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CURRENT PROBLEMS IN RESEARCH

How Volcanoes Grow

Geology, geochemistry, and geophysics disclose the constitution and eruption mechanism of Hawaiian volcanoes.

J. P. Eaton and K. J. Murata

Summarizing the state of volcanological knowledge in 1952, Howel Williams (1) observed: "Much has been learned about the distribution, internal structure, and products of volcanoes, but pitifully little about the causes and mechanism of eruption." To remedy this deficiency he called for more intensive, continuous observations of well-chosen active volcanoes, with geophysics and geochemistry supplementing the traditional tools of geology. Current investigations of the U.S. Geological Survey's Hawaiian Volcano Observatory are much like those envisaged by Williams, and they are yielding an exciting new insight into the internal workings of volcanoes.

No volcano has influenced our conception of the vital processes of active volcanism more than Kilauea. Geologists drawn to Hawaii by travelers' accounts of fantastic activity at this volcano were so impressed by what they saw that they framed whole theories of volcanic action around it. Even though its prime attraction, the renowned lava lake that circulated almost continuously within its great summit caldera for at least a century, was destroyed in 1924, Kilauea and its giant neighbor, Mauna Loa, have remained very active, one or the other having erupted about once in two years since that date. The comparative simplicity, the large size, and the frequent, voluminous, nonviolent eruptions of Hawaiian volcanoes make them ideally suited to illustrate the fundamental processes of volcanism. Here these processes can be studied safely and conveniently, in isolation from the great complications of structure and contaminating rocks that render most volcanoes so baffling.

In 1823 William Ellis (2) found within Kilauea caldera "an immense gulf, in the form of a crescent, upwards of two miles in length, about a mile across, and apparently 800 feet deep. The bottom was filled with lava, and the southwest and northern parts of it were one vast flood of liquid fire in a state of terrific ebullition. . . ." Through the century that followed, visitors to Kilauea recorded successive infillings and collapses of Ellis' "gulf," as lava poured up through conduits beneath its floor and accumulated, crusted over, and partially congealed within it, later to be withdrawn into the depths or poured out through great fissures in the flank of the volcano.

Continuous observation of the lava lake began with the establishment of the Hawaiian Volcano Observatory on the rim of Kilauea caldera in 1912 (3). Detailed measurements of the height, size, and shape of the liquid surface of the lake (Fig. 1) as well as occasional measurements of its temperature and chemical analyses of the gases escaping from it were made from 1912 until the lake was destroyed by the eruption of 1924. The usefulness of seismograph and tiltmeter observations for deciphering unseen subterranean changes in the volcano was also demonstrated during these years when Jaggar (4) and his collaborators were collecting a wealth of data on Kilauea's baffling lava lake.

Setting and Geology

The geologic mapping of the Hawaiian Islands, carried out jointly by the U.S. Geological Survey and the Hawaii Division of Hydrography during the 1930's and 1940's, opened new dimensions in the study of Hawaiian volcanoes (5). A thorough investigation of volcanic processes necessarily awaited an adequate geological description of the volcanoes. By mapping structures visible at the surface, by examining the shallow interior of the volcanoes in the sections exposed by faulting and erosion, and by studying very carefully the nature, variation, and distribution of the lavas composing the great Hawaiian shields, geologists have sketched the framework of the volcanoes' structure and history.

Mauna Loa and Kilauea form the southern part of the island of Hawaii at the southeastern end of the Hawaiian Ridge, a great range of volcanic mountains rising from the floor of the Pacific Ocean and stretching 1600 miles northwestward from Hawaii to Kure Island (Fig. 2, inset). Volcanism appears to have progressed from the northwest toward the southeast along the ridge. Wave-wrecked volcanoes of the northwestern half of the ridge approach the surface as shoals or support low-lying coral atolls. Farther southeastward, remnants of volcanic rock rising in small islands still withstand the vanquishing sea. Only along the southeastern quarter of the ridge do the great volcanoes stand high above the sea, where they form the large inhabited islands of the Hawaiian group. Even here the evidence for migration of activity southeastward is strong, for volcanoes in the northwestern part of this group are deeply dis-

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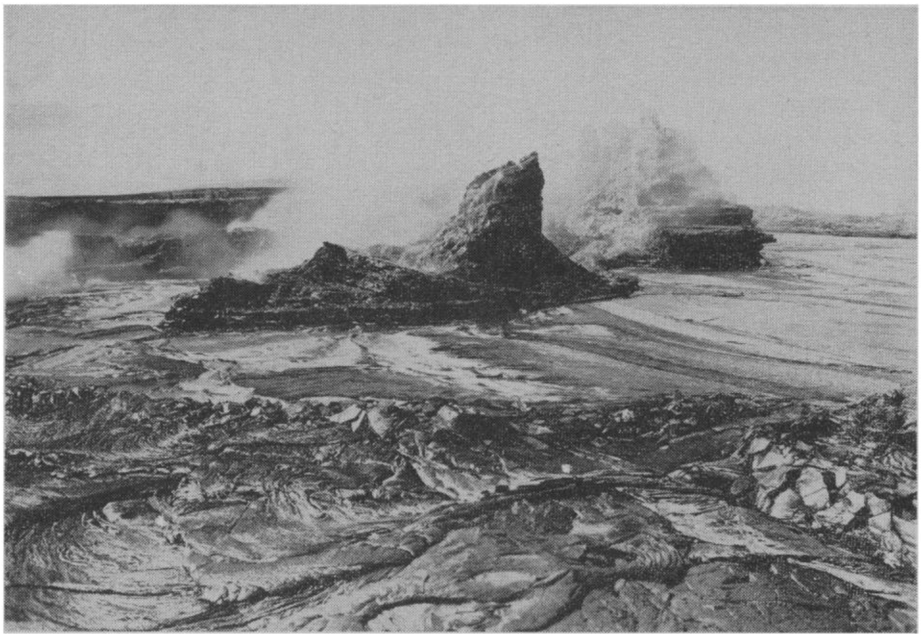

Fig. 1. Lava lake in Halemaumau, 23 January 1918. Floating islands of congealed lava are surrounded by molten lava. In the foreground, an overflow from the lake has chilled to pahoehoe lava. In the background can be seen the wall of Kilauea caldera and the gentle slopes of the southwest rift zone of Mauna Loa.

sected, while Mauna Loa and Kilauea, still in vigorous activity at the southeastern end, are hardly marred by erosion.

From its great length and narrow width it is apparent that the Hawaiian Ridge marks the course of a major fracture in the earth's crust through which lava has poured at different centers and different times to build the volcanoes that form it. The ridge rises from the axis of a broad swell on the ocean floor and is flanked, near its southeastern end, by an ocean deep that runs down its northeast side and hooks around the south end of the island of Hawaii (*6*).

Volcanoes of the ridge are built upon the simplest known section of the earth's crust (the Pacific basin is floored only by approximately 5 kilometers of basalt, covered by about 1 kilometer of sediments and resting directly upon the earth's mantle), and they are separated from other tectonically active regions by at least 2000 miles of seismically quiet ocean floor. Thus, in magnificent isolation, volcanic processes originating in the mantle raise the giant Hawaiian mountains to heights approaching 6 miles (10 kilometers) above the ocean floor.

Hawaiian volcanoes bear little resemblance to steep-sided, central-type composite volcanoes like Fujiyama, in Japan. Rather, they are shaped like a warrior's shield, with a broad domical summit and gently sloping sides, and they attain enormous size. Mauna Loa rises more than 30,000 feet above its base on the ocean floor and has a volume of about 10,000 cubic miles. Even at sea level, about 16,000 feet above its base, it is more than 70 miles long. The volcanoes are built almost entirely of thin flows of fluid basaltic lava, poured out chiefly from long fissures concentrated in relatively narrow rift zones.

On surface evidence, rift zones appear to determine the location and shape of the volcanoes. Most commonly, each volcano has two principal rift zones meeting in the summit region at angles of 130° to 180°. The vertex of this angle usually points away from the unbuttressed flank of the Hawaiian ridge adjacent to the volcano. Rift zones are predominantly either almost parallel or more or less perpendicular to the axis of the ridge, but just how these zones are related to the fundamental fracture beneath the ridge is not clear.

The summits of several volcanoes are indented by calderas formed by collapse of the surface rocks when support was withdrawn from below. Kilauea caldera, subcircular in plan and eccentrically set in the summit of the volcano, is 2½ miles long and 2 miles wide. Its floor, a low dome of lava flows that slope outward from Halemaumau, site of the old lava lake and principal vent of Kilauea, is almost 500 feet below the caldera rim on the northwest but level with the rim on the south. The present floor is about 600 feet higher than that depicted in a sketch by Malden (*7*) in 1825.

Along some rift zones, especially near their upper ends, are found other prominent collapse craters. The variation in size as well as the nature of pit craters, as these features are called, is well demonstrated by the "Chain of Craters" along the upper section of Kilauea's east rift zone. Here, pit craters range from the "Devils Throat," formed by a single collapse that left a pit 50 feet across and 250 feet deep with an overhanging lip, to the giant Makaopuhi (Fig. 3), the result of at least two episodes of collapse and two of flooding by lava that formed a gulf almost a mile across and 900 feet deep.

Prominent lateral faults, some of them submarine, flank several of the volcanoes. Notable among these are the Honuapo-Kaoiki fault system, which separates Kilauea from Mauna Loa and extends from just north of Kilauea caldera southwestward to the sea near Honuapo, and the Hilina fault system (Fig. 4), which drops a 30-mile-long segment of Kilauea's south flank abruptly toward the sea. Although the absolute movement on these faults cannot be specified, it is distinctly possible that the wholesale uplift of the Hawaiian Ridge along such faults has been responsible for a significant fraction of its height.

Hawaiian lava flows, both the smooth, glassy-skinned pahoehoe and the indescribably rough, clinkery-surfaced aa, are intricately broken by the processes that form them. The volcanic edifices built of these shattered flows are mammoth piles of rubble, shored up beneath the rift zones by thousands of thin, nearly vertical dikes of strong, dense basalt. Their bulk density, estimated from measurements of gravity across the Hawaiian Ridge (*8*) and in deep wells on the island of Hawaii, is no greater than 2.3 grams per cubic centimeter, significantly less than the density, about 2.8 grams per cubic centimeter, of an unvesiculated column of basaltic magma at depth.

To judge from the historic and geologically recent behavior of Mauna Loa and Kilauea, Hawaiian volcanoes grow almost to their full size quite rapidly. Intervals between eruptions are only a few years or decades, and the flanks of the volcanoes are blanketed by new flows so frequently that erosion makes little headway. The lavas forming these primitive shields belong to the "tholeiitic" basalt series and differ primarily only in their content of olivine crystals. Although surging fountains of gas-inflated lava are often propelled hundreds of feet into the air by gas released from the lava as it approaches the surface within the vent fissure, these eruptions show little real explosivity and build only small cinder cones, spatter cones, and spatter ramparts around their vents.

After the volcanoes reach maturity the interval between eruptions increases, perhaps to a century or more, erosion begins to predominate over growth, and subtle changes appear in the chemistry and mineralogy of the lavas, which pass over into the alkalic basalt series. Eruptions become more explosive, building larger cinder cones around the vents.

Even after Hawaiian volcanoes are overcome by old age and are transfigured by profound erosion, occasional renewals of volcanism pour out additional lavas of the alkalic basalt series or even more highly differentiated lavas such as the felspathoid-bearing flows of Oahu and Kauai.

The outstanding questions of the origin of magma, the mechanism of eruption, and the differentiation of magma are strongly interdependent, and any answer proposed for one must be compatible with data for the others. The mechanism of eruption plays a central role. It must account for how

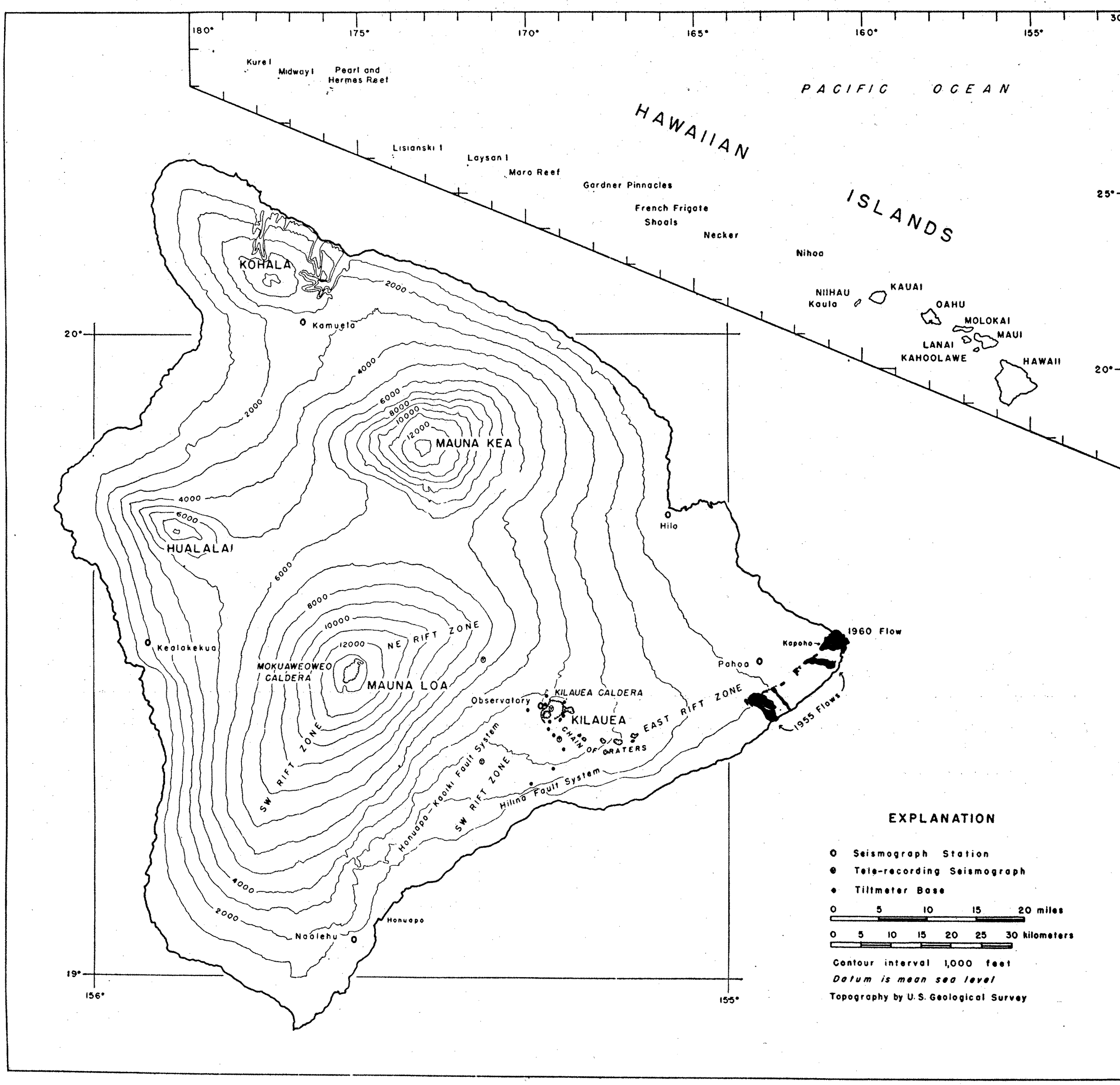

Fig. 2. Map of Hawaii showing seismograph stations, tiltmeter bases, and the Kilauea lava flows of 1955 and 1960. The inset shows the entire chain, stretching 1600 miles northwestward from Hawaii to Kure Island.

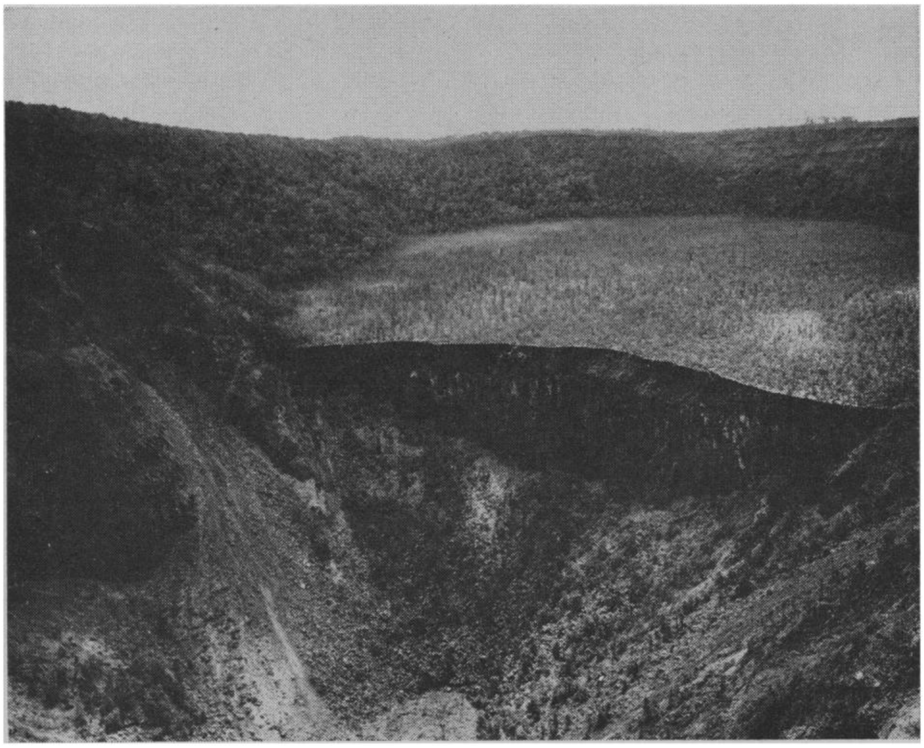

Fig. 3. Makaopuhi viewed from the west. A prehistoric lava pond, in the distance, was exposed by a later collapse in the foreground. The small pond of lava at the bottom of the deeper pit, 900 feet below the present rim, was poured into Makaopuhi in 1922. [R. T. Haugen, National Park Service]

and by what path magma is brought to the surface, why the volcanoes erupt intermittently, and how volcanic structures such as rift zones, pit craters, and calderas are produced, and it must provide the intratelluric environment necessary for the differentiation observed in the lavas.

Current Investigations

To extend the physical description of the volcanoes to depth and to obtain information on the active processes within them, the methods of geology must be supplemented by those of geophysics and geochemistry. During the last few years the staff of the U.S. Geological Survey Volcano Observatory in Hawaii has been augmented, and its facilities have been expanded and modernized to equip it for the necessary multidiscipline attack on the problems of Hawaiian volcanism.

A modernized seismograph network is giving us a better understanding of the internal structure of the volcanoes and is revealing some surprising evidence on processes within them. New instruments for measuring slight deformations of the earth's surface are providing information on the underground movement and accumulation of magma. Work at the Survey's recently constructed Geochemical Laboratory is helping to unravel the mysteries of origin, underground history, and petrographic variations of Hawaiian lavas through a systematic, detailed study of the chemistry and petrology of the lavas and of the chemistry of the gases given off by the volcanoes during and between eruptions.

Evidence from Geophysics

A variety of events within the volcanoes set up characteristic disturbances which are transmitted as elastic vibrations to the surface of the earth through the rocks composing the volcanoes and the crust and mantle of the earth beneath. These fleeting seismic pulsations carry vital information not only on the time, location, intensity, and nature of the events from which they spring, but also on the geologic structure and physical properties of the rocks through which they pass en route to the surface.

To capture these important data, a network of very sensitive seismographs is being developed in the Hawaiian Islands (Fig. 2). At the heart of the system four vertical-component seismometers, located in critical positions within a 15-kilometer radius of the observatory at the summit of Kilauea, transmit signals over telephone wires to the observatory, where four pens trace visible records of the motion of the ground at the seismometers. Seismographs in five other stations on the perimeter of the island of Hawaii provide critical additional data needed to locate earthquakes originating in and beneath the volcanoes, and seismographs in one station on Maui and one on Oahu extend the network to the distances required to permit the delineation of the structure of the crust under the Hawaiian Ridge.

Hawaii has earthquakes because it has volcanoes. In terms of numbers, practically all the earthquakes in the Hawaiian area occur in or beneath the active volcanoes and are intimately associated with eruptions. A significant few, however, including most of Hawaii's largest, originate on lateral faults at some distance from the calderas and rift zones that give rise to so many quakes during eruptions. Although some earthquakes along the lateral faults originate at depths as great as 30 kilometers, most of them are relatively shallow. They appear to mark gross readjustments in the rocky basement in response to the slow growth of the volcanoes and to the internal forces that build them.

Findings on the relation between travel time and distance for the strong seismic waves generated by large earthquakes on Hawaii and transmitted through the Hawaiian Ridge or refracted through the crust and mantle below to the most distant seismographs of the network are the data from which we can compute the "structure" of the earth beneath the volcanoes. Conventional interpretation of the travel-time curves indicates that there is a layered structure which represents a broad approximation of conditions along the Hawaiian Ridge. The implication of flat-lying, smooth contacts between discrete rock units should not be taken literally, especially for the portion of the structure lying above the level of the ocean floor surrounding the islands.

The near-surface speed of the longitudinal wave, *P*, is surprisingly low, only about 3 km/sec, and testifies to the loose, rubbly nature of the flows composing the shields. From a moderate depth below the surface (here taken as about sea level) to a depth of several kilometers below sea level, the speed of P is about 4 km/sec. Below a depth of 3 kilometers the speed of P jumps abruptly to about 5.25 km/sec. The travel-time curves suggest that the speed of P increases still more, perhaps by a slow transition rather than an abrupt increase, to about 6.8 km/sec in the crust above the mantle. At a depth of about 14 kilometers the speed of P jumps to 8.25 km/sec, marking the top of the earth's mantle at the Mohorovičić discontinuity. These data are plotted in Fig. 5 with those obtained by Raitt (9) from a seaborne seismic profile off the coast of Hawaii. Of special interest is the close correspondence in the depth to the Mohorovičić discontinuity beneath the ocean and beneath the Hawaiian Ridge. It appears that the crust under Hawaii has been only slightly depressed by the enormous volcanoes built upon it.

An accurate knowledge of just where earthquakes originate within the volcanoes is very important to our understanding of internal structure. Earthquakes do not occur at random but are concentrated in zones or along structures undergoing strain. Thus, from the earthquakes that occur beneath the Honuapo-Kaoiki fault system, which separates the southwest flank of Kilauea from Mauna Loa, we know that the system extends to a depth of at least 15 kilometers and that it is still very active. Likewise, earthquakes originate from near the surface to depths as great as 30 kilometers along the Hilina fault system just south of Kilauea caldera, but farther east along this fault system earthquakes originating from depths greater than 10 kilometers are rare. Since about 1955, when a seismograph network capable of making reasonably accurate focal-point determinations was developed, the deepest earthquakes in the Hawaiian area have been recorded from a zone approaching a depth of 60 kilometers beneath the summit of Kilauea. In addition, thousands of quakes originate at shallow depths in the vicinity of Kilauea caldera when the volcano is swelling or shrinking in response to the movement of magma below. During the last two major eruptive cycles the east rift zone of Kilauea has produced only very shallow earthquakes, except very close to the caldera, and probably does not extend to a depth lower than the ocean floor.

Insight into processes at work in the volcanoes can also be gained from the nature, sequence, or association of disturbances recorded on the seismo-

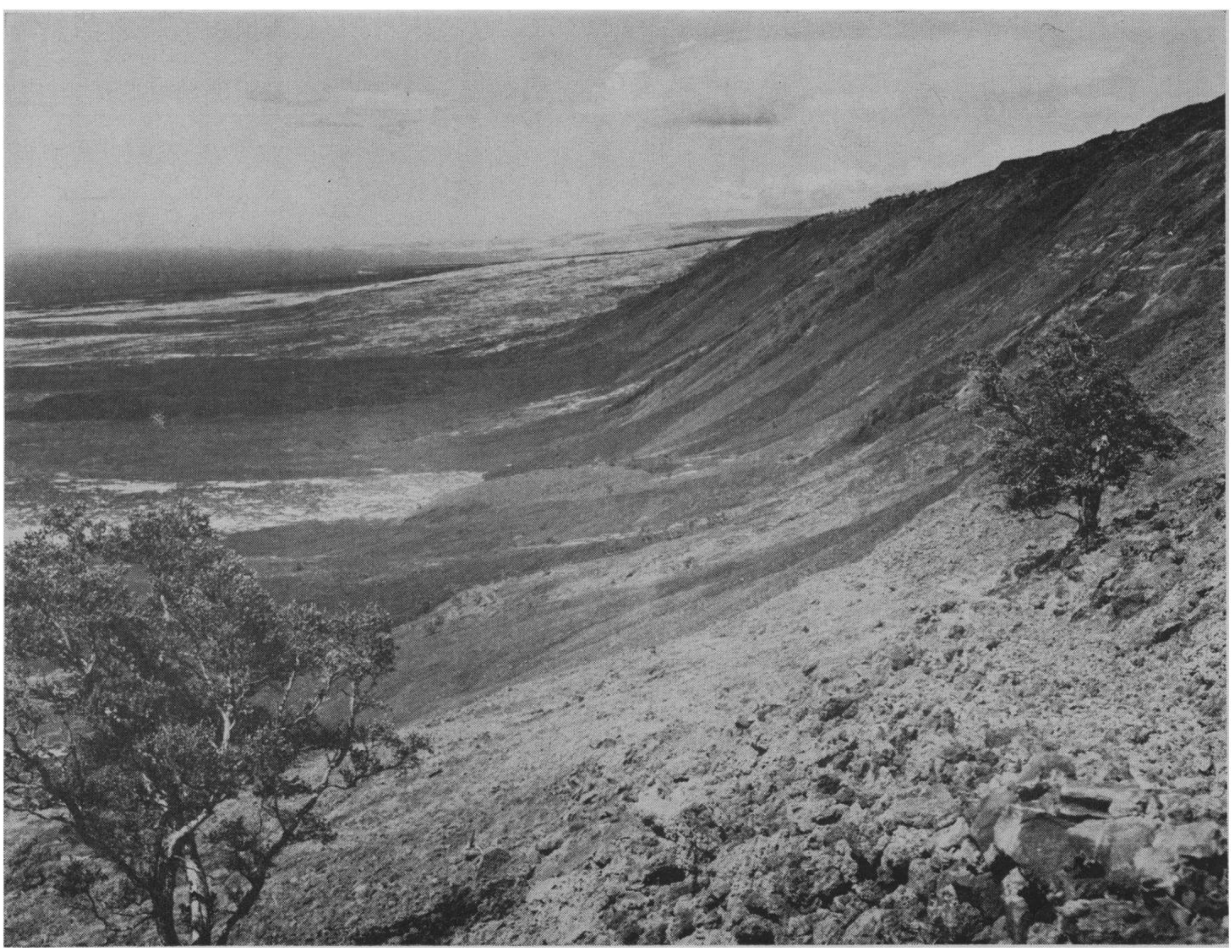

Fig. 4. Hilina Pali fault scarp. This scarp, 1500 feet high, has been almost completely mantled by recent prehistoric lava flows. View is toward the southwest.

graphs. Some of these disturbances are quite unearthquake-like and are apparently generated only by active volcanoes. When lava is pouring out at the surface during an eruption the entire region around the vent rocks gently to and fro as long as the vent is active. From seismographic evidence we know that this disturbance, called harmonic tremor from the sinusoidal nature of its seismic record, is generated near the earth's surface, probably by the rapid flow of magma through the feeding conduits. Because harmonic tremor rarely occurs when no eruption is in progress, its occurrence is excellent evidence that lava is streaming through conduits underground.

Great swarms of small earthquakes accompany several different processes in the volcano. Unlike a large tectonic earthquake and its aftershocks, where one large quake is followed by many smaller ones, the earthquakes in these swarms are uniformly small. The swarm usually begins slowly, rises to a maximum (in both average size and frequency of earthquakes), and then dies off slowly or abruptly, according to the nature of the process generating the earthquakes. Moderate swarms of tiny, sharp, highly localized earthquakes accompany the extension of dikes toward the surface before eruptions. Such swarms cease abruptly when lava pours out at the surface. More impressive swarms of larger, shallow quakes scattered through the summit of Kilauea attend the rapid subsidence of the caldera and its environs when lava drains out through the rift zone of the volcano during flank eruptions. These swarms begin and end gradually.

Occasionally great swarms of tiny-to-moderate, sharp earthquakes, totaling several thousand during the few days they last, emanate from depths between 45 and 60 kilometers beneath the summit of Kilauea. These are the deepest quakes that occur in Hawaii, and they bear no immediate, obvious relation to events closer to the surface. Usually they are accompanied by many hours of continuous, somewhat irregular tremor (spasmodic tremor) of weak-to-moderate intensity. The zone from which these disturbances stem is deep within the earth's mantle, three to four times deeper than the Mohorovičić discontinuity under Kilauea. Such activity appears to mark the zone from which magma is collected and fed into the system of conduits leading to the heart of Kilauea. If the magma rises from greater depths, this is at least the deepest zone in which its upward migration is marked by detectable seismic disturbances.

Whether Mauna Loa has a separate source of such activity beneath its summit we cannot yet say. No such source has been detected in the last five years, since sensitive seismographs have been in operation on Hawaii, but neither has Mauna Loa shown any sign of unrest during this interval.

Although seismic disturbances disclose what is happening within the volcano and when and where these changes are occurring, they tell us very

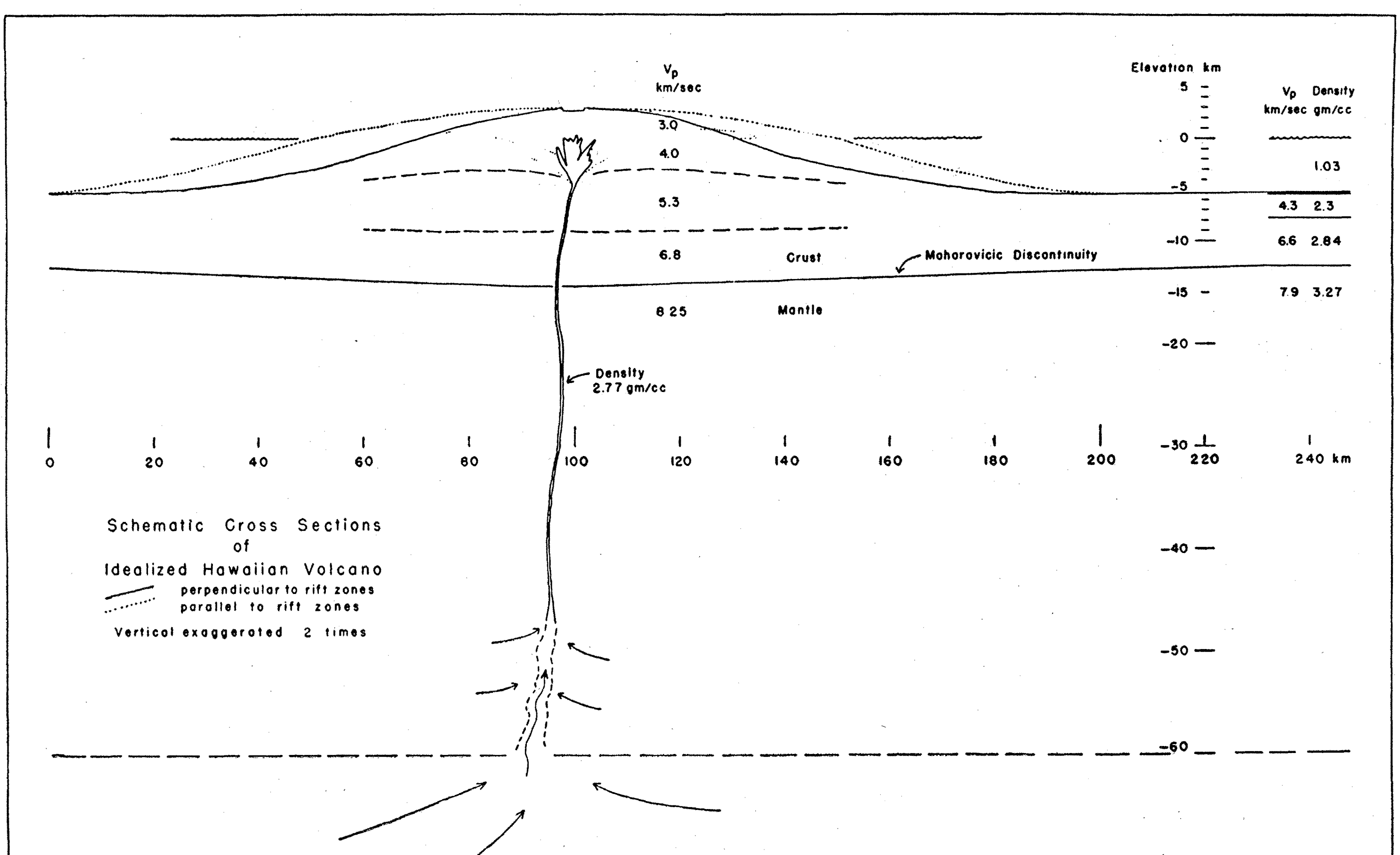

Fig. 5. Schematic cross sections of an idealized Hawaiian volcano. Magma from a source about 60 kilometers deep streams up through permanently open conduits and collects in a shallow reservoir beneath the caldera. Occasional discharge of lava from the shallow reservoir through dikes that split to the surface constitute eruptions. Note the elongation of the volcano along the rift zones and the relatively slight depression of the Mohorovičić discontinuity beneath the volcano. Data for the oceanic cross section on the right are from Raitt (*9*) and Worzel and Shurbet (*13*).

little about the likelihood that a particular disturbance will culminate in an eruption. Geophysical measurements of another sort, the measurement of tilting of the ground surface around the summit of the volcano, provide more direct evidence on the readiness of the volcano to erupt. As lava wells up within the volcano the surface of the ground above bulges upward and the flanks of the bulge tilt outward, and when an eruption pours the lava out at the summit or on the flank of the volcano, the ground above the emptying reservoir subsides.

Before an eruption these changes are subtle and slow, and extreme care is required to detect them. Conventional tiltmeters are sufficiently sensitive, but they are so strongly influenced by accidental local vagaries of earth structure and weather that their records are unreliable. To provide high reliability as well as high sensitivity and to make it possible to set up many low-cost tilt-measuring stations, an unconventional tiltmeter employing permanent tilt bases and an ultrasensitive, portable, water-tube leveling system has been developed. Successive relevelings at a tilt base, which consists of three permanent piers set in the ground at the vertices of an equilateral triangle 50 meters on a side, can detect tilting of the earth's surface as slight as 1 millimeter in 5 kilometers (*10*).

Case History: Kilauea Eruption, 1959–60

Even while the water-tube leveling system was being refined and tested between November 1957 and August 1958, preliminary readings on an experimental tilt base at Uwekahuna showed that the ground surface was tilting steadily outward from the caldera. By October 1958, measurements at additional tilt bases newly installed in a ring around the caldera revealed that the entire caldera rim was tilting outward. Analysis of tilting around the summit of Kilauea detected by the expanding network of tilt bases between October 1958 and February 1959 indicated that the entire summit region was swelling as magma slowly welled up from the depths and accumulated a few kilometers beneath the south rim of the caldera.

After the occurrence of several moderate earthquakes just southeast of the caldera on 19 February, the swelling stopped, and from May until August the summit of the volcano subsided slowly. Then a great swarm of deep earthquakes and associated tremor from a source about 55 kilometers deep and a few kilometers northeast of the Kilauea caldera kept Hawaiian seismographs in almost constant agitation between the 14th and 19th of August (Fig. 6). Magma moving into conduits beneath Kilauea during this episode made itself felt at the surface shortly, for rapid swelling of the volcano resumed between August and October (Fig. 7, inset *A*).

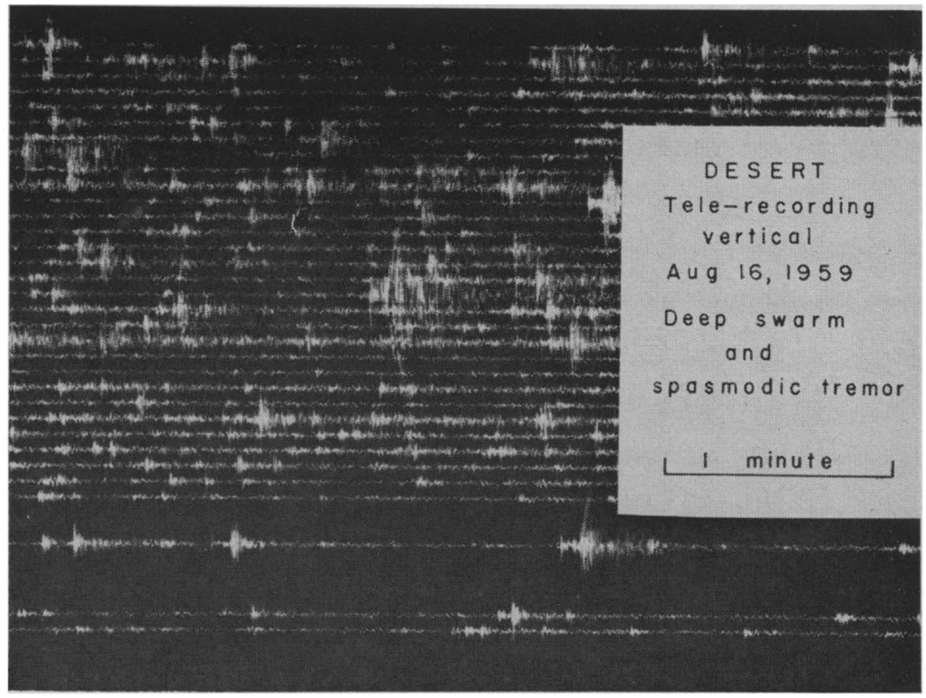

Fig. 6. A swarm of deep earthquakes and spasmodic tremor that originated about 55 kilometers beneath Kilauea caldera on 16 August 1959. Such activity appears to mark the movement of lava into the conduits beneath Kilauea. This seismogram was recorded on smoked paper at the observatory, 14 kilometers from the desert seismometer that detected these disturbances.

In its early stages, swelling of Kilauea took place with little or no seismic accompaniment. Lava rose from the depths and streamed slowly toward the shallow reservoir. At most, occasional intervals of weak harmonic tremor, originating perhaps 5 to 15 kilometers beneath the surface and lasting about half an hour, marked the lava's upward migration.

In the months preceding the 1959 outbreak of Kilauea there was no general increase in seismic activity, as there had been before the 1954 eruption. The first suspicious sign appeared during September 1959, when a series of very shallow, tiny earthquakes began recording on the North Pit seismograph on the northeast rim of Halemaumau. By the first of November, quakes of this swarm exceeded 1000 per day, but they were so small they barely were recorded on other seismographs only one mile away. A hurried remeasurement of tilting at bases around the caldera during the second week of November revealed that dramatic changes were in progress: the summit of Kilauea was swelling at least three times faster than during previous months (Fig. 7, inset *A*). In mid-afternoon on 14 November earthquakes emanating from the caldera suddenly increased about tenfold in number and intensity. At frequent intervals during the next 5 hours the entire summit region shuddered as earthquakes marked the rending of the crust by the eruptive fissure splitting toward the surface. Then, at 8:08 P.M., the lava broke through in a half-mile-long fissure about half-way up the south wall of Kilauea Iki crater, just east of Kilauea caldera. Abruptly the swarm of earthquakes stopped, and seismographs around the caldera began to record the strong harmonic tremor characteristic of lava outpouring from Hawaiian volcanoes (Fig. 8).

During the next 24 hours the erupting fissure gradually shortened until only one fountain remained active. But then the rate of lava outpouring, which had decreased as the erupting fissure shortened, began to increase again, and it continued to increase steadily until the fountain died out suddenly on 21 November. The 40 million cubic yards of lava poured into Kilauea Iki crater filled it to a depth of 335 feet, slightly above the level of the vent.

Seismographs and tiltmeters warned that the eruption was not over. Feeble harmonic tremor that persisted after the fountain died was soon augmented by a growing swarm of tiny, shallow quakes such as preceded the eruption; and tiltmeters, which recorded a rapid deflation of the shallow lava reservoir while the fountain poured out its lava, revealed that the volcano was being inflated rapidly once more (Fig. 7). At 1:00 A.M. on 26 November the main vent of the first phase of the eruption revived. By 4:35 P.M. an additional 4.7 million cubic yards of lava had poured into the pond, increasing its depth to 350 feet and raising its surface high above the level of the original vent. Again the fountain died abruptly, and this time lava began to pour back down the vent. By 12:30 P.M. the next day 6 million cubic yards of lava had disappeared from the lake, leaving a black ring of frozen lava 30 feet above its receding surface.

During the following three weeks 14 more eruptive phases of shorter and shorter duration but with increasingly vigorous fountaining took place at the Kilauea Iki vent (Fig. 9). The highest fountain was measured during the 15th phase, on 19 December, when a column of incandescent, gas-inflated lava jetted to 1900 feet, by far the greatest fountain height yet measured in Hawaii. At its highest stand, at the end of the eighth phase, the lava pond was 414 feet deep and contained 58 million cubic yards of lava. At the end of each phase the fountain died abruptly, and from the 2nd to the 16th phase, a mighty river of lava surged back down the vent as soon as the fountaining stopped (Fig. 10). Of the 133 million cubic yards of lava spewed out into

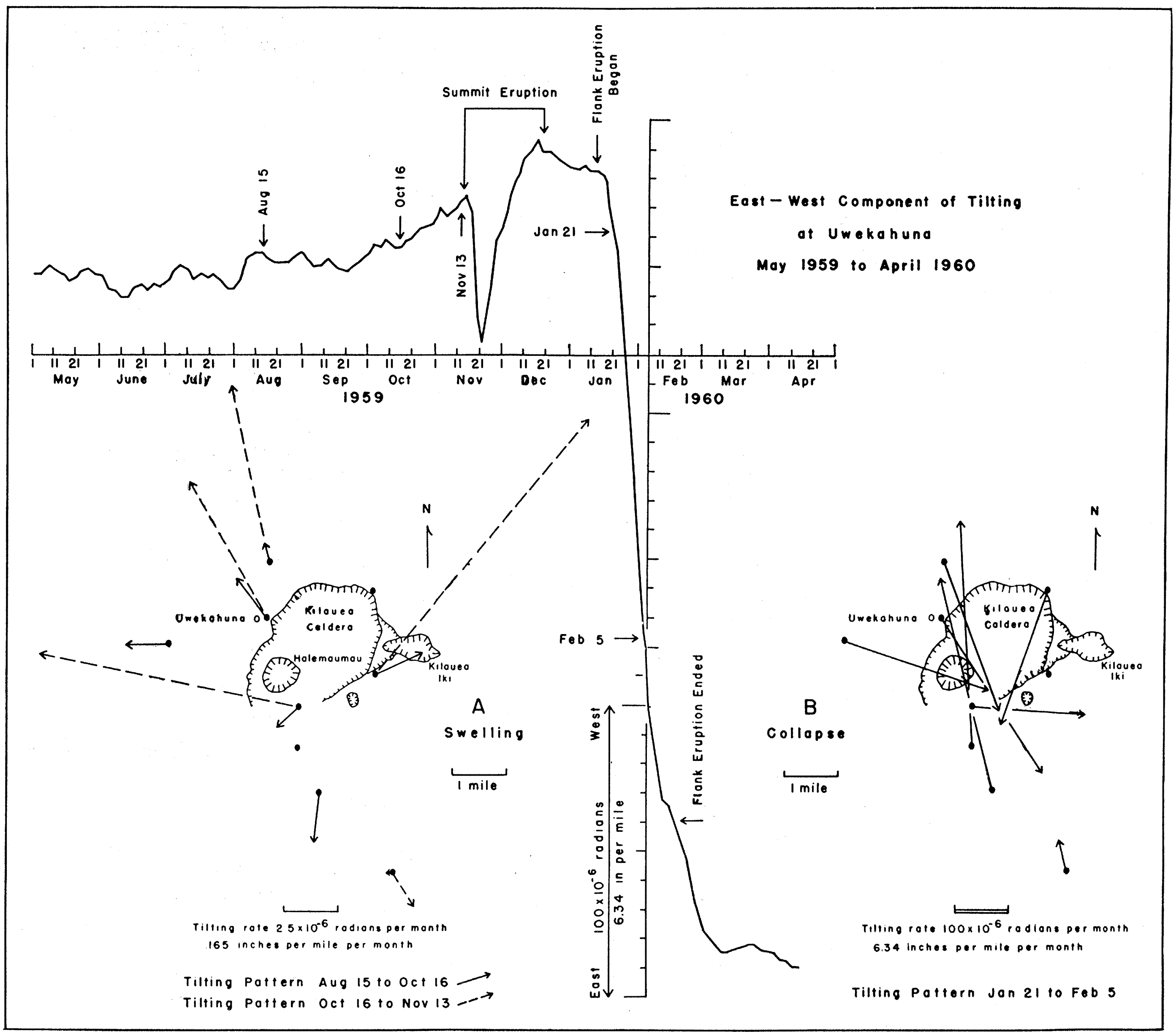

Fig. 7. Ground tilting at stations around Kilauea caldera associated with the 1959–1960 eruption. The east-west component of tilting at Uwekahuna shows the swelling and collapse of the summit of Kilauea as a function of time. Westward tilting (up) corresponds to swelling, and eastward tilting (down), to collapse. Inset *A* illustrates the pattern of tilting around the caldera during two periods of swelling. Inset *B* illustrates the pattern during collapse. Note the 40-fold difference in scale between *A* and *B*.

Kilauea Iki crater during the eruption, only 48 million cubic yards remains in the 367-foot-deep pond. The other 85 million cubic yards poured back underground almost as soon as it collected in the Kilauea Iki lava pond, where its volume could be so conveniently measured.

Tiltmeters around Kilauea caldera showed that the volcano was swelling rapidly as phase after phase of the eruption delivered its lava to the surface and then swallowed it up again. When surface activity ceased at Kilauea Iki on 21 December, far more lava was stored in the shallow reservoir beneath the caldera than when the eruption began (Fig. 7). It appeared that Kilauea was in an unstable state and that further activity was very likely.

During the last week of December a swarm of small earthquakes began to record on the seismograph at Pahoa. By means of a sensitive portable seismograph the source of these earthquakes was soon traced to the east rift zone of Kilauea, about 25 miles east of the caldera, near the site of the first outbreak of the 1955 eruption (Fig. 2). The magma that inflated the summit region most probably exerted pressure on the plastic core of the rift zone, and earthquakes revealed where the rift zone yielded and where dikes began to extend toward the surface.

Early in January the frequency and size of earthquakes from the east rift zone increased, and the region from which they emanated moved on toward the sea. On 13 January the village of Kapoho was rocked by frequent, very shallow earthquakes, and by nightfall a graben 0.5 mile wide and 2 miles long that contained about half of the town had subsided several feet. At 7:30 P.M. the earthquake swarm gave way to harmonic tremor, and the flank eruption broke out along a fissure 0.75 mile long near the center of the subsiding graben, a few hundred yards north of Kapoho and nearly 30 miles east of the summit of Kilauea.

During the next five weeks nearly 160 million cubic yards of lava poured out of the vent north of Kapoho and reshaped the topography of the eastern tip of Hawaii (Fig. 2). As the flow from the vent to the sea 2 miles away gradually built higher and higher, lava crowded out of the natural channel that initially confined it. Sluggish flows spread laterally from the main channel, destroying almost all of Kapoho, south of the vent, and most of the village of Koae, north of the vent. Dikes 15 to 20 feet high, built in a futile attempt to confine or divert flows that threatened a residential community along the seashore 2 miles southeast of Kapoho, were completely overwhelmed, and the lava moved on to destroy a portion of that community.

On 17 January, only four days after the flank eruption began, the summit of Kilauea began to subside precipitously as lava began to drain from beneath

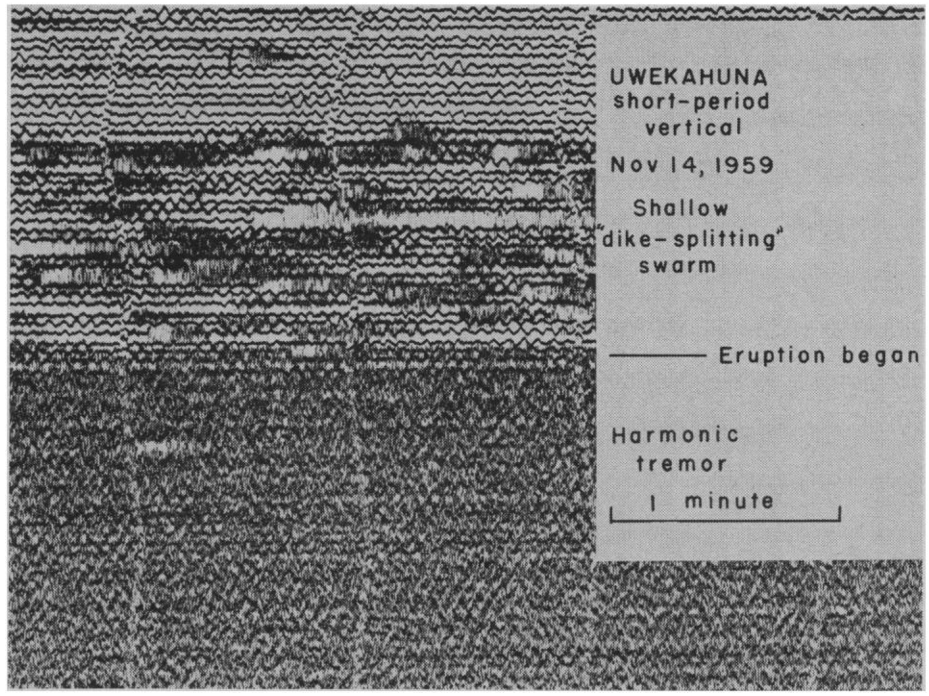

Fig. 8. Seismogram showing a swarm of shallow earthquakes immediately preceding the eruption in Kilauea Iki, followed by harmonic tremor caused by lava streaming through the erupting fissure near the surface. This seismogram is from a short-period vertical seismograph at Uwekahuna.

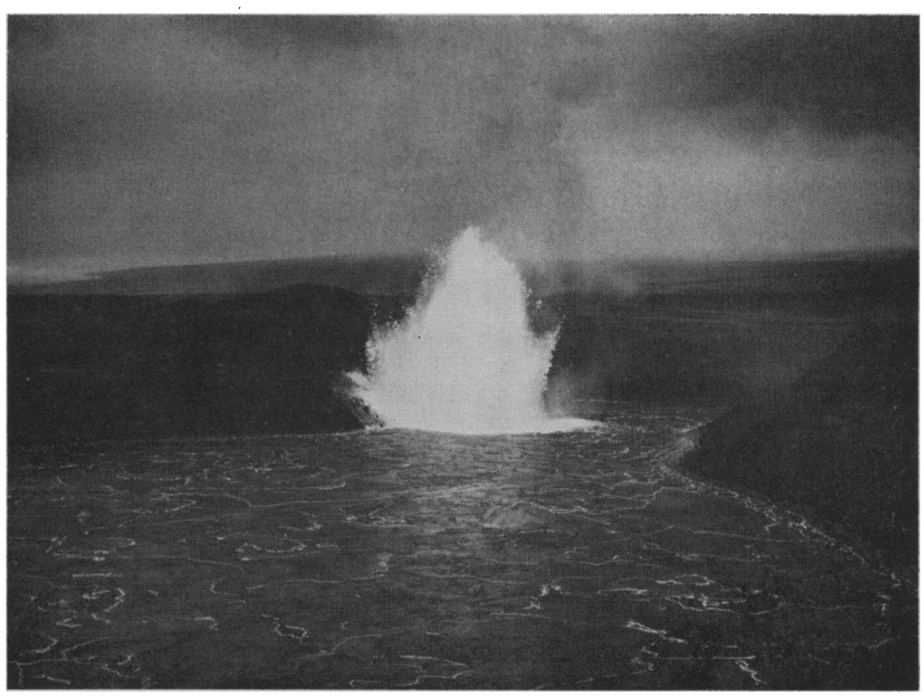

Fig. 9. Five-hundred-foot lava fountain in Kilauea Iki crater at 7:00 A.M. on 5 December, 1959. Note the new cinder cone at left of the fountain and the lake of fresh lava 400 feet deep in the foreground. The west wall of Kilauea caldera and the southeast flank of Mauna Loa are in the background of the picture, which was taken with the camera facing west.

the caldera and to move through the rift zone toward the Kapoho vent (Fig. 7, inset *B*). By the end of January a strong swarm of shallow earthquakes was in progress at Kilauea caldera, where the brittle surface rocks were failing under the rapid and severe deformation caused by continuing subsidence (Fig. 11). On 7 February an unseen fissure broke through into the still liquid core of the 300-foot-deep pond of lava erupted into Halemaumau in 1952, and the floor of Halemaumau settled about 150 feet as the liquid beneath it drained away. A smaller area in the center of the floor dropped an additional 200 feet, but it was partially refilled by sluggish flows of viscous lava draining from under the subsiding crust of the pond around it.

By the first of April, when rapid subsidence and the swarm of earthquakes it caused had ceased, tiltmeters around the summit indicated that the ground surface above the shallow reservoir that was deflated during the flank eruption had sunk about 5 feet. The total volume of collapse at the summit (the volume swept out by the surface of the volcano as its summit subsided), estimated from tiltmeter data, is close to the total volume of lava erupted at the surface.

Comparisons of temperatures and silica content of the lava erupted at Kilauea Iki and at Kapoho provide additional data on the underground history of Hawaiian lava. Temperatures measured in the core of the fountain at Kilauea Iki were consistently above 1120°C (measured with a hot-wire optical pyrometer and uncorrected for departure from black-body radiation). During a single phase of the eruption the temperature of the lava usually increased from about 1120°C near the beginning of the phase to about 1150°C near the end. The maximum temperature was measured during the fourth phase, when 1190°C was recorded. During early phases the silica content of the lava varied between 46.3 and 49.5 percent, but after the fourth phase it stabilized at about 46.8 percent. Petrographically the lava is a tholeiitic picrite basalt, consisting of olivine phenocrysts set in a fine-grained groundmass of plagioclase feldspar, pyroxene, and glass.

The lava erupted during the first two weeks of the flank eruption closely resembled the lava erupted in the same region in 1955. These lavas are tholeiitic basalts, poor in olivine but containing abundant phenocrysts of plagioclase feldspar and pyroxene. The silica content was about 50 percent, and the temperature was only 1050° to 1060°C, fully 100°C cooler than the lava at Kilauea Iki. After the second week the lava emerging from the Kapoho vent began to change; the silica content dropped, and the temperature increased. During the last week of voluminous lava eruption in February the temperature reached a maximum of 1130°C and the composition approached that of the lava erupted at Kilauea Iki.

It seems quite probable that the lava poured out during the first two weeks of the flank eruption had remained stored in the rift zone since at least 1955, if not since 1924, when lava drained from the summit into the east rift zone but failed to reach the surface. The chemical composition and mineralogy of this lava reveal a degree of differentiation that is unusual for Kilauea. The last lava erupted at Kapoho petrographically resembles Kilauea Iki lava, and it is entirely possible that magma moved from the summit reservoir, down through the rift zone, to the Kapoho vent during the course of the flank eruption.

Origin of the Magma

Although the geophysical evidence presented above permits us to trace the movement of magma through the volcano, it does not suggest why nor how magma enters the volcano at depth and rises through it to heights approaching 10 kilometers above the ocean floor to pour out at the surface. The "ascensive force of the lava," as it was called by Dana (*11*), was attributed by Daly (*12*) to the lower average density of the column of lava

Fig. 10. A river of lava pouring back into the Kilauea Iki vent at 7:30 A.M. on 19 December 1959. The top of the cone is 400 feet higher than the vent. The picture was taken with the camera facing south.

as compared to that of the crust of the earth above the zone in which the lava begins its journey to the surface. New information on the structure of the earth's crust beneath the Pacific basin requires that we revise the details of the model presented by Daly. We suggest that the crust here is much thinner than he believed it to be, and few geologists would now subscribe to the view that there is an eruptible basaltic glassy substratum underlying a crystalline crust. In principle, however, no better explanation of the ascensive force has been offered than that proposed by Daly.

If we assign densities to the molten lava column and to the various earth layers reported by Raitt for the Pacific basin in the Hawaiian region, we can compute the minimum depth at which lava can enter the volcanic system and be forced to the summits of the volcanoes. The densities given in Fig. 5 for the layers in Raitt's oceanic crust are those of the standard oceanic crustal gravity section adopted by Worzel and Shurbet (*13*). For the average density of the basaltic lava column we shall adopt Daly's estimate of 2.77 grams per cubic centimeter. Balancing the densities of the lava column and the crust, we find that to raise the lava z kilometers above sea level the lava column must extend at least to a depth x below sea level, where $x = 32.34 + 5.54\ z$ kilometers. Thus, to raise lava to the summit of Kilauea (1.2 kilometers), the lava column must extend to a depth of at least 39 kilometers below sea level; and to raise lava to the summit of Mauna Loa (4.2 kilometers), it must extend to a depth of at least 57 kilometers. These figures are in good agreement with the depth at which, according to the evidence of swarms of deep earthquakes and tremor, lava is fed into the Kilauea system.

Data from still another quarter, the study of surface waves of large earthquakes, throw additional light on the origin of Hawaiian lavas. Recent analyses of the dispersion of Rayleigh waves crossing the Pacific basin reveal that the rigidity of the mantle decreases somewhat at a depth of 60 kilometers (*14*). In view of the two other lines of evidence suggesting that Hawaiian magma originates at about this depth, it seems reasonable to conclude that the softening of the mantle at 60 kilometers is caused by partial melting of a peridotite mantle to yield an eruptible basaltic fraction. Perhaps, to go back to glassy substratum like that postulated by Daly but of higher density, the cooling and the consequent partial crystallization of a noneruptible, dense, glassy mantle drives off a lighter basaltic fraction that can be erupted to the surface.

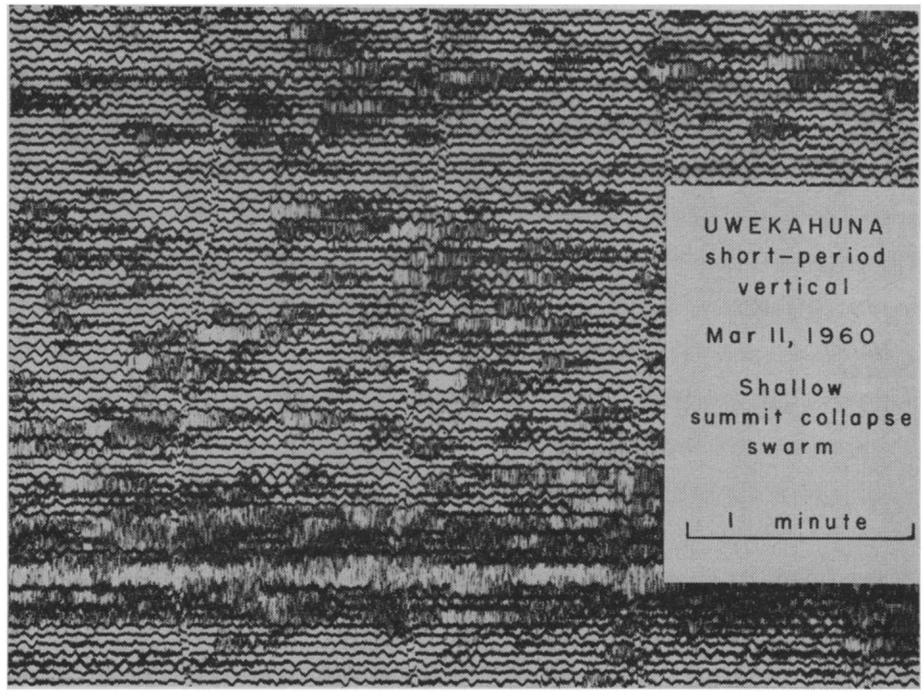

Fig. 11. Seismogram showing a swarm of shallow earthquakes caused by rapid subsidence and deformation of the summit of Kilauea. This swarm lasted for several weeks. The seismogram was recorded on a short-period vertical seismograph at Uwekahuna.

Mechanism, Composition, and Kinetics of Eruption of the Lavas

Let us recapitulate the evidence on the mechanism of eruption presented above and examine, by following the magma on its course through the volcano, how that mechanism explains surface geologic features. When magma enters the deep conduit beneath Kilauea (a portion of the fundamental fracture beneath the Hawaiian Ridge that is currently active) it begins a slow ascent through the heated depths toward the cooler crust and volcanic pile above. The movement of magma into the conduit at depth is relatively slow and steady, being governed, perhaps, by the rate at which the magma can be separated from the mantle and funneled into the open conduit. After leaving the upper portion of the mantle and traversing the basaltic layer that floored the ancient ocean, the magma emerges into the lighter, weaker rocks composing the volcanic pile and collects in a reservoir only a few kilometers beneath the surface. Upwelling of lava and consequent inflation of the high-level reservoir are slow processes that continue for months or even years prior to an eruption. Mounting pressure within the expanding reservoir finally drives the magma into dikes that split the frozen crust above the reservoir. When one of these dikes breaks through to the surface, an eruption ensues; the reservoir shrinks, and the pressure within it decreases as lava is discharged.

Basalt occupies a key position in modern theories of petrogenesis, and most, if not all, other kinds of igneous rocks are considered to have their ultimate origins in basaltic magmas. Thus, the chemical differentiation of basaltic magmas is a fundamental geochemical problem that has occupied the attention of many investigators throughout the world. Study of this differentiation in basaltic areas on the continents is complicated by the ever-present possibility that basaltic magmas may become contaminated by the diverse rocks that make up the crust of the continents. In the Hawaiian province, with its simple basaltic substratum, the possibility of such contamination is minimal, so magmatic differentiation may be investigated here with confidence.

Occasionally magma from the main reservoir is driven laterally into the mobile core of a rift zone, and failure of the confining rocks at some point along the rift results in a flank eruption,

Table 1. Chemical composition of typical Hawaiian rocks (these compositions are plotted on Fig. 12).

Compound	Tholeiitic basalt series*				Alkalic basalt series†		
	A	*B*	*C*	*D*	*E*	*F*	*G*
SiO_2	50.94	50.08	46.59	62.23	50.09	62.19	43.28
Al_2O_3	12.97	13.73	6.69	12.03	19.49	17.43	14.43
Fe_2O_3	1.95	1.32	2.20	5.55	0.73	1.65	0.70
FeO	8.96	9.79	10.46	4.76	8.47	2.64	10.92
MgO	10.68	7.89	21.79	2.05	4.33	0.40	11.68
CaO	9.88	11.50	7.41	4.25	6.92	0.86	11.22
Na_2O	1.99	2.18	1.33	3.20	4.82	8.28	2.49
K_2O	0.37	0.56	0.28	1.36	1.93	5.03	0.83
H_2O^+	0.12	0.02	0.37	0.33	.32	0.39	0.05
H_2O^-	0.04	0.00	0.04	0.52	.08	0.14	0.03
TiO_2	1.78	2.60	1.83	2.18	2.47	0.37	4.12
P_2O_5	0.21	0.26	0.11	0.01	0.78	0.14	0.31
MnO	0.17	0.17	0.18	0 43	0.15	0.32	0.13
CO_2	0.04	0.01				0.02	
Cr_2O_3			0.13			tr.	0.10
NiO			0.12				
SO_3			0.00			0.00	0.20
Total	100.10	100.11	100.53	99.21‡	100.58	99.93§	100.54‖

*(*A*) Tholeiitic olivine basalt, Mauna Loa, at highway at south boundary of Waiakea Forest Reserve, 2.65 km northwest of the Olaa sugar mill, island of Hawaii. Analyst, L. N. Tarrant (*31*). (*B*) Tholeiitic basalt, Kilauea, splash from lava lake, 1917, island of Hawaii. Analyst, L. N. Tarrant. Reanalysis of a previously described sample. New analyses published with permission of H. A. Powers (*19*). (*C*) Mafitic gabbro porphyry, Kilauea, Uwekahuna laccolith in the wall of the caldera, island of Hawaii. Analyst, G. Steiger (*32*). (*D*) Granophyre, Koolau Volcano, quartz dolerite dike at Palolo quarry in the southeastern part of Honolulu, island of Oahu. Analyst, K. Nagashima (*33*). †(*E*) Hawaiite (andesine andesite), Mauna Kea, elevation 2700 feet, on northwest flank near Nohonaohae, island of Hawaii. Analyst, H. S. Washington (*16*). (*F*) Trachyte obsidian, Hualalai, Puu Waawaa, island of Hawaii. Analyst, W. F. Hillebrand (*15*). (*G*) Picritic alkalic basalt, Haleakala Volcano, lava flow of 1750(?) on the southwest slope near Makena, island of Maui. Analyst, M. G. Keyes (*34*). ‡Includes 0.31 SrO. §Includes 0.03 BaO and 0.04 ZrO_2. ‖Includes 0.05 BaO.

sometimes miles from the summit of the volcano. Discharge of lava at a low elevation along a rift zone can cause a much greater drop in reservoir pressure than can result from a summit eruption. The volume of flank eruptions and the consequent reservoir deflation and ground-surface subsidence are much larger than for summit eruptions.

Rift zones, like the central reservoir, appear to be relatively shallow structures. They are zones split by countless dikes seeking to discharge lava at a low elevation through a long channel that cuts the cold crust in competition with other dikes that provide shorter channels through the cold crust to higher elevations near the summit. Concentration of these dikes in a zone and the ultimate generation of a molten rift-zone core result from the tendency for each dike to heat the rocks around it and lessen the freezing effect of the cold crust on later dikes that follow nearby paths.

Rapid, severe deflation of the central reservoir or of its lateral protrusions into the rift-zone cores can lead to the collapse of the ground surface by withdrawal of support from below. This process, which is especially severe for flank eruptions far down the slopes of the volcano, seems to be responsible for the formation of pit craters and calderas.

The work of Cross (*15*), Washington (*16*), Macdonald (*17*), Wentworth and Winchell (*18*), and Powers (*19*), among others, has disclosed a wide range in chemical composition among Hawaiian basaltic lavas and has established the broad outline of genetic relationships among rocks of different composition. Analyses of typical examples of the different types of Hawaiian rocks are given in Table 1.

The division of basaltic rocks into a tholeiitic series and an alkalic series, first made for the basaltic rocks of Scotland by Bailey and others (*20*), is also useful in the study of the Hawaiian rocks, as was recently shown by Tilley (*21*). As emphasized by Macdonald (*17*), the fundamental primitive magma of Hawaii is tholeiitic olivine basalt (Table 1, sample *A*). Sample *A* closely approximates the average composition of tholeiitic lavas from the currently active mature volcanoes Kilauea and Mauna Loa, and this general type of lava makes up the great bulk of each of the Hawaiian Islands. Rocks of the alkalic basalt series are produced in lesser quantities in the declining stages of volcanic activity and, on the island of Hawaii, characteristically occur as mantles over the tholeiitic shields of the extinct or late-stage volcanoes Mauna Kea, Kohala, and Hualalai.

The analyses in Table 1 pose the fundamental geochemical problem of explaining the differentiation of primitive tholeiitic magma to produce the other types of rocks with such greatly different composition. An adequate theory must not only satisfy the chemical criteria but must also correlate existing information on the relative amounts of the different types of rocks, their sequence of eruption, the melting and reaction relationships among the constituent minerals, and the kinetics of ascent and cooling of molten magmas.

All investigators of Hawaiian basalts since Cross (*15*) have emphasized the role of kinetics of eruption in controlling the extent and nature of differentiation of basaltic magma, but they have not agreed on the precise mechanism of control. Particularly, the mechanism of transition from tholeiitic to alkalic magmas during the life cycle of a volcano has remained in doubt. Our studies suggest that the transition is mainly the result of progressively more favorable conditions becoming established for extensive fractional crystallization of pyroxene during the later stages of a volcano, when magmas rise and cool very slowly and eruptions become very infrequent. This dynamical-chemical relationship is here discussed briefly with the aid of Fig. 12.

Of the many different ways in which analyses of basaltic lavas may be plotted for study, the one shown in Fig. 12 offers the great advantage of indicating the compositions of the three major minerals of the lavas—namely, pyroxene, plagioclase feldspar, and olivine. In this diagram differences in chemical composition are directly interpretable in terms of differences in the proportions of the three minerals. The diagram was originally derived by plotting the composition of 150 basaltic rocks from Hawaii and the British Hebridean province, and it has been published in full elsewhere (*22*). The skeletonized version is presented here for the sake of simplicity and clarity.

The parallelism in composition between the tholeiitic basalt series (*C-a-A-B-b-D*) and the alkalic series (*G-c-E-d-F*) is well shown in Fig. 12. Both series have olivine-rich members (*C-a-A* and *G-c*) and a group of closely related differentiates with progressively increasing content of silica (*B-b-D* and *E-d-F*). In the tholeiitic series, this group includes rocks, such as granophyre (*D*), that are rich in quartz, whereas in the alkalic series even the most siliceous member (trachyte *F*) is free of quartz but is rich in alkalic feldspar.

Molten tholeiitic magma of composition *A*, rising toward the surface, cools and first precipitates olivine [$(Mg, Fe)_2SiO_4$] crystals, which grow rapidly in size to a diameter of several millimeters (*23*). Olivine, having a greater specific gravity, tends to sink in the molten magma. This simple act of separating the crystal from the melt in which it formed changes the composition of the melt along the line *A* to *B*, and the composition of the underlying magma that receives the settling olivines, along the line *A* to *C*. Thus originate two complementary types of lavas, tholeiitic basalt (*B*) which is poorer in olivine, and picritic basalt (*C*) which is richer in olivine, than the parent magma. It should be noted that a shift in composition anywhere in the diagram involves such a fractional crystallization of one or more minerals.

There is a limit to changing the composition of the melt by settling of olivine because, at around point *B*, olivine precipitation ceases, and with decreasing temperatures augitic pyroxene [(Ca, Mg, Fe^{2+}, Fe^{3+}) $(Si, Al)_2O_6$] begins to crystallize. If the rate of cooling is very gradual and pyroxene is crystallized fractionally, the composition of the residual melt will move along *B-E* into the zone of the alkalic series. If the cooling is rapid, as in the currently active volcanoes, plagioclase feldspar [(Ca, Na)(Al, Si) $AlSi_2O_8$] soon starts to crystallize along with pyroxene, and the fractional syncrystallization of the two minerals yields residual melts with tholeiitic compositions along *B-b-D*. Therefore, the rate of ascent and hence cooling of the magma within the temperature range of the initial crystallization of pyroxene is of utmost importance in the differentiation of basaltic magma.

The spectacular eruptions of Kilauea and Mauna Loa permit us to observe tholeiitic lavas in the making. As indicated in Fig. 12, however, only a part of the tholeiitic series is represented among the lavas of these two volcanoes. Compositions between *b-D* apparently require a somewhat slower regimen of cooling than that experienced by materials that reach the surface, and rocks with such compositions may be crystallizing at depth within the two volcanoes. In the deeply dissected Koolau Volcano on Oahu and in Tertiary volcanoes of the British Hebrides, such rocks are found characteristically as dikes, sills, and other intrusive bodies. The entire tholeiitic series of rocks, therefore, appears to be a product of conditions that prevail in basaltic volcanoes that erupt vigorously and frequently.

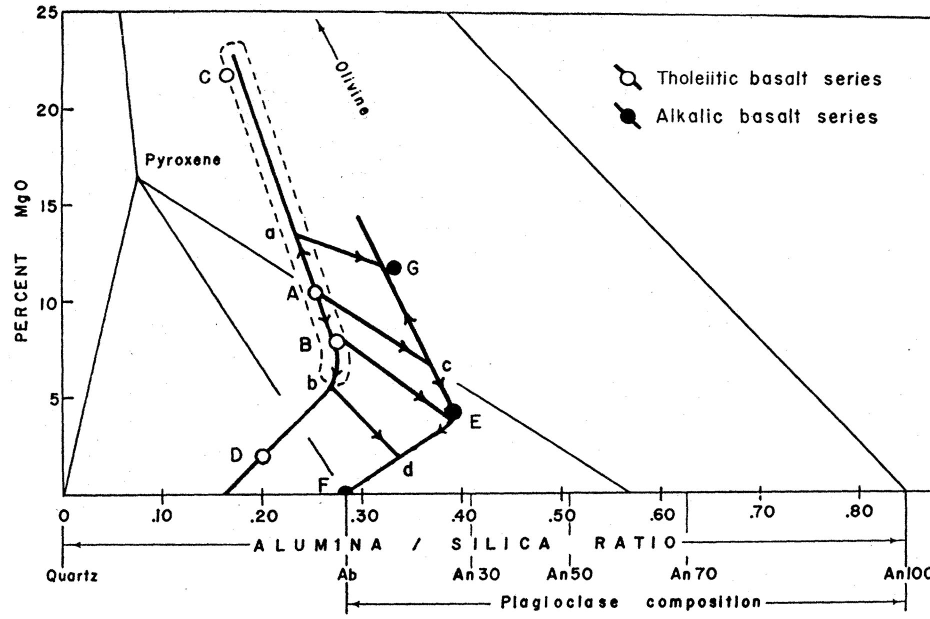

Fig. 12. Diagram showing interrelationships among typical Hawaiian volcanic rocks as manifested by their composition with respect to magnesia and alumina-silica ratio. Open circles, rocks of the tholeiitic basalt series listed in Table 1; solid circles, rocks of the alkalic basalt series. Tholeiitic olivine basalt (point *A*) is the primary magma of Hawaii; all other rock types are derived from it by fractional crystallization. The fractional crystallization of the different minerals and the resulting changes in the composition of tholeiitic and alkalic magmas are as follows: Olivine loss; *A-B* and *c-E*; olivine gain; *A-C* and *c-G*; pyroxene plus plagioclase loss; *B-b-D* and *E-d-F*; pyroxene loss; *a-G, A-c, B-E,* and *b-d.* The zone enclosed by a dashed line marks the range in composition found in tholeiitic lavas of the currently active volcanoes Kilauea and Mauna Loa.

Kilauea and Mauna Loa erupt on the average every few years. The reduced vigor of volcanoes that have reached the stage of producing alkalic lavas is illustrated by Hualalai on the island of Hawaii and Haleakala on the island of Maui. One hundred and sixty and about 210 years, respectively, have passed since these volcanoes last erupted (*24*). The more sluggish and halting ascent of the magma in such volcanoes allows the very slow cooling that is necessary for fractional crystallization of pyroxene.

The general derivation of alkalic magmas through fractional crystallization of pyroxene is shown in Fig. 12, starting from four illustrative points (*a, A, B,* and *b*) in the tholeiitic series. There are differences in the details of the fractional crystallization process along the four paths, but discussion of these differences will be deferred to a subsequent article. Within the alkalic series itself, the same fractional crystallization of olivine and of pyroxene and feldspar takes place as in the tholeiitic series and accounts for the parallelism in composition between the two series. In general, the olivine and pyroxene that are fractionally crystallized from the cooler alkalic magmas are richer in ferrous iron.

The world-wide problem of the origin of tholeiitic and alkalic basalts is being actively investigated by many petrologists, some of whom favor a separate derivation of the two compositional series from different depths in the mantle of the earth. Our studies suggest, rather, that the composition of basaltic rocks is primarily a function of the rate of ascent and cooling of a single fundamental magma. With the geological, geophysical, and geochemical techniques now available at the observatory located on an active volcano, it should be possible to obtain experimental verification of this interesting relationship between kinetics of eruption and composition of erupted lavas, at least within the tholeiitic basalt series.

Volcanic Gases

In Hawaii, volcanic gases are manifested most spectacularly during an eruption in the effervescing fire fountains, which squirt a pulsating stream of molten lava up to heights of a thousand feet and more. In other volcanic regions, such as Indonesia (*25*), they give rise to more explosive and deadly phenomena like *nuée ardente* eruptions.

A typical composition (in volume percent) of Hawaiian magmatic gases, as established through the work of Shepherd (*26*), Jaggar (*27*), and Naughton and Terada (*28*), is as follows: H_2O, 79.31; CO_2, 11.61; SO_2, 6.48; N_2, 1.29; H_2, 0.58; CO, 0.37; S_2, 0.24; Cl_2, 0.05; A, 0.04. The proportions of the constituents vary over a certain range, and Ellis (*29*) has shown that the variations are largely accountable in terms of shifts in gas equilibria with changing temperature. The role of gases in controlling the state of oxidation of the magma requires thorough investigation (*30*).

Volcanic gases, in whole or in part, represent primordial materials reaching the surface of the earth for the first time. Thus, over the span of geological time the accumulation of such gases from innumerable eruptions determined the evolutionary course of our atmosphere and hydrosphere. The new Geochemical Laboratory is equipped with a mass spectrometer for rapid analysis of gases, and a program of systematically analyzing all volcanic exhalations has been started.

Summary

Hawaiian volcanoes offer an unmatched opportunity for studying the mechanism of eruptions and the differentiation of primitive tholeiitic basaltic magma. They are located near the center of the Pacific basin, more than 2000 miles from the nearest region of active tectonism, and the story of their origin and continuing activity is one of pure volcanism. Because their lavas experience a minimal exposure to contamination by heterogeneous crustal rocks as they rise to the surface, fractional crystallization plays the dominant role in producing changes in the chemical composition of the lavas extruded at different stages in the life cycle of the volcanoes.

The enormous size, relatively simple structure, and frequent voluminous eruptions of Hawaiian volcanoes all permit the effective use of seismographs and tiltmeters in delineating their internal structure and in detecting the movement and accumulation of magma within them. Other more general geophysical investigations of the Pacific crust and the mantle below provide additional evidence on where Hawaiian magma originates and how it is driven to the surface.

The ultimate cause of volcanism is the fundamental instability of the crust and upper mantle of the earth. About 60 kilometers beneath the Pacific the rocks of the mantle yield a fluid fraction with the composition of tholeiitic basalt. The density of this basaltic magma fraction is less than the average density of the 50 kilometers of mantle (peridotite?), 5 kilometers of basaltic crust, and 5 kilometers of water that lie above it, and if the opportunity arises it can be squeezed to the surface by the weight of the material above. The fundamental fracture beneath the Hawaiian Ridge has tapped this source of magma and provides the avenue through which it can escape to the surface.

Lava rising through the fundamental fracture beneath Kilauea accumulates slowly in a shallow reservoir only a few kilometers beneath the caldera. At irregular intervals dikes project upward from the expanding reservoir, and if the expansion and consequent pressure within the reservoir are great enough, the dikes break through to the surface and discharge the accumulated lava in an eruption.

Geochemical studies show that while the volcanoes are vigorously active, the most striking variation in their lavas is the content of olivine. Rapid delivery of magma to the surface permits only slight cooling underground, and the only mineral that is fractionally crystallized in significant amounts is olivine, which is depleted from some flows and concentrated in others. When activity declines and magma wells up from depth much less rapidly, it remains in the shallow reservoirs for increasingly longer periods of time. Here the magma cools so slowly through the temperature range in which pyroxene crystallizes that this mineral, as well as the early-formed olivine, settles out of the melt and is immobilized on the floor of the reservoir. Such separation of pyroxene "desilicates" the tholeiitic parent magma and changes its composition to that of alkalic basalt, the predominant lava of the declining stage of Hawaiian volcanism. The temperature, composition, and rate of ascent of the basaltic magma to the surface, therefore, are closely interrelated, and the study of the complex interrelationships of these geophysical and geochemical factors constitutes the fascinating work of observing how volcanoes grow.

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