Historic Littoral Cones in Hawaii

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ABSTRACT: Littoral cones are formed by steam explosions resulting when lava flows enter the sea. Of about 50 littoral cones on the shores of Mauna Loa and Kilauea on the island of Hawaii, three were formed in historic time: 1840, 1868, and 1919. Five new chemical analyses of the glassy ash of the cones and of the feeding lava show that there is no chemical interchange between molten lava and sea water during the brief period they are in contact. The littoral cone ash contains a lower $Fe_2O_3 / (Fe_2O_3 + FeO)$ ratio than does its feeding lava because drastic chilling reduces the amount of oxidation.

A large volume of lava entering the sea (probably more than 50 million cubic yards) is required to produce a littoral cone. All the historic littoral cones were fed by aa flows. The turbulent character of these flows and the included cooler, solid material allows ingress of sea water to the interior of the flow where it vaporizes and explodes. The cooler, more brittle lava of the aa flows tend to fragment and shatter more readily upon contact with water than does lava of pahoehoe flows.

LITTORAL CONES are common features on the shores of the younger volcanoes of Hawaii (Wentworth and Macdonald, 1953:28). These cinder cones do not mark the site of a primary volcanic vent but rather are produced by the violent steam explosions which result when some lava flows enter the sea. Upon such occasions the contact of molten lava with sea water produces great jets of steam hundreds of feet high. These blasts carry the chilled and shattered lava high into the air. If wind and topography permit, some of this material falls back on the land and builds up a cone. Most of the material falls into the sea and is removed by ocean currents.

Because of their location on the sea coast, littoral cones are very transient features and are rapidly removed by the sea; consequently they are found only on the youngest active volcanoes. On the shores of Kilauea and Mauna Loa on the island of Hawaii there are approximately 50 littoral cones. No cones are known on the other three volcanoes (Mauna Kea, Kohala, and Hualalai) of which the island is composed, nor have any littoral cones been mapped on any of the other Hawaiian Islands.

In historic time, cones have been formed at only three localities (Fig. 1). These three cones are of particular interest because their age and conditions of formation are known and because the lava flows which fed them can be identified. The three historic littoral cone localities are: (1) Sand Hills, produced by the 1840 Kilauea flow; (2) Puu Hou, produced by the 1868 Mauna Loa flow; and (3) the cone produced by the 1919 Mauna Loa flow.

1840 Cones

The remnants of the littoral cones produced in 1840 are on the coast 5 miles northwest of Cape Kumukahi, the east cape of the island (Fig. 1). The largest remnant is called Sand Hill and has an altitude of 118 ft, as shown on the 1924 topographic sheet. Shortly after its formation it was more than 300 ft high, according to Coan (Brigham, 1909:52), but it has been largely removed by the erosive action of the sea.

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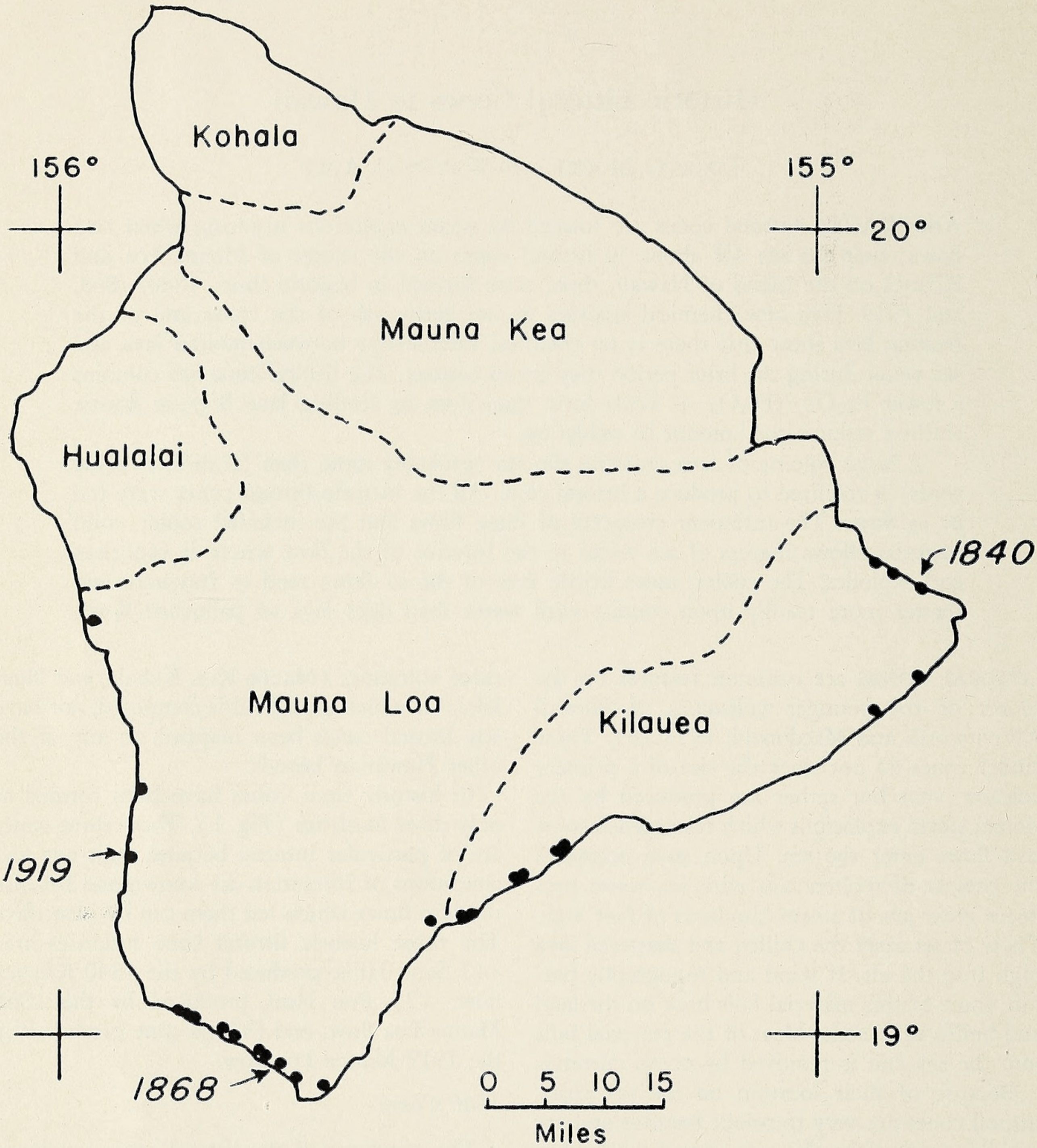

FIG. 1. Index map of the island of Hawaii, showing littoral cone localities (after Stearns and Macdonald, 1946) and year of formation of three historic littoral cones.

These cones were formed by a lava flow which broke out 7 miles inland at an altitude of 750 ft on the east rift zone of Kilauea on May 30, 1840, and continued flowing for a period of 26 days. The flow totaled approximately 281 million cubic yards, of which approximately 200 million flowed into the sea (Stearns and Macdonald, 1946:111).

The following vivid account by the Rev. Titus Coan (Brigham, 1909:52–54) describes the entry of the flow into the sea:

The flow . . . rolled down with resistless energy to the sea, where leaping a precipice of forty or fifty feet, it poured itself in one vast cataract of fire into the deep below, with loud detonations, fearful hissings, and a thousand unearthly and indescribable sounds. . . . The atmosphere in all directions was filled with ashes, spray, gasses, etc.; while the burning lava, as it fell into the water was shivered into millions of minute particles, and, being thrown back into the air fell in showers of sand on all the surrounding country. The coast was extended into the sea for a quarter of a mile, and a pretty sand beach, and a new cape were formed. Three hills of scoriae and sand were also formed in the sea, the lowest about two hundred, and the highest about three hundred feet.

For three weeks this terrific river disgorged itself into the sea with little abatement. Multitudes of fish were killed, and the waters of the ocean were heated for twenty miles along the coast. The breadth of the stream, where it fell into the sea, is about half a mile, conforming itself, like a river, to the face of the country over which it flowed.

Brigham states further (1909:54) that:

The sand hills thrown up at this place were found to be one hundred and fifty, and two hundred and fifty feet high eight months after their formation, but since then the sea has removed the whole mass. Even in 1865 they were not a third of the measured height and nodules of olivine were abundant in the sands of the beaches at considerable distance.

Most of the remnants of the 1840 cones are composed of rather thin-bedded glassy ash and lapilli. In the wave-cut cliff facing the sea, the bedded ash lies on top of lava which is probably from the same eruption. A second lava flow overlies the bedded lapilli on the north side of the larger cone remnant. This lava flow has baked and oxidized the littoral cone ash a few inches below it. The upper flow represents continued movement of 1840 lava over the cone which was produced by the littoral explosions.

The littoral cone ash is crudely bedded, ranging from material 1 or 2 mm in size down to abundant silt-size dust. The 1840 flank lava was quite picritic, with approximately 20% olivine; consequently many of the ash particles are whole or fractured olivine crystals. Much of the cone is composed of beds of glassy ash about 5 cm thick, interbedded with layers about 1 cm thick of slightly coarser material. The coarser material is similar but contains a higher percentage of the larger chunks of glassy cinder, many from ½ to 1 cm in diameter, and some as much as 4 or 5 cm in diameter.

These beds can be traced for a hundred feet or more. The coarser beds may have been formed during the more violent phases of the steam explosions, or they may represent periods of wind gusts which momentarily blew away the finer material.

1868 Cones

The littoral cones produced in 1868 are located on the coast 4 miles northwest of Ka Lae, the south cape of the island (Fig. 1). The main feeding flow passes between two cones; the one on the northwest is now 118 ft high, and the one on the southeast, called Puu Hou (new hill), is more than 240 ft high and about 1,500 ft in diameter at the base. A large part of Puu Hou has been eroded since its formation, and a substantial part has been removed since 1924, judging by photographs taken at that time by Stearns (Fig. 2).

The cones were formed by the lava flows from the Mauna Loa flank eruption at 2,500 ft altitude, which began April 7, 1868, and continued for 15 days. Of the 190 million cubic yards of lava erupted, about 100 million cubic yards flowed into the sea (Stearns and Macdonald, 1946:79).

There are no detailed descriptions by eyewitnesses of the actual formation of Puu Hou. However, Rev. Titus Coan, who visited the area in August, 5 months after the eruption, writes (Brigham, 1909:115):

Since three miles from the head the main stream went altogether over the precipice, and pursued its rapid course over the pahoehoe some seven miles to the sea which it reached in two hours. There it formed, as is usual when lava streams enter the sea, two cones of lava sand, or lava shivered into millions of particles by coming in contact with water while in an intensely heated state. There is no island there and there is nothing but what is common under similar circumstances. This stream is about half a mile wide, and it entered the sea some three-fourths of a mile from the big pali before spoken of. After running a day or two, in this channel, partial obstructions occurred, by cooling masses, when the shell of the stream was tapped some five miles from the sea, and a torrent of white-hot lava pushed out on the east side, running off to the great precipice and following its base in a breadth of half a mile down to the sea. . . .

In general the cinders composing Puu Hou are coarser than those of the other littoral cones studied. The cinders are crudely bedded, the differences between beds being mainly slight differences in size and sorting of the fragments.

Among the fine cinders and glassy ash are a

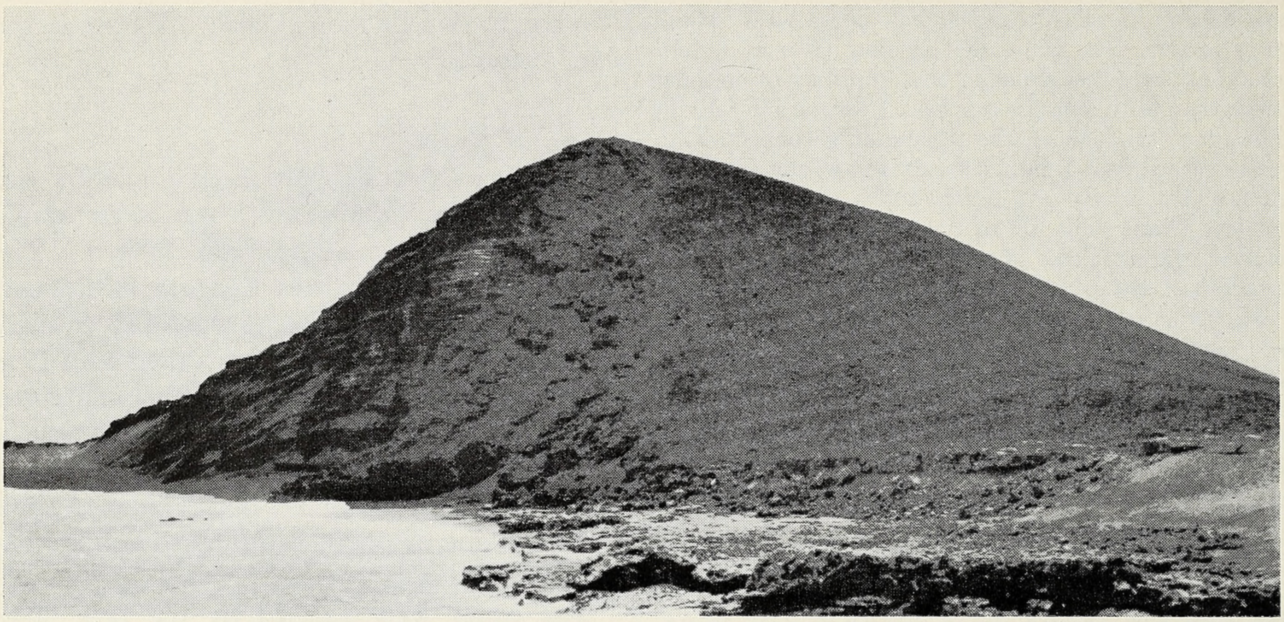

FIG. 2. Puu Hou, the littoral cone formed as the 1868 Mauna Loa flow entered the sea. Both photographs were taken from approximately the same point 38 years apart; above, June 14, 1924 (Stearns and Clark, 1930:7), below, by Moore and Ault, Feb. 1962.

great number of basalt bombs and spatter. Many of the bombs are subspherical, with concentric structure, and show evidence of having flattened when they hit. Most of them are covered with fine cinders which adhered to them when they struck the surface of the growing cone. The bombs are commonly 3–5 inches in diameter, but some more than 1 ft in diameter are present. Large masses of spatter as much as 8 inches in diameter drape over the cinders as high as the summit of the cones.

Puu Hou is notable in that it contains more bombs and spatter than the other cinder cones studied, indicating that a large amount of the material thrown into the air was still molten and was apparently not chilled and shattered. Very likely the steam explosions occurred near the base of a lava stream and threw molten material from the interior of the flow up onto the cone.

1919 Cones

The cone produced by the 1919 Mauna Loa flow is the smallest of the historic littoral cones. It is located on the southwest coast of the island, about 25 miles northwest of Ka Lae (Fig. 1). The cone is only about 50 ft above sea level and 15–20 ft above the general level on the landward side.

The 1919 Alika flow which formed the cone broke out 11 miles east of the coast at an elevation of 7,500 ft on the southwest rift zone of Mauna Loa. The source vents opened about midnight, September 28–29, and the lava reached the sea at 4:30 AM, September 30. This aa lava stream continued to flow into the sea for 10 days. About 350 million cubic yards of lava were erupted, of which 200 million cubic yards flowed into the ocean (Stearns and Macdonald, 1946:79).

Many details of the contact of the lava with the sea were recorded by Thomas Jaggar of the Hawaiian Volcano Observatory (Jaggar, 1919: 133–134). When the lava poured into the sea, he wrote:

> Noises were heard underwater of seething and of tapping concussions. The uprush of steam where the lava made contact with the sea carried up rock fragments and sand and built a black sand cone. The lava "rafts" or blocks of bench magma which rolled down the live channel, were seen to bob up, make surface steam, and float out some distance from the shore without sinking at first, as though buoyed by the hot gas inflating them. Lightnings were seen in the steam column. There was much muddying of the water and fish were killed in considerable number. . . . For 50 or more feet out to sea from the base of the great column of vapor which was rising opposite the lava channel somewhere beyond, the water was dotted with small jets and sometimes a swirling "steam spout" or tornado effect, a foot or two in diameter, would rise from the water a few feet away from the main steam column and join the cloud above. Sometimes a shower of small rock fragments each two or three inches in diameter would be jetted up from a place in the water close to shore, each projectile followed by a tail of vapor, to heights 15 or 20 feet above the sea.

In describing the littoral cone as it appeared on October 23, a few weeks after the eruption, Jaggar stated (1919:151):

> This cone, at the lower terminus of the channel was built by the steam explosions resulting from the incandescent torrent rushing into water, a crater being there formed, surrounded by a heap of black sand. This horse shoe heap was 75 feet high above sea level, and the front of it had broken down on the ocean side, revealing a section of bedded sands over a rock wall beneath. . . . The material was black and rather fine lava sand. . . . There were a few scattered small lava fragments on the surface of the sand. Everywhere the sand was coated with a thin film of crystalline white salt, common sea salt, to judge by the taste, and this made the cone white as seen at a distance.

The 1919 cone is composed of crudely bedded glassy ash and cinders. In the sea cliff this pyroclastic material is about 40 ft thick and extends from the crest of the cone almost to sea level, where it rests on top of a shattered and contorted lava flow. It is not known whether this flow is a 1919 lava flow or is older.

The east (landward side) of the cone is partly covered by a younger lobe of the 1919 flow. This lobe flowed on top and around the north side of the completed cone and reached the sea, forming a prominent peninsula containing a major channelway. In the sea cliff this younger lobe lies on top of the littoral cone ash and cinders and has baked them to a reddish color for a distance of 4 ft below its base. The younger lobe is not covered by cinders and apparently marks the last phase of the 1919 lava which flowed into the sea after the cone was formed.

The lower part of the clastic material of the cone is relatively coarse. It is composed of rather large masses of spatter as well as angular blocks which are probably parts of the shattered solid top of the feeding aa flows. Many of these masses of spatter are 5–6 inches in diameter and 2 inches thick and are crudely disk-shaped. They occur in a matrix of finer cinders and glass sand. Higher in the cone the material is considerably finer grained and is composed predominantly of glass sand averaging less than a few millimeters in size.

The glass sand or ash from all three of the historic littoral cones appears very similar under the microscope. It is composed principally of angular fragments of fresh, light brown, transparent glass containing abundant crystallites. In addition, 10 to 20 percent of the ash is composed of fragments of basalt and black, opaque glass. Small vesicles are common in both the transparent and opaque glass. They occupy 15 to 20 volume percent of the fragments and are generally 0.2 to 0.3 mm in diameter.

CHEMISTRY

Chemical analyses have been made of the glassy ash of each of the three historic littoral cones as well as of the lava flows which fed the cones (Table 1). Ash samples were collected 2 ft below the surface on the upper slopes of the littoral cones. Lava samples were collected from

TABLE 1

CHEMICAL ANALYSES OF HISTORIC LITTORAL CONE ASH AND ASSOCIATED LAVA FLOWS, HAWAII

	1	2	3	4	5	6	7	8	9	10
SiO_2	48.86	48.43	— .43	51.03	50.58	— .45	51.89	51.83	— .06	— .31
Al_2O_3	11.46	10.70	— .76	13.20	12.63	— .57	13.90	13.95	+ .05	— .43
Fe_2O_3	2.13	1.15	— .98	3.26	1.65	—1.61	3.24	1.75	—1.49	—1.36
FeO	9.09	10.08	+ .99	8.04	9.35	+1.31	7.88	9.17	+1.29	+1.20
MgO	14.13	16.29	+2.16	9.40	11.08	+1.68	7.21	7.05	— .16	+1.23
CaO	9.27	8.67	— .60	10.02	9.44	— .58	10.61	10.58	— .03	— .40
Na_2O	1.84	1.71	— .13	2.22	2.01	— .21	2.25	2.31	+ .06	— .09
K_2O	.36	.35	— .01	.42	.38	— .04	.36	.35	— .01	— .02
H_2O+	.23	.22	— .01	.11	.33	+ .22	.06	.14	+ .08	+ .10
H_2O-	.01	.00	— .01	.01	.13	+ .12	.01	.01	.00	+ .04
TiO_2	2.14	2.00	— .14	2.13	1.94	— .19	2.10	2.11	+ .01	— .11
P_2O_5	.19	.18	— .01	.24	.21	— .03	.22	.22	.00	— .01
MnO	.17	.17	.00	.17	.17	.00	.18	.17	— .01	.00
CO_2	.01	.00	— .01	....	.01	....	.01	.00	— .01	
Cl	.04	.02	— .02	....	.02	....	.01	.02	+ .01	
F	.03	.02	— .01	....	.03	....	.03	.02	— .01	
Total	99.96	99.99	+ .03	100.25	99.96	— .35	99.96	99.68	— .28	— .16

1. Olivine basalt from 1840 flow between 1840 littoral cone remnants at Sand Hill, Puna, Hawaii. D. F. Powers, U.S. Geological Survey, analyst.
2. Glassy basaltic sand 80 ft below summitt of southern 1840 littoral cone remnant, Puna, Hawaii. D. F. Powers, U.S. Geological Survey, analyst.
3. Difference between 1 and 2.
4. Hypersthene basalt, lava of 1868, road near east edge of flow in Kahuku Ranch, Hawaii. J. H. Scoon, Univ. of Cambridge, analyst. Tilley and Scoon, 1961.
5. Glassy basalt sand, 100 ft below summit, Puu Hou (1868) littoral cone, Kau, Hawaii. D. F. Powers, U.S. Geological Survey, analyst.
6. Difference between 4 and 5.
7. Basalt from 1919 Alika flow 50 yards east of Alika littoral cone, Kona, Hawaii. D. F. Powers, U.S. Geological Survey, analyst.
8. Glassy basaltic sand from Alika (1919) littoral cone, Kona, Hawaii. D. F. Powers, U.S. Geological Survey, analyst.
9. Difference between 7 and 8.
10. Average of 3, 6, and 9.

near the surface of the aa flows; every effort was made to break out fresh rock and to avoid oxidized zones. A modern analysis is available (Tilley and Scoon, 1961) for one of the three flows (1868), and this is shown in Table 1. The purpose of these analyses was to investigate any chemical changes which occurred as the result of contact of incandescent molten lava with sea water.

In Table 1 the differences between the weight percent of the oxides of littoral cone ash and feeding lava are shown. These differences show virtually no chemical interchange between the lava and the sea water. Except for iron, MgO is the only oxide which shows an average difference of more than 1% between feeding lava and littoral cone ash in all three littoral cones. However, SiO_2 differs in a comparable, though smaller, degree in the opposite sense, suggesting that this difference in MgO is due to olivine control. Apparently the lava-flow material sampled had slightly less olivine than the littoral cone ash, and this difference in the amount of olivine is believed to be fortuitous.

Macdonald (1955:35) has had lava analyzed from above and below the tidal zone for two of the 1955 flows of Kilauea. These analyses also show virtually no interchange and no significant change in MgO or SiO_2 content.

All the analyses, however, do show a very interesting change in the oxidation state of the iron. The littoral cone ash is invariably higher in FeO and lower in Fe_2O_2 than is the corresponding feeding lava flow, the littoral cone ash averaging about 1.2% more FeO and 1.4% less Fe_2O_3 than the feeding flow. Likewise, the tidal zone 1955 lava is higher in FeO and lower in Fe_2O_3 than is the subaerial part of the same flow (Macdonald, 1955:35), but the differences are smaller, averaging only about 0.5%. The reason for this difference, apparently, is that the rapid quenching of the water-chilled lava inhibits oxidation, whereas oxidation of iron proceeds in the subaerial part of the flow long after it has solidified, but while it is still hot. The smaller difference between tidal zone lava and its feeding flows, as compared with littoral cone ash and its feeding flows, suggests that the less drastic chilling of the tidal zone lava has allowed some oxidation to proceed in it, whereas that in the littoral cone ash was largely prevented.

Washington (1923:415–416) has pointed out that the more glassy forms of a lava flow contain a higher proportion of ferrous to ferric iron than do the more crystalline phases of the same flow. He has shown further that FeO is uniformly higher relative to Fe_2O_3 in the pahoehoe form of lava flow than in the aa form; this difference is apparently due to the more glassy character of pahoehoe as compared with aa. Figure 3 is a compilation of modern analyses in which the $Fe_2O_3/(Fe_2O_3 + FeO)$ ratio is plotted for different kinds of flows, for pumice, and for littoral cone ash. These new data clearly support Washington's concept that iron in aa flows is more highly oxidized than that in pahoehoe flows. They also show that littoral cone ash and pumice from the Kilauea Iki eruption (1959) on the average are slightly less oxidized than the average pahoehoe flows.

All the feeding flows of the littoral cones are aa flows, yet the chilled littoral cone ash is in general less oxidized than pahoehoe lava and, with pumice, is some of the least oxidized of historic tholeiitic Hawaiian lava. Presumably, the characteristic high-oxidation state of the aa flows had not developed when the flow was in motion or when the littoral cones were built. Apparently the aa lava becomes highly oxidized rather late in the cooling history of the flow, probably after it solidifies, but before it is entirely cool. The greater thickness of the aa flows, as well as the insulating layer of rubble on the surface, would cause them to cool more slowly than pahoehoe flows, and hence they would be subject to oxidation for a longer period.

The state of oxidation of the iron in truly juvenile, unaltered Hawaiian tholeiitic lava is not known. However, the littoral cone glassy ash and basaltic pumice, both of which are drastically quenched, include the least oxidized of historic lava (Fig. 3) and may represent most closely the unoxidized lava.

MECHANISM OF FORMATION

The most important single factor in the formation of a littoral cone is that a flow of sufficient volume enters the sea. At most only a small amount, probably never more than 5%,

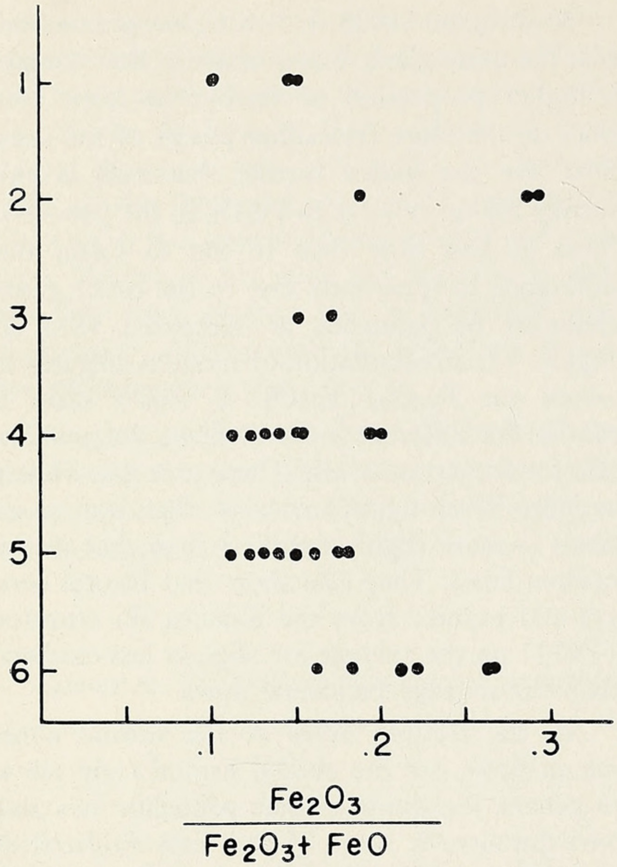

FIG. 3. Scatter diagram showing the $Fe_2O_3/(Fe_2O_3 + FeO)$ ratio for different forms of historic basaltic lava from Kilauea and Mauna Loa.

1. Littoral cone glassy ash.
2. Aa flows feeding littoral cones.
3. 1955 lava collected in tidal zone.
4. Basaltic pumice.
5. Pahoehoe lava flows.
6. Aa lava flows.

of the lava is thrown into the air and back on land by the steam explosions. Hence, the volume of material which flows into the sea must be great. Judging from historic littoral cones, probably more than 50 million cubic yards of lava must enter the sea to produce a cone of appreciable size.

In Table 2 are tabulated the 12 historic lava flows which reached the ocean on the island of Hawaii. Of the nine which did not produce littoral cones, five poured too little lava into the sea. These five are the flows of 1750?, 1823, 1926, 1955, and 1960. Of these, the 1926, 1955, and 1960 flows produced observed littoral explosions and probably would have formed cones had the flows been more copious or more localized. The 1960 eruption poured a sizeable volume into the sea, but it was distributed along a 2-mile front.

All the littoral cones were fed by aa flows. Probably these lava flows are more likely to produce littoral explosions for two reasons: (1) The turbulent and fragmented character of the flow and the presence of much included, cooler, solid material, will allow ingress of sea water to the hot interior of the flow; this water will expand, form steam pressure upon heating, and explode. The pahoehoe flows, on the other hand, form an elastic crust on their surface but continue flowing within; hence the hot mobile interior is effectively sealed off from contact with the sea water. (2) The cooler, more brittle aa flows tend to fragment and shatter more readily upon contact with water than do the more fluid pahoehoe flows.

However, all large aa flows do not produce extensive littoral explosions and resultant cones. Aa lava flows differ greatly in the character of their flow. When the active feeding channel of the aa front is smooth and regular in its flow into the sea, littoral explosions and generation of steam appear to be inhibited. Macdonald (1954:166) pointed out that the unbroken liquid surface of the 1950 lava river which plunged into the sea prevented water from gaining access to the interior of the flow. When steam generation occurs only on the surface of the flow, the pressure required for the littoral explosions cannot build up. When the smooth surface of the flow where it entered the sea was disturbed, as by a floating raft of solid lava, a brief ash-making explosion occurred.

Undoubtedly other factors also contribute to the intensity of littoral explosions. In addition to the volume, rate, and character of the flow as it enters the sea, the character of the shore bottom is probably important. If the flow moves rapidly into deep water on a steep slope, the force of the explosions is lessened by the greater depth of overlying water.

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