5
Hualalai	1801	24-38	1969	168	25	11-14.5
Etna	1381	12	1970	589	23-24	9-16
Fuji	864	10	1965	1101	5-15	7-9

south of Iceland, recovered glassy tephra that was examined for palagonite thickness (Jakobsson and Moore, 1982). Much of the 1963-64 tephra composing the island remains at elevated temperatures, and steam rising from numerous cracks on the surface suggests that parts of the tephra above sea level are now (and probably have been since formation of the volcano) maintained at a temperature of 100 °C. Measurements on samples of the drill core above sea level show that the palagonite thickness varies, but for a considerable volume of tephra the maximum thickness is 30 µm. Consequently, that part of the drill-core tephra that has the maximum palagonite thickness is believed to have been subjected for its entire life of 15.4 years to steam at 100 °C. The palagonitization rate for Surtsey tephra at 100 °C is therefore estimated to be 1.9 µm per year table 3).

The search for a method of dating archeological material led Morgenstein and Riley (1975) to explore the subaerial palagonitization rate of basaltic glass in artifacts from ancient Hawaiian living sites. They calibrated their system by measurements on glass from historical subaerial lava flows and found that at 24 °C the palagonite formed at a constant rate of 0.012 µm per year. They also reported rates of 0.0073 µm per year at 17 °C and 0.0029 µm per year at 5 °C. This last rate is nearly identical with the 3 mm per thousand years determined by fission-track dating of young submarine basalts of the mid-Atlantic ridge (Hekinian and Hoffert, 1975).

Measurements of palagonite rims on 1877 lava samples show a dramatic difference between the shallow and deep lavas. Lava collected from shallow depths nearshore has palagonite thicknesses of 4-9 µm (rate: 0.04-0.09 µm per year), and that collected from depths of 700-1,000 m has palagonite thicknesses of about 0.5-1 µm (rate: 0.005-0.01 µm per year). Since the basaltic glass from which the palagonite is forming by hydration is virtually identical in composition among the different samples (table 2), we attribute the variation in alteration rate to differences in water temperature. The surface temperature of the sea at this latitude is generally between 25 and 26 °C (fig. 7). This surface temperature prevails to depths of about 100 m, below which the temperature decreases to about 4-5 °C at depths of about 1,000 m. The ambient water temperature at the collection site of the shallow samples is about 23-24 °C and that of the deep ones about 4-6 °C. The thickness of palagonite (and hence the rate of palagonitization) increases by an order of magnitude for this 20-°C increase in temperature. Apparently an Arrhenius-type increase in the rate of palagonite formation occurs as water temperature increases.

Comparison of the available data on palagonitization rates (table 3) indicates a strong temperature dependence for the palagonitization process (fig. 6).

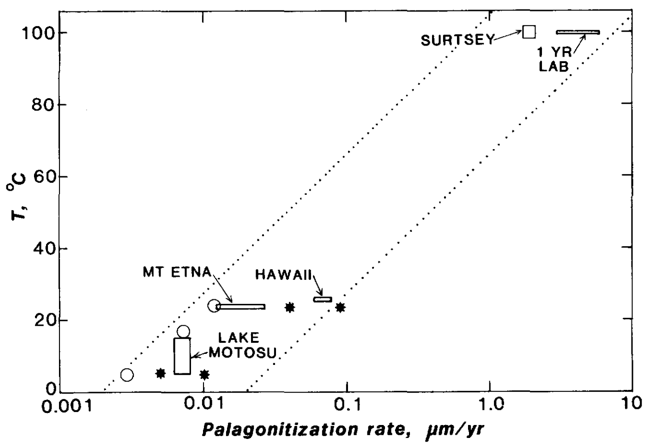

Figure 6. Rate of palagonitization of subaqueous basaltic glass as a function of water temperature. Stars, 1877 basalt in Kealakekua Bay; circles, data from Morgenstein and Riley (1975); other data are discussed in the text.

The data show considerable scatter, and at present it is possible only to define the palagonitization rate at a given temperature to within about one order of magnitude. The rate increases by a factor of about 1.8 for each temperature increase of 10 °C or by a factor of 360 for each increase of 100 °C. The palagonitizaton rate at 4-5 °C, the general temperature of the deep ocean, including the sites of most spreading-ridge lavas, is probably in the range 0.003-0.03 μm per year. A simple extrapolation of the trend in figure 6 suggests that the rate of palagonitization would be 2.7-27 mm per year at 200 °C, and 100-1,000 mm per year (or 0.27-2.7 mm per day) at 300 °C. Basalt glass subjected to the high temperatures of submarine hot springs would be completely hydrated in a matter of days.

CONCLUSIONS

Vesicular lava blocks collected about 1 km offshore at shallow depths (113-122 m) in Kealakekua Bay prove to be identical in petrology and chemistry to dense lava from submarine vents 3-4 km offshore. At both locations these basaltic rocks are believed to be from the 1877 submarine eruption of Mauna Loa for the following reasons:

1. The shallow vesicular blocks were found only in the general region of the bay reported to be affected by the 1877 eruption, in which vesicular blocks similar to those found were seen at the sea surface.
2. The vesicular blocks are distinct in chemistry and petrology from the dominant submarine lava in the same region, which is the submarine extension of a large lava flow on land.
3. The high vesicularity and moderate sulfur content of the vesicular blocks are consistent with eruption at the depth where the blocks were found.
4. The palagonite thickness on the vesicular blocks, when compared with that on the submarine extensions of various historical lava flows, is consistent with eruption in 1877.

Studies of lava samples from the 1877 eruption, together with those of other nearby lava flows, have led to the following conclusions:

1. Although the 1877 vents are not on any known rift zone of Mauna Loa volcano, their location suggests that they are related to the Kealakekua fault, which apparently bounds the north side of a large slump structure on the west flank of the volcano. Tensional fractures associated with this fault may have intersected the plumbing system of Mauna Loa, permitting the eruption of submarine lava in 1877.
2. The vesicularity change which occurs when a subaerially erupted lava flow crosses the shoreline and flows into progressively greater water depths has been measured and can provide information on the depth of cooling of similar ancient lava flows. The proportions of vesicles and glass and the diameter of the vesicles both decrease with increase in pressure (and water depth); the decrease is generally consistent with Boyle's law. However, the total volume of vesicles and their sizes are slightly smaller at increasing depth than would be expected, probably because of re-solution of volatiles back into the melt as pressure increases.
3. Because the 1877 eruptive vents occurred at different depths and hence different ambient water temperatures, new data are available on the temperature-dependence of the rate of palagonitization. The rate increases by a factor of about 1.8 for every increase of 10 °C in temperature. The rate at 4-5 °C (the prevailing temperature at the deep ocean floor) is 0.003 to 0.03 μm per year, and the extrapolated rate at 300 °C (the temperature of some deep-sea hot springs) is 0.27-2.7 mm per day, or about 90,000 times as great.

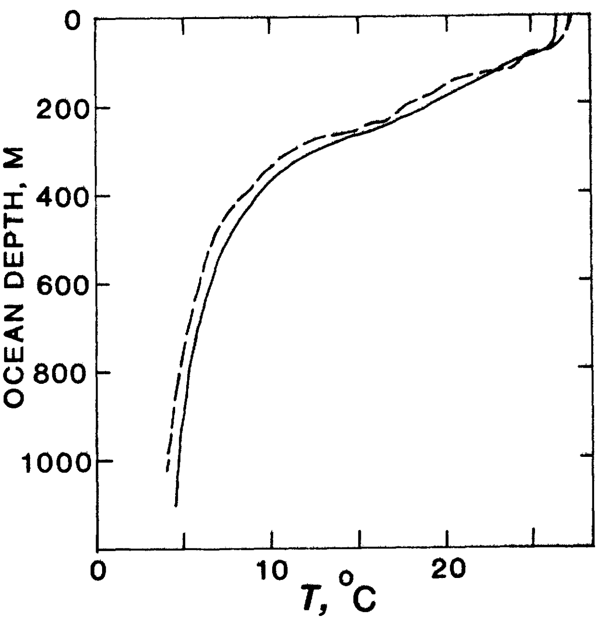

Figure 7. Gradient of ocean temperature with water depth off west Hawaii. Solid line, average of five bathythermograph profiles on Kohala terrace (Campbell and Erlandson, 1979); dashed line, measurements from submersible Sea Cliff on a dive west of Napoopoo, Kealakekua Bay (see fig. 2A).

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APPENDIX—FROM THE <u>HAWAIIAN GAZETTE</u>, FEBRUARY 28, 1877

From the Volcano! A new and remarkable VOLCANIC OUTBREAK! in Kealakeakua Bay!

The Steamer Kilauea, which left this port on Tuesday of last week for the scene of the eruption on Hawaii, returned on Monday morning, having proceeded as far as Kau, which point she left on Friday evening, nothing being visible of the summit eruption, which occurred on the 14th, and which lasted only six hours. Returning from Kau, we reached Kealakeakua Bay, on Saturday morning, Feb. 24, where a most singular outbreak was found to have taken place, being nothing less than a SUBMARINE VOLCANO, near the entrance of the harbor. On approaching the scene of action, three canoes were observed cruising around the crater, in which were Judge Hoapili, Hon. Simon Kaai, and others, who were attracted thither by the reports which had spread rapidly over the country.

As the steamer approached nearer, columns of smoke or steam were seen rising from the surface of the sea, resembling the spouting of a school of whales, and numerous pieces of lava were floating about. A boat was immediately despatched to the scene, which returned with specimens of the floating lava, which have been brought to Honolulu, and can be seen at our office.

The natives report that the eruption was first observed in the sea, at three o'clock on the morning of the 24th, about a mile from shore, and it appeared like innumerable red, blue and green lights. Some thought these were the steamer's lights—only they were so numerous as to excite some consternation. Morning disclosed the fact that a new volcano had broken out, and that it was the cause of the strange illumination seen during the night.

Those who are acquainted with Kealakeakua Bay, will recollect that Keei Point forms its southern shore. The volcano appears to consist of a sub-marine rupture, running in a straight line out to sea, steam and lava rising as far out as one mile from the point. The depth of water here has been from twenty to sixty fathoms, and the new volcano lies directly across the track of vessels bound south from the bay. The course of this land and submarine ground rent is about W.N.W. by E.S.E.

In the afternoon of the 24th, three boats from the steamer visited the scene of the eruption, cruised directly over the most active part, where the water was in a state of peculiar activity, boiling and appearing as if passing over rapids, or very much like the water at Hellgate, New York. While the boats were in this position, blocks of lava, two feet square, came up from below, frequently striking and jarring the boats. In one minute, we counted no less than six of these stones hitting the boat. Yet as the lava was quite soft, no harm was done. Nearly all the pieces, on reaching the surface were red hot, emitting steam and gas, strongly sulphurous. A fine block of this has been secured for the Museum.

At one time the surface of the sea was covered with several hundred pieces of this lava; but we observed that as soon as they became cold they sank, as rapidly as they had risen. Several were taken into the boats, perfectly incandescent and so molten in the interior, that the lava could be stirred with a stick, like pudding, the water having penetrated not more than an inch from the surface.

A rumbling noise was heard, like that of rocks in a freshet, caused no doubt by the eruption of lava from the submarine crater, which is supposed to be a crack or line of rupture extending at least a mile from the shore. Another rupture, doubtless a continuation of the submarine fissure, was traced inland from the shore nearly three miles, varying in width from a few inches to three feet. In some places the water was seen pouring down the opening into the abyss below—food for the fiery element.

A severe earthquake shock was felt, by those living at Kaawaloa and Keei during the night of the eruption, which must have preceded the outbreak. It was quite severe, but no damage is reported.

The lava thrown up from the new volcano is quite porous, brittle and light, similar to what is frequently emitted at the commencement of these eruptions, called by Hawaiians aa. When hot and burning, it floats readily, sustained on the surface partly by the gases, which give a strong sulphurous smell to the vicinity. When cold and saturated with water, it sinks to the bottom. It is probable that only the very lightest lava reaches the surface, while most of it remains at the bottom, the water here varying from ten to fifty fathoms in depth. Some of this lava consists of what is known as "Pele's hair," and when first taken out is red hot, and yet preserves its peculiar characteristics. This singular volcanic glass has always been supposed to be formed by the wind blowing the floating lava as it rises from the crater, and causing it to spin out. How it gets down under Kona is a question for scientists to solve.

Numerous fishes were killed by the action of the volcano, and were picked up on the surface by natives cruising around the spot in their canoes.

The foreigners residing on the hill at Kealakeakua watched this singular eruption with glasses, but so far as we could learn it was not visited by boats until after the passengers by the steamer had done so.

What is most singular in this connection, is the fact that no volcanic eruption has been known to have occurred in the Kona district of Hawaii, during the residence of foreigners there, or within the last hundred years. The active fires and flows were supposed to be confined to the summit crater of Mokuaweoweo, and to the districts of Puna and Kau. The present outbreak indicates that the internal fires are again at work undermining the earth crust below Kona, though it is to be hoped that there will be no further outbreak. How long this eruption will continue in action, no one can tell; but it is highly probable that the volcano will soon burst out again, either near this spot or somewhere else on the islands of Hawaii.

It is quite probable that H.B.M's Ship Fantome, Captain Long, will visit Kealakekua Bay during the present week, and if so will make investigations regarding this eruption which will be of public interest.

In conclusion, we cannot avoid remarking that our visits to Pele's domains have been exceedingly fortunate and well timed; or else that she is very partial to editors who volunteer to visit her solely to see and describe her pyrotechnic displays. Four times we have been thus singularly favored - once in 1859; then in 1865, when the eruption lasted only four days, and we were among the few who saw it; again in 1872, when we visited the summit crater of Mokuaweoweo, and witnessed it in all its glory; and lastly the present most remarkable submarine eruption, the first of the kind recorded in Hawaiian history.

Among those who visited the submarine crater, in the steamer's boats, were His Lordship Bishop Willis, A. S. Cleghorn, H. M. Whitney, W. W. Hall, W. Wilder, S. Myers of California, John M. Sheldon, A. Moot of Canada, Engineer Campbell, and several officers of the steamer Kilauea.

GPO 587-044/10029