STUDIES IN GEOPHYSICS

Explosive Volcanism: Inception, Evolution, and Hazards

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Explosive Eruptions of Kilauea Volcano, Hawaii

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ABSTRACT

Although most Kilauea eruptions produce effusive basaltic lavas, about 1 percent of the prehistoric and historical eruptions have been explosive. Multiple steam explosions from Halemaumau Crater in 1924 followed subsidence of an active lava lake. A major hydromagmatic explosive eruption in 1790 deposited most of the Keanakakoi Formation—a blanket of pumice, vitric ash, and lithic tephra that is locally more than 10 m thick around Kilauea's summit area. The Keanakakoi was deposited in multiple air-fall and pyroclastic-surge phases, probably accompanied by caldera subsidence. The Uwekahuna Ash, exposed near the base of the present caldera cliffs and on the southeast flank of Mauna Loa, was formed by a major sequence of explosive eruptions about 1500 yr before present (B.P.). Beneath the Uwekahuna Ash in a few localities are two to three similar pyroclastic deposits. The Pahala Ash, extensive on the south flank of Kilauea and on adjacent Mauna Loa, reflects many explosive eruptions from about 25,000 to 10,000 yr B.P. Although it is not clear whether parts of the much weathered and reworked Pahala are of lava-fountain or hydromagmatic origin, much of it appears to be hydromagmatic. Pyroclastic deposits are present in the Hilina Formation on the south flank of Kilauea near the coast; about six of these deposits are estimated to be 40,000 to 50,000 yr old, and others are both younger and older. None of the deposits older than 2000 yr is well dated, but if we assume generally uniform growth rates for Kilauea's shield during the past 100,000 yr, an average, but not periodic, recurrence of major explosive eruptions is about every 2000 yr; minor explosive eruptions may be more frequent. The occurrence of relatively rare but dangerous explosive eruptions probably relates to sudden disruptions of equilibrium between subsurface water and shallow magma bodies, triggered by major lowering of the magma column.

INTRODUCTION

The eruptions of Hawaiian volcanoes have a reputation for being nonexplosive and relatively benign. They produce spectacular lava fountains, sometimes more than 500 m high, but by far the bulk of the erupted material forms effusive basaltic flows of relatively low viscosity. Although these flows commonly destroy property, they move slowly enough that they seldom threaten the lives of people. Since 1823, the time of the first well-recorded Hawaiian eruptions, only one person is known to have been killed by a volcanic eruption in Hawaii.

The major eruptions with high lava fountains do produce pyroclastic materials, including basaltic pumice, small drops of basaltic glass (known as Pele's tears), and threads of volcanic glass (known as Pele's hair). Such pyroclastic deposits are purely magmatic in origin and commonly occur near and downwind from major vent areas. Among the most recent major deposits of this type is that associated with the Kilauea Iki eruption of 1959, which formed a pumice cone and downwind trail of pumice that together totaled about 2.5×10^6 m^3 in volume. The lava lake formed in that same eruption totaled about 39×10^6 m^3 in volume, and so the proportion of pyroclastic deposits to flows is about 6.4 percent by volume.

The overall proportion of pyroclastic deposits to flows for

Hawaiian volcanic products visible above sea level has been estimated at less than 1 percent (Macdonald, 1972, p. 355). This proportion of pyroclastic deposits to flows has been used as a measure of explosiveness for volcanoes throughout the world. For some island-arc volcanic provinces it exceeds 90 percent; the 1 percent in Hawaii is nearly the minimum. Why, then, is there any concern at all about explosive eruptions on Hawaii?

THE 1924 ERUPTION

In 1924 an unusual explosive eruption occurred from Halemaumau crater of Kilauea Volcano (see Figure 9.1; Finch and Jaggar, 1924; Jaggar and Finch, 1924). Before 1924, Halemaumau, an oval pit about 530 m across, had contained an active lava lake for many decades; extensive overflows of this lava lake covered large parts of the floor of Kilauea caldera in 1919 and 1921. The east rift zone of Kilauea had been inactive for nearly 40 yr, until a series of small eruptions broke out along it in 1922 and 1923. At the beginning of 1924 the lava-lake surface in Halemaumau was 50 m below the rim. During February 1924 the lava lake subsided and disappeared, and the floor of Halemaumau sank to a level 115 m below the rim. During March and April 1924 an earthquake swarm along the middle and lower east rift zone indicated that magma was being injected into the rift zone; the subsiding magma column at the summit was apparently related to this downrift intrusion. The earthquakes in the lower east rift, 50 km east of Halemaumau, increased in late April, and major ground cracks as much as 1 m wide, appeared in the Kapoho area. Subsidence of 1 to 3 m along a 1-km-wide graben parallel to the lower east rift indicated that major extension of the rift was taking place, possibly associated with a submarine eruption but certainly associated with magmatic injection into the rift zone below sea level.

Sinking of the floor in Halemaumau was renewed in late April, and by May 6, 1924 the floor was 200 m below the rim. Subsidence continued, and on May 10 steam explosions began from Halemaumau. Up to 13 explosions per day, lasting from a few minutes to 7 h, continued for 18 days (see Figures 9.2 and 9.3). The largest explosions, which occurred on May 18, expelled ash clouds more than 2 km high; one of these explosions ejected blocks that fatally wounded a man who was 500 m southeast of Halemaumau, and other blocks, weighing as much as 8 tons, landed nearly 1 km from the crater. The dust-to block-size ejecta from all the explosions consisted largely of old lithic material from the walls and floor of Halemaumau and a few cored lava bombs. The blocks ranged in temperature from ambient to about 700°C (barely incandescent at night). Some large rock masses exposed in the walls of the collapsing crater were also observed to have a dull red glow. The gases propelling the explosions were not of the sulfurous variety normally emitted from the active lava lake. Most observers downwind of the explosion clouds considered these gases to be mainly odorless steam. Electrical storms and small showers of accretionary lapilli also were produced by the eruption clouds. Although the 18-day series of explosions deposited a field of blocks and ash about 1 km wide around Halemaumau, the total ejecta volume was estimated to be less than 1 percent of the volume of subsidence formed by the withdrawing magma column. In June 1924, after the subsidence and explosions, Halemaumau crater was 960 m wide and 400 m deep to its rubble-filled floor (see Figure 9.4).

In contrast to the 1959 Kilauea Iki pyroclastic deposits, which were entirely magmatic in origin, the pyroclastic material from Halemaumau in May 1924 was derived from older rocks, bro-

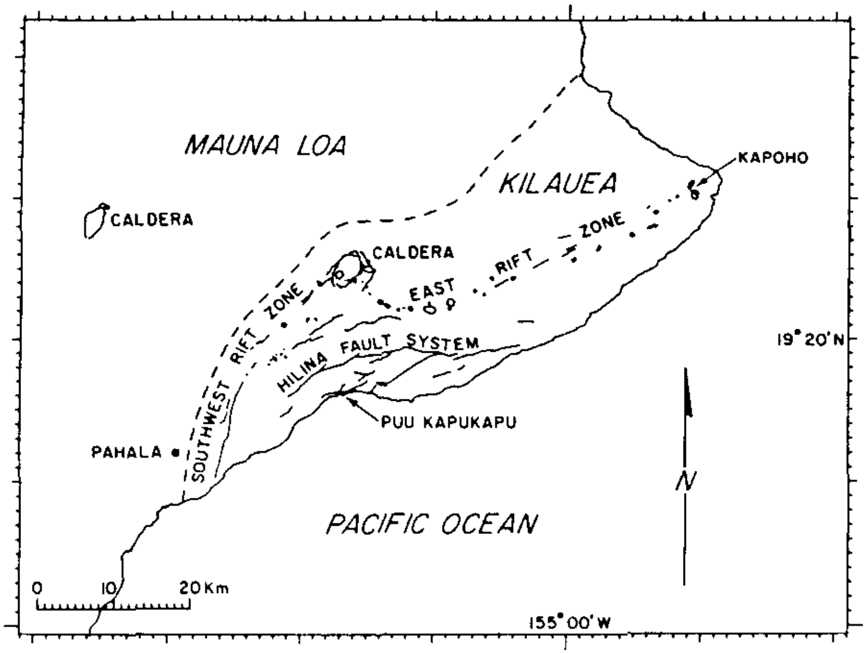

FIGURE 9.1 Index map of southeastern part of the island of Hawaii, showing all of Kilauea Volcano and part of Mauna Loa Volcano.

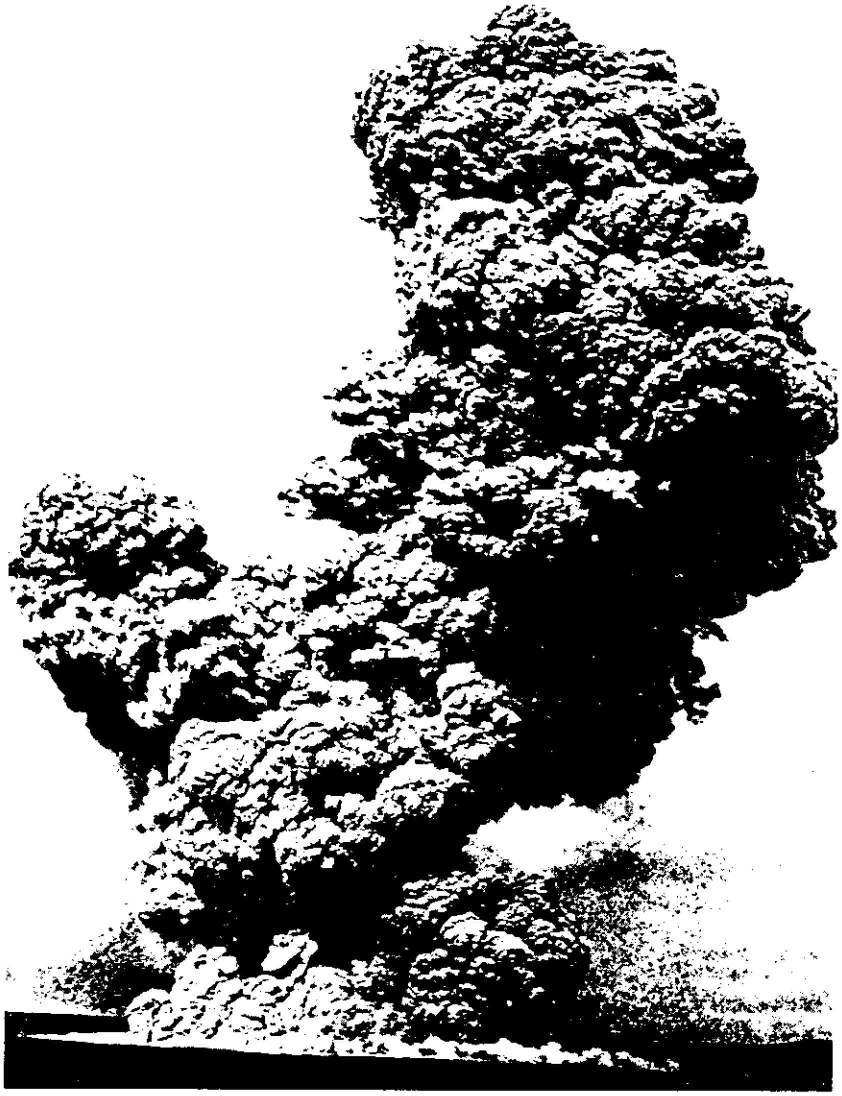

FIGURE 9.2 Explosive eruption from Halemaumau crater in Kilauea caldera about 8:20 A.M. (local time), May 24, 1924. Photograph by Tai Sing Loo.

ken up and expelled by steam explosions. The steam is thought to have come from subsurface water moving in to replace the subsiding magma column as it was lowered by injection far down the east rift zone; the water flashed to steam by contact with the hot but largely solid rocks that had surrounded the magma. Even though the crater was only partly clogged by collapsing and fall-back rubble, some intermittent steam generation was apparently rapid enough to cause strong explosions. In addition to steam generated by the rapid interaction of subsurface water and hot rocks, local hydrothermal systems near the high-level magma column may have flashed to steam as their hydrostatic pressures were suddenly reduced.

A 1262-m-deep well drilled for scientific information 1 km south of Halemaumau in 1973 (Zablocki *et al.*, 1974, 1976; Keller *et al.*, 1979) revealed a standing-water level in that area 491 m below the surface (611 m above sea level). This observation appears to confirm the hypothesis of Finch (1943) and Stearns (1946, p. 44) that the explosions of 1924 were produced not from a basal water table near sea level but from water confined at higher levels by dikes around the vent area. Assuming that similar conditions existed near Halemaumau in 1924 to those at the well in 1973, these explosions probably originated near a depth of 500 m below the rim of Halemaumau.

Though unusual and spectacular, the explosive eruptions of 1924 produced so little ejecta that they will probably not be evident in the eventual stratigraphic record of Kilauea, in sharp contrast to the extensive hydromagmatic deposits produced from the major explosive eruption in 1790.

THE 1790 ERUPTION

William Ellis, after an extensive tour of the island of Hawaii in 1823, wrote the first systematic account of Hawaiian erup-

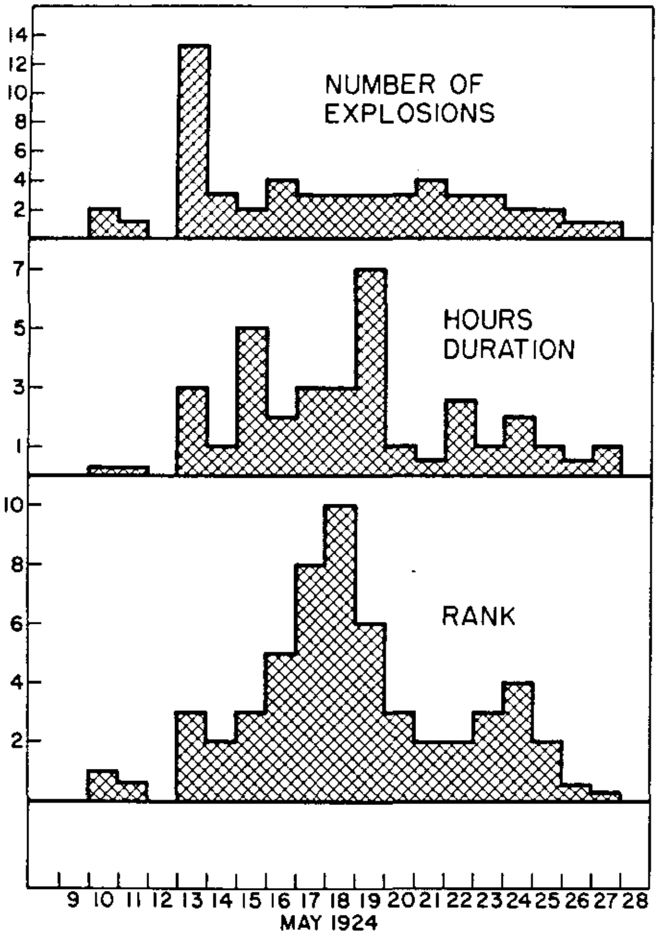

FIGURE 9.3 Characteristics of multiple explosions during 1924 explosive eruption of Kilauea. Top graph shows the number of separate explosions per day. Middle graph shows the total duration of explosions during each day. Bottom graph shows the relative ranking of various explosions on a scale of 1 to 10 (10 being the greatest) by geologists who witnessed the eruption (Finch and Jaggar, 1924).

tions, based on his own observations and on a lively oral tradition among the Hawaiian people (Ellis, 1827). Still vivid in memories at that time was an explosive eruption that had occurred at Kilauea in 1790, during the wars that first brought the Hawaiian Islands together under a single ruler. About a third of the warriors who were marching across Kilauea to oppose the dominant chief, Kamehameha, were killed in that eruption. Preliminary studies (Swanson and Christiansen, 1973; Christiansen, 1979) have reconstructed the events of the 1790 eruption and its immediate precursors and successors from their stratigraphic record—preserved in the Keanakakoi Formation (Wentworth, 1938)—and from early records of the traditional Hawaiian accounts.

Bedded pyroclastic deposits that make up the Keanakakoi Formation, locally more than 10 m thick, mantle the area around Kilauea caldera and can be traced more or less continuously for more than 20 km from the summit (see Figures 9.5 and 9.6). All who have studied these deposits agree that at least their upper part dates from the eruption of 1790. Although early researchers assumed that all of the Keanakakoi had formed in that eruption, H. Powers (1948) showed in a detailed study that these deposits include numerous unconformities. He concluded that only the uppermost layer of lithic ash and blocks (below a significantly younger layer of fallout pumice) dates from the 1790 explosive eruption.

Current study of the Keanakakoi shows that it contains both fallout and surge deposits. A generalized stratigraphy from bottom to top is as follows, with each major unit separated from its neighbors by surfaces of broad truncation (see Figure 9.7): (1) basal wind-redeposited Pele's hair and lapilli of basaltic pumice; (2) predominately well-sorted vitric ash, generally with more or less continuous planar mantle bedding; (3) somewhat less well-sorted lithic-vitric ash, commonly with wavy or lenticular bedding, accretionary lapilli in the finest layers, cross-stratification, and bedding sags beneath lithic blocks; (4) a thin local lava flow, erupted from a fissure circumferential to the caldera near its southwest margin and associated minor fallout deposits of Pele's hair and pumice; (5) lithic ash and blocks, commonly poorly sorted and with abundant accretionary lapilli, cross-stratification, and many discontinuous layers; (6) an uppermost deposit of fallout and wind-resorted pumice and Pele's hair. Units 2, 3, and 5 are the principal units of the Keanakakoi; the other units have smaller volumes. Units 1 and 6, which are wholly to partially reworked, clearly preceded and succeeded, respectively, the explosive eruptions that deposited the bulk of the formation.

Distinctive nonplanar bedding characteristics of many layers in the Keanakakoi Formation demonstrate that these layers were deposited by pyroclastic surges. It is now clear that most of the local unconformities recognized by H. Powers (1948) in the Keanakakoi have broad, open to U-shaped profiles (Figure 9.5) that reflect scouring during the emplacement of such surges. Only the surfaces between the principal units represent continuous widespread disconformities. These surfaces, however, also appear to represent mainly scour by strong pyroclastic surges, probably after pauses in the eruption sequence that may have allowed the formation of local gullies to guide the surge flows; any such gullies must have been completely modified by those surges. Careful search has revealed no clear evidence of stream erosion, channel gravel, or soil formation within the Keanakakoi section between the base of unit 2 and the top of unit 5, although groundwater oxidation at the tops of poorly permeable layers mimics soil colors locally. No remnants of vegetation have been found within the Keanakakoi other than carbonized material near its base that appears to represent vegetation killed in the eruption and buried in the initial deposit. Recent ^{14}C dating of this material (Kelley *et al.*, 1979) has consistently given nominal ages that range from less than 200 to about 350 radiocarbon years.

The features described above indicate that the bulk of the Keanakakoi Formation was deposited without significant time breaks and are consistent with its emplacement during the eruption of 1790. The traditional Hawaiian accounts of this eruption are interpreted to indicate that its most powerfully explosive phases occurred over a period of about 3 days and

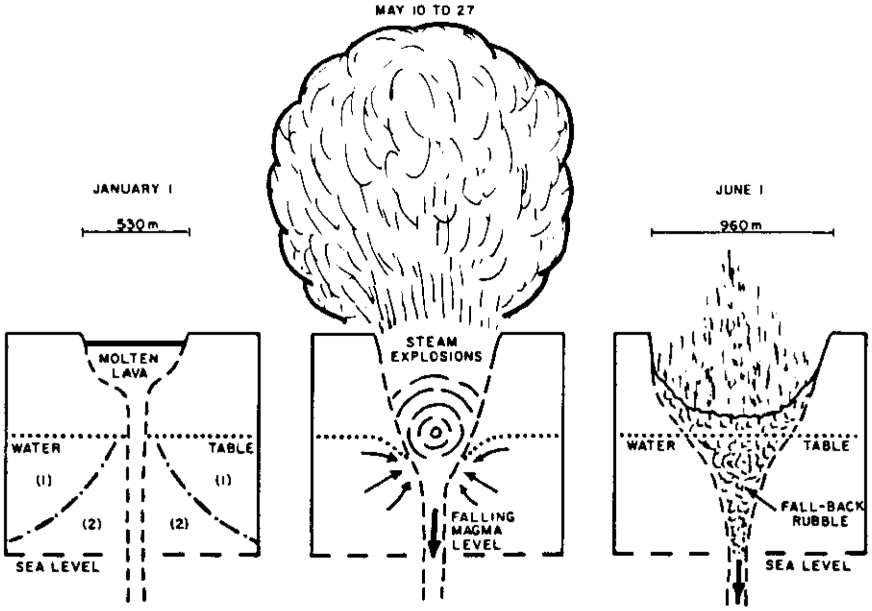

FIGURE 9.4 Schematic cross sections showing conditions at Halemaumau crater before, during, and after the 1924 explosive eruption. On January 1, zone of subsurface water 1 is cooler than the H_2O boiling temperature, and zone 2 is at the H_2O boiling temperature for that depth; dash-dot line denotes approximate boundary between these two zones. As magma column subsides below the water table, equilibrium between subsurface water and magma is destroyed, and water from zone 1, rushing into broken hot rocks surrounding subsiding magma column, flashes into steam. Water from zone 2 also flashes into steam as hydrostatic pressures are suddenly reduced. Explosions are multiple because of progressive lowering of the magma column; the explosions stop when exhaustion of thermal energy above subsiding magma column leaves a collapsed crater on June 1. Drawings by Maurice Sako, U.S. Geological Survey.

that the deaths of the Hawaiian warriors occurred during a rapidly emplaced pyroclastic surge (Swanson and Christiansen, 1973). The Keanakakoi Formation appears to contain the stratigraphic record of a nonrandom sequence, the principal events of which occurred within a fairly short period whose exact duration remains uncertain—possibly a few days to a few weeks. The sequence of units is interpreted as follows: (1) The magma column before the explosive eruption stood high and at times produced lava fountains in the caldera high enough to generate the extremely inflated variety of pumice called *reticulite* (or thread-lace scoria). This state probably was analogous to but more gas-rich than that of the high-standing magma column that generated the long-lived lava lakes of Halemaumau before the explosive eruption of 1924. During such a time the subsurface water would have developed a quasi-equilibrium boiling front in the heated rocks around the magma column. (2) Rapid lowering of the magma column, possibly related to the lava flows erupted about 1790 on Kilauea's lower east rift zone (Macdonald, 1941; Holcomb, 1980), allowed the subsurface water near Kilauea's summit to enter the vicinity of the emptied magmatic conduits; contact of that water with magma in the subsiding column chilled and fractured the magma, and explosive boiling of the water caused eruptions of the type called *hydromagmatic* and generated fallout deposits and some pyroclastic surges close to the vent. (3) As the magma level continued to drop with continuing injection into the rift zone, more water entered the conduit system and its surrounding envelope of hot rocks and the eruptions became more intense. Progressively more lithic material was erupted along with the vitric ash, and pyroclastic-surge deposition became prevalent.

FIGURE 9.5 Pyroclastic deposits of the Keanakakoi Formation in sand wash about 1 km southwest of Kilauea caldera. Average height of gully wall is about 5 m. Major disconformities, apparently caused by scouring from pyroclastic surges, are clearly visible.

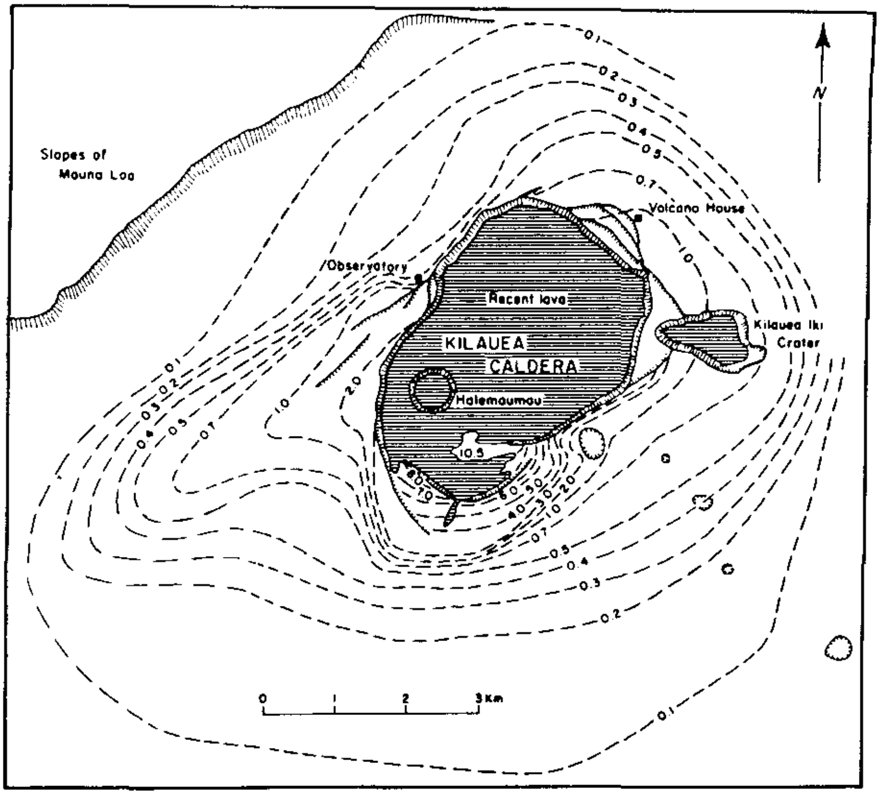

FIGURE 9.6 Isopach map of the approximate thickness (in meters) of the Keanakakoi Formation. Because of internal disconformities, thicknesses shown are generally less than reconstructed stratigraphic thicknesses. Areas shown as recent lava covering the Keanakakoi are those up to 1930; additional areas have been covered by lavas since 1930. Adapted from Stearns and Clark (1930).

(4) With surface subsidence of the summit area accompanying lowering of the magma column, magma from an isolated, shallow storage chamber was able to open a circumferential fracture and erupt as a small lava flow. (5) As magma dropped below the level of the explosions, increasing amounts of water entered the system, and violent steam blasts ensued; only lithic ash and blocks were ejected in these blasts, commonly in pyroclastic surges. The major caldera subsidence that followed destroyed the eruptive conduit and vent system, to end the eruptions. (6) Ultimately, but some time before the visit of William Ellis in 1823, magma returned to surface levels and again erupted high lava fountains in the caldera.

THE UWEKAHUNA ASH

The Uwekahuna Ash is a hydromagmatic deposit exposed near the base of the present caldera cliffs at Kilauea and on or near the surface of some areas on the southeast flank of Mauna Loa. These deposits mantle an irregular buried topography, including a steep slope on the west wall of Kilauea caldera, that may be part of an earlier caldera rim.

A 5-m-thick section of the Uwekahuna Ash along the west wall of Kilauea caldera was described by S. Powers (1916, p. 230) as consisting of ". . . yellow ash with some rock fragments 1-2 inches in diameter, lava droplets, thread-lace scoria, and a few bombs 6 inches in length." This exposure was buried by a lava flow in 1919.

Work in progress by D. Dzurisin, J. P. Lockwood, and T. J. Casadevall (U.S. Geological Survey) indicates that the Uwekahuna Ash, which is comparable to or greater in volume and extent to the Keanakakoi Formation, was formed by similar explosive eruptions. They recognize a basal deposit of lithic blocks and lapilli stained pink to dull red by an oxidized vitric matrix. This basal layer is overlain by fine-bedded vitric ash and dust with accretionary lapilli layers, followed by lithic ash containing scattered lithic blocks and cored lava bombs. Above this lithic ash is another unit of vitric ash and dust containing dense lithic and black glass fragments, followed by a coarser unit of lithic blocks mixed with some pumice and glassy-lava drops and scoria. The uppermost unit is dominantly pumice and glass fragments containing some lithic ash and blocks. Lateral variations in the stratigraphy, and internal cross-stratification and unconformities, indicate a pyroclastic-surge origin for parts of the Uwekahuna Ash.

A zone of 2.4 m of pyroclastic material at a depth of 34 m in a drill hole south of Halemaumau may be part of the Uwekahuna Ash.

Radiocarbon dates on charcoal from overlying and underlying flows, and on charcoal from the lower part of the Uwekahuna Ash near the town of Volcano, indicate an approximate ^{14}C age of 1500 yr for this episode of explosive hydromagmatic eruptions (Kelley *et al.*, 1979; J. P. Lockwood, U.S. Geological Survey, personal communication, 1982).

At two exposures of the Uwekahuna Ash—one in a roadcut near the town of Volcano and the other in a cesspool on the

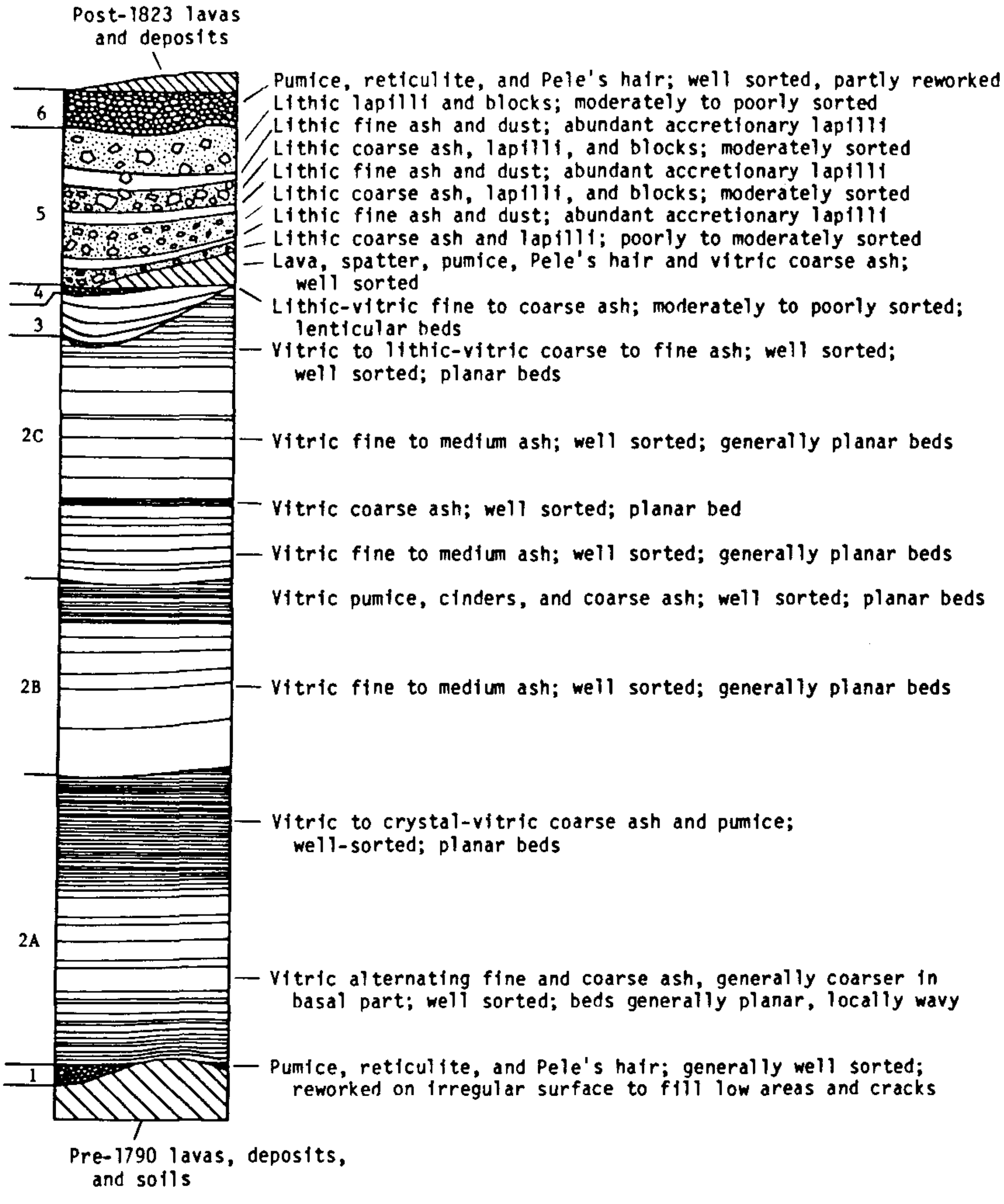

FIGURE 9.7 Idealized stratigraphic section of the Keanakakoi Formation.

southeast flank of Mauna Loa, 7 km west of Halemaumau Crater—are similar pyroclastic deposits, with an aggregate thickness of about 1 m, which immediately underlie the Uwekahuna. Oxidized layers in these deposits suggest, but do not prove, that they represent two or three episodes of explosive hydromagmatic eruptions. Carbonized material from the uppermost of these units beneath the Uwekahuna Ash near the town of Volcano yields a ^{14}C age of about 2100 yr. In both these exposures the relatively unaltered pyroclastic deposits that underlie the Uwekahuna Ash clearly overlie the deeply weathered, more indurated pyroclastic material normally identified as the Pahala Ash.

THE PAHALA ASH

About 32 km southwest of Kilauea caldera is the town of Pahala. The rich agricultural soil in this area is developed on a volcanic-ash section, as much as 15 m thick (see Figure 9.8). The Pahala Ash in the area is apparently the partially reworked accumulation of several pyroclastic eruptions of Kilauea, deposited on old Mauna Loa lavas. Much of the Pahala ash has been modified by weathering and by wind and water reworking during its long period of accumulation, and its original character is difficult to decipher. Stearns and Clark (1930), Wentworth (1938), and Stearns and Macdonald (1946) concluded that most of the Pahala Ash is of lava-fountain origin but allowed the possibility of an explosive hydromagmatic origin. Stone (1926) and Fraser (1960) preferred hydromagmatic eruptions as the major source; we agree with their interpretation. Physical evidence for hydromagmatic origin includes accretionary lapilli and some lithic fragments as well as the predominant vitric ash, much of which consists of angular fragments like those of hydromagmatic deposits rather than of the Pele's hair and pumice glass shards typical of distal lava-fountain deposits.

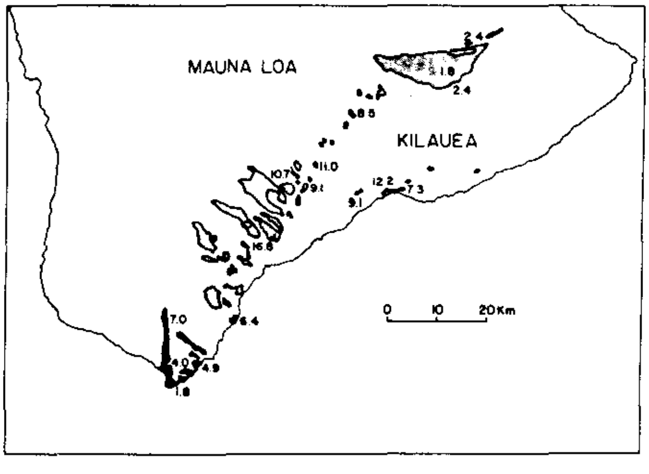

FIGURE 9.8 Exposures of the Pahala Ash in south half of Island of Hawaii. Thicknesses in meters. Deposits northeast of Kilauea's summit region may have originated mainly from Mauna Kea Volcano, situated in the northern part of the island; other exposures probably originated mainly from Kilauea Volcano. Adapted from Stearns and Macdonald (1946).

The age of the Pahala Ash ranges from approximately 10,000 to 25,000 yr, on the basis of radiocarbon dates on charcoal from beneath lavas within or overlying all or part of the ash sequence (Kelley *et al.*, 1979; J. P. Lockwood and P. W. Lipman, U.S. Geological Survey, personal communication, 1981). Although a firm interpretation is not possible at this stage of investigation, it appears probable that the Pahala Ash south of Kilauea caldera includes the accumulated and reworked deposits of several major explosive hydromagmatic eruptions from Kilauea caldera. If this interpretation is correct, the eruptions that resulted in the Pahala Ash may have deposited material at distances considerably farther than did the eruptions responsible for the Keanakakoi Formation and Uwekahuna Ash.

PYROCLASTICS IN THE HILINA FORMATION

The previously named Hilina Volcanic Series, now renamed Hilina Formation, is an approximately 250-m-thick sequence of Kilauea lava flows and pyroclastic deposits that occurs beneath the Pahala Ash. These rocks form the oldest exposures of Kilauea's eruptive products, and their age is estimated by Easton and Garcia (1980) to range from about 25,000 to as much as 100,000 yr. The best exposures of the Hilina are on the fault escarpments of the Hilina Pali and on the faulted and wave-cut escarpment of Puu Kapukapu, 12 to 15 km south of Kilauea caldera.

Pyroclastic deposits are common in the Hilina Formation exposures. Easton (1978) mapped 8 horizons on the Hilina Pali, and 9 layers of ash beds are visible on the 300-m-high cliffs at Puu Kapukapu. The major pyroclastic unit capping the summit of Puu Kapukapu is the Pahala Ash, which is 12 m thick at that location.

Below the Pahala Ash, Easton and Garcia (1980) named several pyroclastic units in the Hilina Formation, which are separated by major sequences of lava flows. From youngest to oldest these pyroclastic units are as follows: (1) the Mo'o Member, a 50- to 250-cm-thick deposit of yellow-brown ash and palagonite (hydrated basaltic glass) containing some accretionary lapilli; (2) the Pohakaa Member, comprising as many as 6 pyroclastic layers of vitric ash, palagonite, and soil ranging in thickness from 1 to 4 m, separated by intercalated lava flows—some layers contain abundant lithic and crystal fragments and appear to be pyroclastic-surge deposits; (3) the Kahele Member, a 10- to 125-cm-thick deposit of crudely bedded red clay containing some palagonite and, in one exposure, a layer of glassy vesicular scoria and glass fragments; and (4) the Halape Member, a 10- to 50-cm-thick deposit of poorly bedded clay and palagonite. The age of the Pohakaa ash layers and intercalated flows is estimated at 40,000 to 50,000 yr.

The Hilina Formation in the areas of exposure consists of about 95 percent flows and 5 percent pyroclastic deposits (Easton and Garcia, 1980). This relatively high proportion of pyroclastics to flows, compared with Hawaiian subaerial volcanic products in general, may be due in part to the semidownwind location of exposures of the Hilina Formation in relation to

Kilauea's summit. Although there is no unequivocal evidence that the pyroclastic deposits within the Hilina Formation are of explosive hydromagmatic origin, the thickness of the layers and the occurrence of surge-bedded layers and locally abundant lithic material suggest that they are. Furthermore, there is no direct evidence that they are not hydromagmatic.

Although the exposed lavas and pyroclastic deposits of Kilauea are no older than about 100,000 yr, the general subsidence of the island of Hawaii implies that subaerial lavas and pyroclastic deposits probably continue well below sea level.

DISCUSSION

The general similarity of the older volcanic products of Kilauea to its eruptive products of the past 200 yr suggests that the 1790 Keanakakoi explosive eruption was not a unique event. It is difficult, however, to establish a recurrence interval with any precision. The total number of preserved and exposed pyroclastic deposits is about 15, but the Pahala Ash and some of the pyroclastic units within the Hilina Formation probably result from the accumulation of several episodes of major explosive eruptions. During accumulation of the Pahala Ash, few lava flows moved down the south slopes of Kilauea over a time span of about 15,000 yr. Perhaps flows were largely contained within a major summit caldera during this interval, or perhaps most of the eruptive activity was along the east rift zone at Kilauea. R. M. Easton (U.S. Geological Survey, personal communication, 1981) noted that the Pohakaa deposits, which resemble the Pahala Ash, were deposited over a period of 10,000 yr during which few flows reached the south flank of Kilauea.

Allowing for the multiple ash units, such as the Pahala Ash and the Pohakaa Member, the total number of major explosive hydromagmatic eruptions indicated by the exposed pyroclastic deposits is about 25 during the past 100,000 yr (see Table 9.1). Only the largest or most recent explosive eruptions are represented by these exposed pyroclastic deposits; materials from older explosive eruptions comparable in size to the Keanakakoi and Uwekahuna events are largely or completely buried by the copious lava flows from the summit and upper parts of the rift zones of Kilauea. In the deeper part of the drill hole south of Halemaumau (Zablocki *et al.*, 1974, 1976; Keller *et al.*, 1979), there are many intervals with larger than normal hole diameter; these intervals may have been formed by washing out of softer pyroclastic layers during drilling. The incomplete coring, however, and the contamination of drill cuttings with pyroclastic material from sections higher up in the well preclude any firm interpretation of the total number of pyroclastic units penetrated by the drill hole.

The number of buried and completely unexposed Kilauea pyroclastic deposits is probably at least equal to that of the exposed deposits (25). Therefore, a reasonable but not unequivocal estimate of the total number of explosive eruptions of Kilauea as large or larger than the 1790 Keanakakoi eruption is about 50 in the last 100,000 yr. On the basis of this estimate, major explosive eruptions have probably recurred from Kilauea's summit on an average of about once every 2000 yr during the past 100,000 yr or more. We have no reason to assume that this 2000-yr interval is even approximately periodic; very large explosive eruptions may have recurred more frequently during deposition of the Pahala Ash and the Pohakaa ash beds and less frequently before and since. Minor explosive

TABLE 9.1 Data on Exposed Pyroclastic Deposits of Apparent Explosive Origin from Kilauea's Summit Region[a]

Name	Number of Separate Deposits	Age (years)	Observed Maximum Thickness (meters)	Approximate Area in km^2[b]	Approximate Volume in m^3[b]
1924	1	58	trace	10	10^5
Keanakakoi Formation	1	192	11	300	10^6-10^9
Uwekahuna Ash	1 or 2	~ 1,500	5	300?	unknown
Unnamed	2 or 3	≳ 2,100	1	300?	unknown
Pahala Ash	5 to 10?	~10,000 to 25,000	16[c]	1000?	unknown
Mo'o Member[d]	1	~30,000	2.5	1000?	unknown
Pohakaa Member[d]	6	~40,000 to 50,000?	15[c]	1000?	unknown
Kahele Member[d]	1	~60,000?	1	1000?	unknown
Halape Member[d]	1	~70,000?	0.5	1000?	unknown

[a] Data from S. Powers (1916), Finch and Jaggar (1924), Stearns and Clark (1930), Easton (1978), and D. Dzurisin and J. P. Lockwood (U.S. Geological Survey, written communication, 1982).

[b] Area and volume estimates are for deposits on land.

[c] Cumulative thickness of pyroclastic layers.

[d] Nomenclature of Easton and Garcia (1980).

eruptions similar to the 1924 event, which were probably more frequent than the major explosive eruptions, are not evident in the stratigraphic record.

Although most major explosive eruptions at Kilauea appear to have originated in the summit area, some evidence for smaller explosive eruptions exists near sea level in the rift zones. Kapoho Cone and the Puulena craters along the lower east rift have associated hydromagmatic deposits, and part of the 1960 Kapoho eruption in this same area was characterized by nearly explosive ejection of black clouds of condensed steam laden with lithic ash. One adjacent segment of the same 1960 fracture that was erupting steam blasts was erupting incandescent lava fountains. This unusual eruption has been attributed either to contact of subsurface water with the intruding dike or to explosive boiling of an existing shallow hydrothermal reservoir through an extension of the eruption fracture.

The general cause of hydromagmatic eruptions at Kilauea appears to be closely connected with explosive boiling of subsurface water. The low gas content of Hawaiian magmas—about 0.5 percent by weight (Moore, 1970)—and their relatively low viscosity indicate that purely magmatic eruptions of pyroclastic material probably do not exceed in violence the spectacular but generally harmless ejection of incandescent lava fountains. Steam-blast eruptions from the summit area, such as the one in 1924, seem best explained by a sudden lowering of the magma column beneath Kilauea, which would cause intermittent explosions of steam from movement of subsurface water into the zone evacuated by the shallow magma. A larger version of this same process probably caused the 1790 Keanakakoi, the 1500 yr ago Uwekahuna, and perhaps earlier explosive eruptions. It is likely that sudden flashing of large hydrothermal systems beneath the summit of Kilauea also contributed to the major explosive eruptions. In all cases a sudden lowering of the magma column by a far-downrift intrusion or eruption probably triggered the instability needed to initiate the sudden conversion of thermal into mechanical energy.

Explosive release of superheated H_2O or CO_2 seems to be the fundamental mechanism of all explosive volcanic eruptions (see Chapter 12). Given the complexity of both magmatic and hydrologic systems, that fundamental mechanism can take many forms.

VOLCANIC HAZARDS IN HAWAII

The old proverb that "familiarity breeds contempt" is certainly true with regard to volcanic hazards in Hawaii. The historical record of eruptions covers only the last 160 yr, a period that has been one of many spectacular but relatively harmless effusive eruptions of lava fountains and flows. Only one small explosive eruption in 1924, more curious than dangerous, has occurred during this period. In contrast, the geologic record indicates that major explosive eruptions do occur, the latest one less than 200 yr ago. If the Hawaiian Volcano Observatory had been at its present location in 1790, it would have been destroyed. Our present concept of the onsets of these explosive eruptions suggests that they can be identified in time to evacuate the danger area. So says the theory; in practice, we must remember to try to become more familiar with our subject without becoming contemptuous.

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