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DISTRIBUTION OF EARTHQUAKES RELATED TO MOBILITY OF THE SOUTH FLANK OF KILAUEA VOLCANO, HAWAII

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Abstract.–Many earthquakes at Kilauea are related to magmatic (extrusive or intrusive) events within the caldera or along the rift zones. During the early stage of a rift event, earthquakes are often concentrated near the site of extrusion or intrusion. During and after the later stage of the event, earthquakes spread southeastward across the south flank away from the site of initial seismicity. The seismic data are consistent with geodetic measurements and suggest that the south flank of Kilauea is mobile and that the north flank is relatively stable.

Fiske and Kinoshita (1969) first proposed that the entire south flank of Kilauea Volcano (fig. 1), bounded by the east and southwest rift zones and by the Koae fault system, is being displaced seaward by the wedging action that accompanies forceful injection of dikes into the rifts (principally the east rift). They suggested that the north flank of Kilauea is a relatively stable block that is undergoing little or no displacement away from the rift zones. Swanson, Duffield, and Okamura (1971a, b) examined geodetic data for this century and found them to be mostly consistent with the Fiske and Kinoshita model. Analysis of the triangulation and trilateration data for part of the south flank indicates a maximum seaward displacement of about 4.5 m since 1914, and recent geodimeter measurements have been used to key specific magmatic events along the upper east rift to measured seaward displacement of the south flank.

The large magnitude of this displacement and the fact that it is still continuing suggest that the recent record of seismicity of the south flank should show a clear relation to the magmatic events that caused the displacements. We show in this paper that such a relation does exist and that it supports the south-flank model of Fiske and Kinoshita (1969) and Swanson, Duffield, and Okamura (1971a, b).

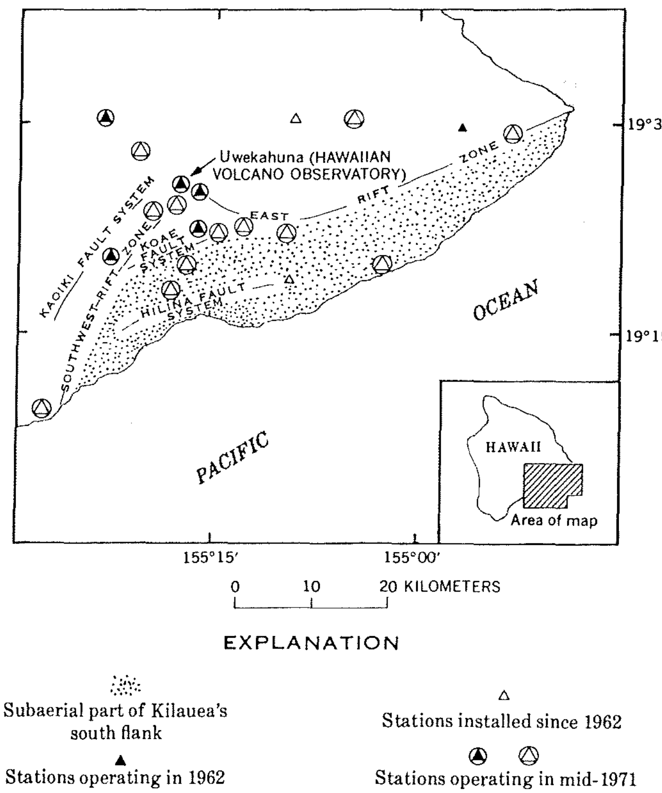

Figure 1.–Index map showing major structural features of Kilauea Volcano and locations of Hawaiian Volcano Observatory seismic stations.

THE SEISMIC NET AND OTHER TECHNICAL ASPECTS

The network of seismic stations maintained by the Hawaiian Volcano Observatory consists primarily of short-period instruments operated at high magnification to record local events (Koyanagi, 1968b). The network at Kilauea is constantly being expanded and improved, and 14 new stations have been installed since 1962, although two of these stations were operated only temporarily. As of mid-1971, 17 of the Observatory's 28 stations are located where they can extensively monitor the seismic activity of the Kilauea volcanic complex (fig. 1); their signals are telemetered to the observatory and recorded on Develocorder 16-mm strip film.

Formerly, earthquake data were processed manually with the aid of traveltime charts. In 1969, the operation was converted to computer processing, which led to a systematic documentation of large quantities of data (Koyanagi and Endo, 1971). The determination of earthquake hypocenters is based on Eaton's Model B, a layered velocity model (Eaton, 1962):

Depth to layer (km)	*Layer velocity (km/sec)*
0.00	3.90
3.10	5.00
11.20	6.80
14.80	8.25

After most of the earthquakes considered in this paper had been processed, trial determinations were made for a selected number of events, using an alternative model based on seismic refraction data compiled by Hill (1969). For earthquakes beneath Kilauea's south flank, the two models show only slight differences in epicentral locations, but focal depths appear to be about 2 km shallower with Hill's model. Additional considerations, such as traveltime anomalies, irregular station distribution, and differences of station elevations not accounted for in our calculations, suggest that several kilometers of error should be expected in the focal-depth determination. Recently, comprehensive studies oriented toward examining the accuracy of earthquake locations in Hawaii were being made by P. L. Ward, of the U.S. Geological Survey (oral commun., 1972).

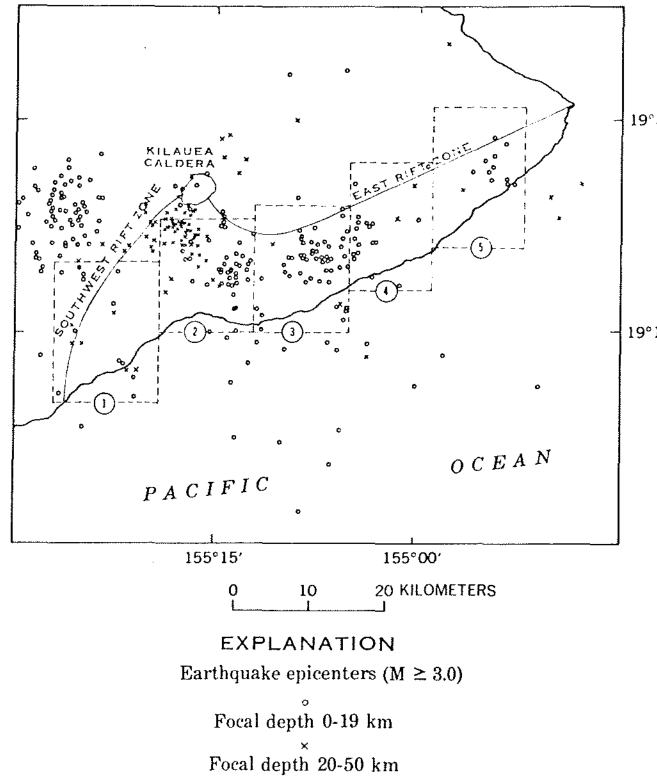

Figure 2.—Epicenters of earthquakes of magnitude 3.0 or greater located within or beneath Kilauea for the period 1965–70. The distribution of the shallow quakes along the south flank is arbitrarily subdivided into five groups, as shown by dashed lines and circled numbers. These events are heavily concentrated in groups 2 and 3 adjacent to and south of the areas of recent volcanic activity.

GENERAL SEISMIC PATTERN AROUND KILAUEA

Most of Hawaii's seismic activity is centered on the active volcano of Kilauea. Figure 2 shows the distribution of earthquakes of magnitude 3 (modified after Richter scale) or larger for the period 1965–70; the distribution of smaller quakes is nearly similar, except for somewhat more localized occurrences around the caldera complex and rift zones. The persistent seismic zones within the volcano are presumably the result of stresses ultimately generated by the continuous ingress of magma. In addition to a highly seismic region beneath the caldera, earthquakes are concentrated along the rift zones and adjacent fault systems. The high frequency of eruptions on the east rift in recent years (table 1) has been accompanied by high seismic activity in that area. The lower and more distant parts of the rift zones have recently been only spasmodically seismic, with moderate flurries occurring once or twice a year. Another source of earthquakes, 10 to 15 km west of Kilauea Caldera beneath the northwestern part of the Kaoiki fault system, may be related to the stresses generated within Kilauea because of loading by the Mauna Loa volcanic system.

Earthquakes outside the summit area of Kilauea are scattered along the southwest rift and are strongly concentrated on the south side of the central and western parts of the east rift. Earthquakes with focal depths of less than 15 km (that is, those mainly within the crust) are distributed parallel to the major rift and fault zones. However, earthquakes deeper than 15 km cluster beneath the region south of the summit and scatter quite conspicuously to the southwest; these earthquakes conform only slightly to surface traces of the rift zones and fault systems.

EFFECT OF THE RIFT ZONES ON EARTHQUAKE DISTRIBUTION

Shallow (less than 15 km deep) seismic activity on the south flank is bounded by the rift zones, particularly by the east rift (fig. 2). Many earthquakes take place along and to the south of the east rift but not to the north; the rift zone itself acts as the northern boundary of the seismic region. Consequently, a highly seismic east rift and south flank contrast strikingly with an aseismic zone north of the rift.

The asymmetric distribution is less conspicuous along the southwest rift because of moderate seismicity on both sides of the rift. The seismically active southwest rift is complemented

Table 1.—*Kilauea eruptions and seismic swarms associated with movement of magma between 1962 and 1969*

[Asterisks (*) denote well-recorded events from which earthquakes were located and plotted in figure 7]

Date	Nature of event	Approximate number of small earthquakes	Relative intensity of tremor	Relative summit deflation indicated by tiltmeter at Uwekahuna
December 1962	Eruption: east rift.	500	Moderate.	Moderate-slight.
*May 1963	Earthquake swarm: Koae fault system, southwest rift.	3,000	Weak.	Do.
*July 1963	Earthquake swarm: Koae fault system, east rift.	2,000	....do.....	Do.
*August 1963	Eruption: east rift.	1,000	Moderate.	Slight.
*October 1963	........do.........	1,000	....do.....	Moderate.
*March 1965	........do.........	1,000	....do.....	Do.
*December 1965	Eruption: east rift and Koae fault system.	10,000	Moderate-weak.	Do.
November 1967 to July 1968	Eruption: summit.	......	....do.....	Slight.
*August 1968	Eruption: east rift.	500	Moderate.	Moderate.
*October 1968	........do.........	1,000	....do.....	Do.
*February 1969	........do.........	500	....do.....	Do.
May 1969	........do.........	......	Moderate-weak.	Moderate-slight.

by equally active areas to the northwest and along the adjacent Kaoiki fault system of Mauna Loa; the area about 15 km west of Kilauea Caldera makes up an especially active seismic zone (figs. 1 and 2). However, any given shallow earthquake swarm or main shock-aftershock sequence that originates on the southeast side of the rift has its epicentral distribution confined along or southeast of the rift. Conversely, earthquakes associated with usual "Kaoiki" swarms and aftershock sequences do not occur southeast of the rift. This mode of occurrence is generally suggested by quarterly and annual plots of earthquake epicenters at Kilauea (Koyanagi, 1968a; 1969a, b, c; Koyanagi and Endo, 1971), which show eipcentral concentrations either northwest or southeast of the rift, depending on the type of activity for a particular period. In general, then, the highly fractured east and southwest rifts appear to disrupt strain release patterns and significantly affect the distribution of earthquakes with depths less than 15 km.

RIFT AND SOUTH-FLANK SEISMIC EVENTS RELATED TO MAGMATIC ACTIVITY

Rift and south-flank earthquakes are related in time and space to extrusive activity or inferred intrusive activity unaccompanied by eruption (fig. 3). Earthquakes are more common during extrusive or intrusive episodes and in areas closest to the site of the magmatic activity. This association is straightforward and of utmost importance, for it virtually proves that seismicity is directly and genetically related to the intrusive and extrusive processes.

During the past 10 years, eruptive activity along the central and western part of the east rift was associated with many earthquakes, harmonic tremor, and contraction of Kilauea's summit region. The contraction is interrupted to result from transfer of magma from beneath the summit, where it is presumably held in a storage reservoir, toward the site of eruption. Several earthquake swarms have accompanied summit contraction without eruptive activity (table 1); these events are interpreted as intrusive episodes, during which magma moved from beneath the summit into the east rift and was emplaced as dikes. Earthquakes associated with such intrusive events have been located in the western part of the east rift zone and the neighboring part of the Koae fault system. In contrast, earthquake flurries that occurred along the eastern part of the east rift (area 5 in fig. 2) were unaccompanied by summit contraction and hence are not considered to have recorded migration of magma from the summit reservoir. Similarly, isolated moderate-sized earthquakes and aftershock sequences in the Hilina and Kaoiki fault systems were apparently not related directly to concurrent magmatic processes, but probably to long-term structural adjustments which indirectly result from these processes.

SEQUENCE OF EARTHQUAKES AFTER MAGMATIC EVENTS IN THE EAST RIFT

During the early stage of intrusive and extrusive events, earthquakes occur primarily at shallow depths (about 5 km or less) near the eruptive fissures, the intrusion, or active faults inferred to slip as a result of intrusion. In the subsequent period of rapidly increasing magmatic activity, earthquakes and harmonic tremor are so numerous that they largely obscure individual small earthquakes (often those of magnitude less than 2.0) on the seismograms. Such high intensities are usually short lived, persisting for less than a day during the peak times of activity. As the magmatic activity continues, the earthquakes scatter broadly throughout the south flank, but principally southeast of the initial center along an azimuth roughly perpendicular to the trend of the fissure and fault

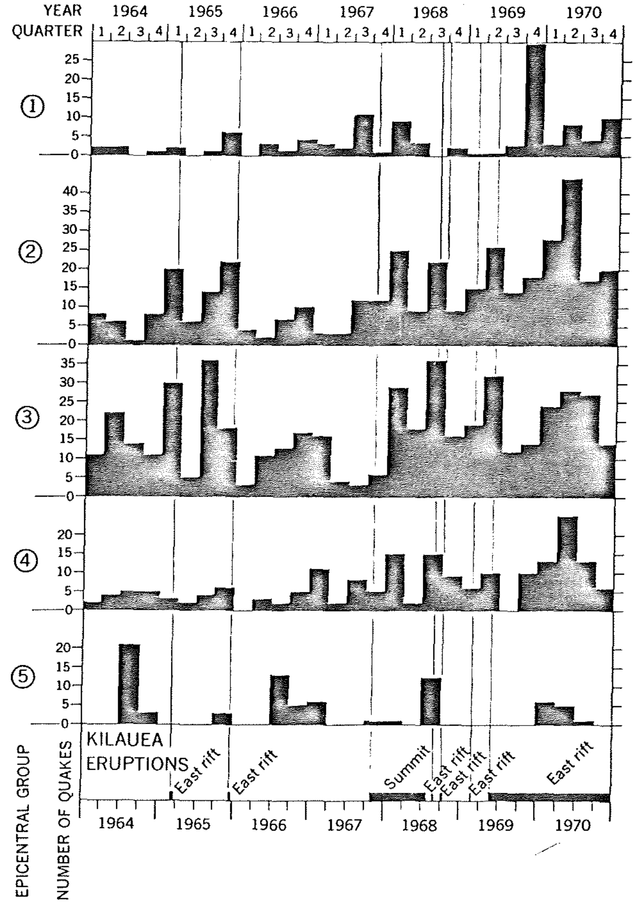

Figure 3.—Frequency of earthquakes grouped into the five geographic areas along the south flank of Kilauea shown in figure 2. The number of quakes for each group is plotted quarterly and compared with periods of extrusive activity. All earthquakes with magnitude 2.0 or greater and focal depths of less than 15 km are shown. There is a general tendency for periods of high extrusive activity to be accompanied by increased seismic activity along the upper and middle parts of the east rift zone and to some degree along the southwest rift. Periods with few or no eruptions tend to have comparatively weak seismic activity.

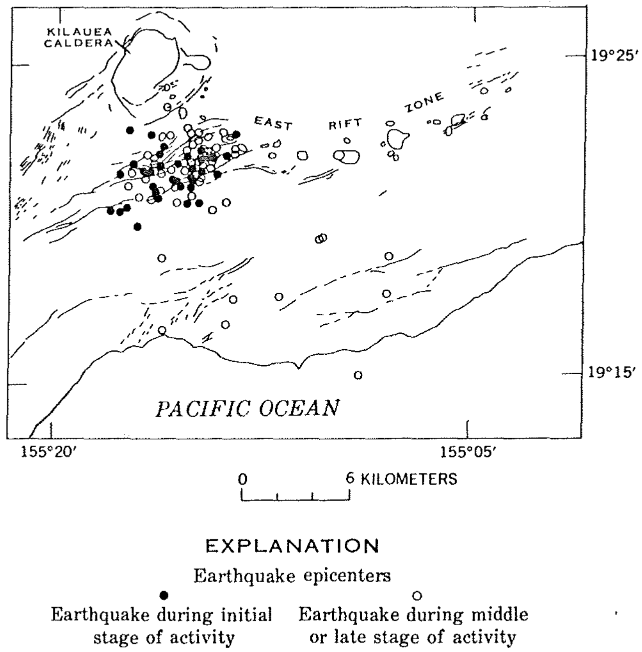

Figure 4.—Epicenters of earthquakes located during the Koae-east rift seismic episode and the Kilauea summit contraction in July 1963. These earthquakes ranged in magnitude from 1.5 to 3.8, and focal depths were generally 10 km or less. Earthquakes during the initial 4-day period of activity were located near the active major fault system and east rift; those during the later 4-day period of activity were scattered to the south and at greater depth.

zones (fig. 1; Moore and Koyanagi, 1969, fig. 1; Wright and Kinoshita, 1968, p. 3188). These later earthquakes have a wider range in depth (Koyanagi and Endo, 1971), and some are as deep as about 10 km. During the largest magmatic events, an almost immediate increase in south-flank seismicity is noticeable. In the days after the initial magmatic activity, the epicentral region spreads southeastward, sometimes for more than 18 km.

One example of such a sequence of events took place during the intrusive event of July 1963 (figs. 4 and 5), which was accompanied by marked contraction of Kilauea's summit (for a comparable event in May 1963, see Kinoshita, 1967). During the first 4 days of this event, earthquakes occurred within or very close to the Koae fault system, which was interpreted to have been affected by the intrusive event. For 4 days after the principal event, abnormally high earthquake activity took place on the south flank, some epicenters being located as far as 14 km southeast of the fault system. Several additional earthquakes occurred on the south flank during the following 2 weeks (fig. 5).

Figures 6 and 7 show compilations of nine earthquake swarms from the east and southwest rifts (table 1) similar to that of July 1963. Some of these swarms accompanied eruptions, and others, intrusive events. The compilations clearly show the same trends as the isolated July 1963 event and indicate that, as a general rule, the epicentral area enlarges southeastward away from the east rift zone and from the Koae fault system after a particular magmatic event begins.

The first southwest-rift eruption since 1920 took place on September 24 to 29, 1971, while this paper was being prepared. Numerous earthquakes occurred within the south flank south of the site of eruption. The seismic activity continued almost constantly at high levels for a month after the eruption and in sporadic swarms for several months thereafter. Seismicity was highest beneath the western part of the south flank, especially near the intersecting area of the Hilina fault system and the southwest rift. A major earthquake swarm occurred in this region in late December 1971; several dozen earthquakes of about magnitude 3 to 5 were recorded and felt by residents of southern Hawaii.

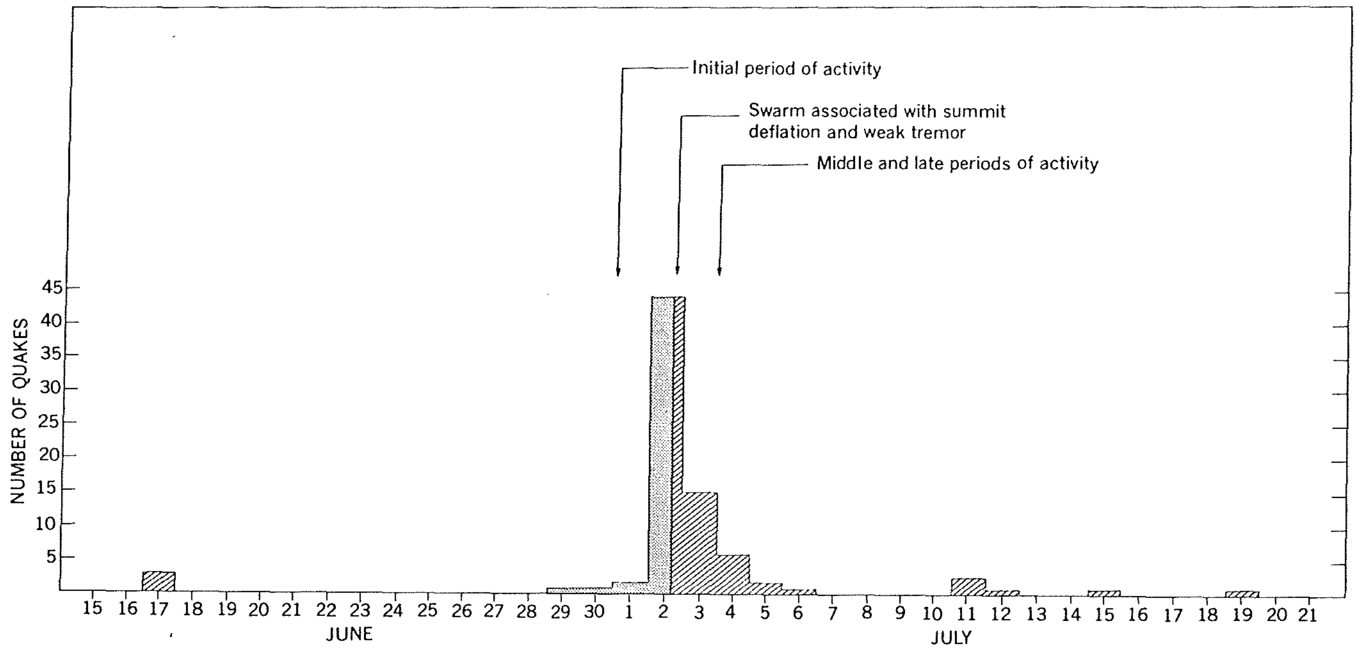

Figure 5.—Daily frequency pattern for small earthquakes during the July 1963 Koae-east rift seismic swarm. The shaded area indicates the early period when earthquake epicenters concentrated along the Koae faults and east rift; the ruled area following indicates the period when earthquake hypocenters scattered southeastward.

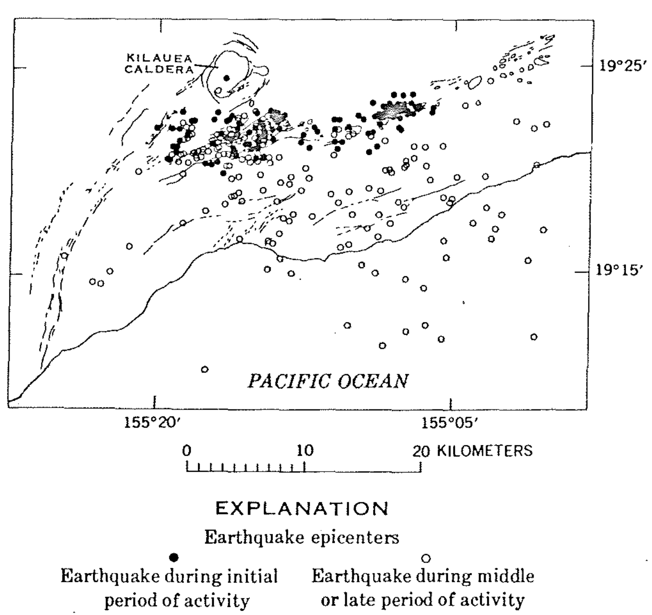

Figure 6.—Compilation of earthquake epicenters from short seismic swarms apparently associated with magmatic processes from 1963 to 1969. Earthquakes selected are of magnitude 2.0 and greater and depth less than 15 km. The epicenters were plotted according to two time categories in which they occurred. Earthquakes during the initial stages of activity were concentrated near the outbreak area along the Koae faults and east rift. Earthquakes during the middle and late stages scattered far to the south.

Preliminary focal determinations for the south-flank earthquakes of September–December 1971 suggest that depths were generally less than 10 km, using Eaton's Model B. Comparable to the earthquakes located on the eastern part of the south flank, these earthquakes also concentrated within the crust. The pattern of seismic activity after the southwest-rift eruption appears to be similar to that after east rift and Koae events, because the distribution of epicenters widened seaward with time.

AFTERSHOCK ACTIVITY WITHIN THE SOUTH FLANK

Do the widening of epicentral distribution southeastward from the site of magmatic activity and the deepening of foci simply reflect a "normal" relation between main shock and aftershocks? The asymmetry of epicentral distribution suggests otherwise. To further investigate this possibility, we examined several definite aftershock sequences on the south flank (figs. 8 and 9). Some of the largest quakes (magnitudes between 3.5 and 5.5) beneath the south flank are associated with aftershock activity. The magnitude of the main shock and the stress conditions of the rocks appear to determine the extent of the aftershocks, and as many as several hundred shocks of magnitude 0.1 to 2.5 may occur within several hours after the main shock. Most of the main shock-aftershock sequences occurred along the fault systems south of the east rift, and

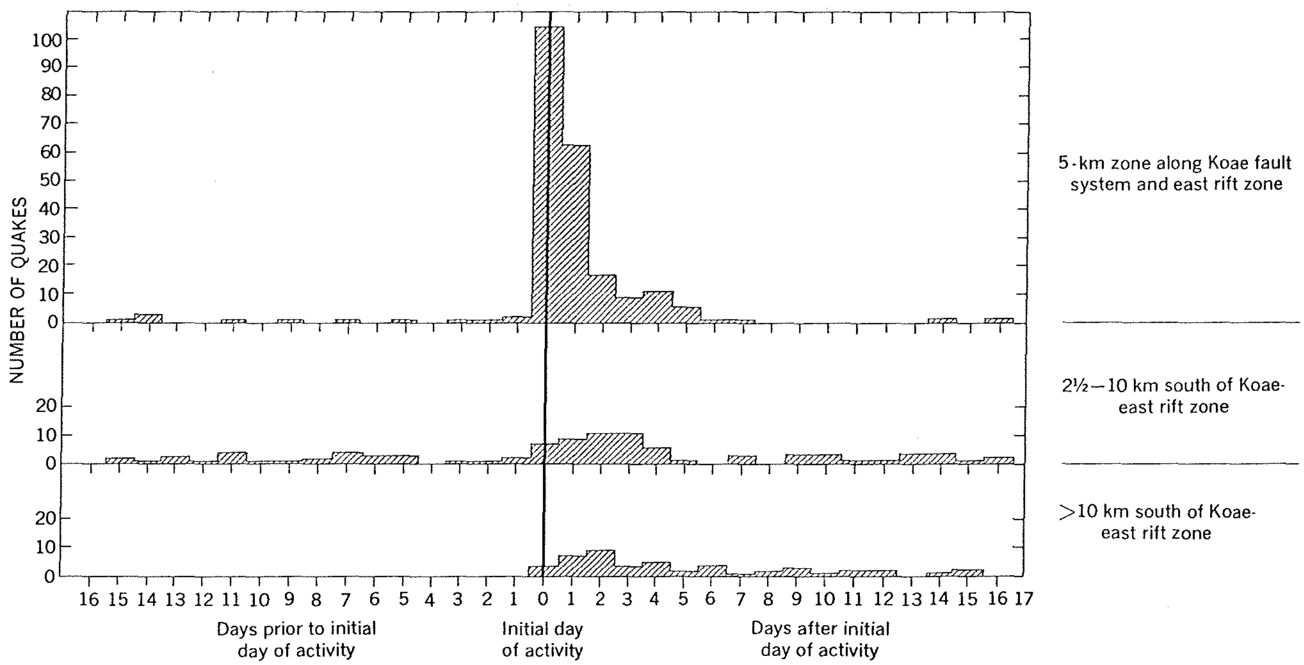

Figure 7.—Frequencies of earthquakes associated with some short extrusive or intrusive episodes between 1963 and 1969 (see table 1). The numbers of earthquakes were plotted according to various epicentral distances south of the Koae fault system and the east rift zone. Earthquakes plotted are of magnitude 2.0 or greater and depth less than 15 km. The graphs show the increased number of shallow- to intermediate-depth earthquakes along the south flank during the first and second weeks after the start of the magmatic event.

their epicentral zones were elongate parallel to the major trend of the rift and fault system, instead of broadly perpendicular to the trend, as are those of earthquakes related to magmatism. Moreover, the aftershocks occurred in a zone completely surrounding the main shock, instead of in a zone confined to the seaward side, as do magmatic earthquakes. The most extensive series of aftershocks occurred in areas of only about 50 km^2 (figs. 8 and 9). The epicentral area outlined by aftershocks after a moderate-sized earthquake is thus relatively limited compared to the wide distribution of earthquakes after magmatic episodes (compare figs. 4 and 6 with 8 and 9). The mechanisms involved in a sizable magmatic event apparently cause the release of strain across larger areas than do single earthquakes of magnitude 4 or 5 along the south flank of Kilauea.

STRESS AXES

Preliminary results of a focal mechanism study being carried out by Endo and Koyanagi suggest that the orientation and sense of stress axes of well-located south-flank earthquakes (all of which have focal depths of 5 km or more) follow a consistent pattern. Figure 10 shows that most of the maximum stress axes are oriented southeast and plunge gently seaward. The average azimuth is within 20° of a normal to the trend of east-rift fissures and Koae faults.

SUMMARY OF PRINCIPAL RESULTS

1. Earthquakes outside the summit area of Kilauea generally take place along or seaward of the rift zones and the Koae fault system.
2. Many of these earthquakes are related in space and time to magmatic events, either extrusive or intrusive.
3. Most earthquakes during the early stage of a magmatic event are located along the rifts or along the Koae fault system at depths of 5 km or less.
4. Many of the earthquakes during the later stages of or immediately after a magmatic event are located seaward of the initial activity at depths of as much as 10 km.
5. Aftershocks of "tectonic" earthquakes not immediately related to magmatic events show a different pattern of occurrence than magmatic earthquakes.
6. Maximum stress axes of most south-flank earthquakes plunge gently seaward and are oriented within 20° of a normal to the trend of east-rift fissures and Koae faults.

DISCUSSION AND COMPARISON WITH RESULTS OF GEODETIC STUDIES

The seismic data presented in this paper indicate that the south flank of Kilauea undergoes deformation during episodes of magmatic activity in or near the rift zones. The north flank, however, is not seismically active, consistent with horizontal

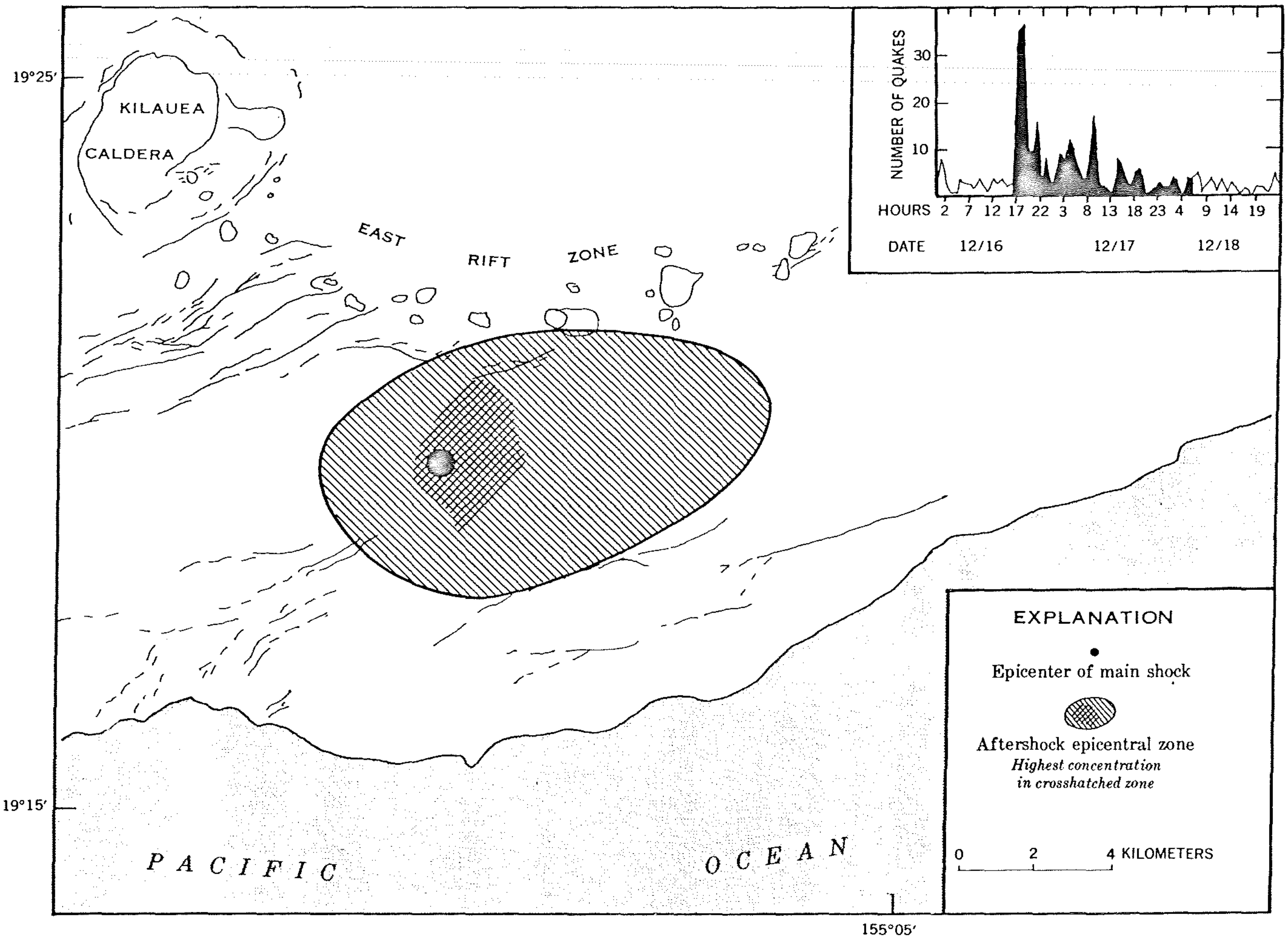

Figure 8.—Aftershock sequence from a magnitude-4.7 earthquake on December 16, 1968, located on the south flank at a depth of about 10 km. Map shows location of the main shock, the zone of concentrated aftershock activity, and the extent of the epicentral zone in relation to conspicuous structural features. Inset shows hourly frequency pattern; the darkened area indicates the period of aftershock activity.

and vertical geodetic observations (Swanson and others, 1971b) that show it is a relatively stable block in the Kilauea structure.

Flurries of south-flank earthquakes that are related directly to magmatic activity take place after, not before, the initial phase of the eruption or intrusive episode. Thus the earthquakes are a response to, and not a precursor of, the magmatism. Swanson and others (1971b) reached the same conclusion on the basis of recent geodimeter studies, which show that episodes of seaward-directed displacement of the south flank can be keyed to specific magmatic events that took place slightly earlier. These relations suggest that the south flank deforms in response to stresses induced by forceful dike intrusion, rather than in response to some process unrelated to magmatism. It thus seems reasonable that, as Fiske and Kinoshita (1969) suggested, magma injected as dikes into the rift zones makes room for itself by wedging the south flank seaward.

Over a period of a few days, earthquakes spread southeastward from the site of extrusion or intrusion, implying that an increasingly large part of the south-flank block is responding to magmatic stresses; eventually the entire block is probably displaced seaward away from the rift zone. South-flank seismicity usually peaks several days after the first day of magmatic activity (fig. 7), but abnormally high earthquake counts continue for 2 weeks or more. Geodimeter studies (Hawaiian Volcano Observatory, unpub. data), however, suggest a lag time of 2 to 4 weeks between the onset of a magmatic event and seaward displacement of the south flank at a point about 6 km southeast of the western part of the east rift. This major observed displacement event seems to be unaccompanied by significant seismic activity. Instead, the earthquakes apparently record the first stages of this displacement at depth, perhaps marking the initial opening of the fractures along which major seaward displacement ultimately takes place.

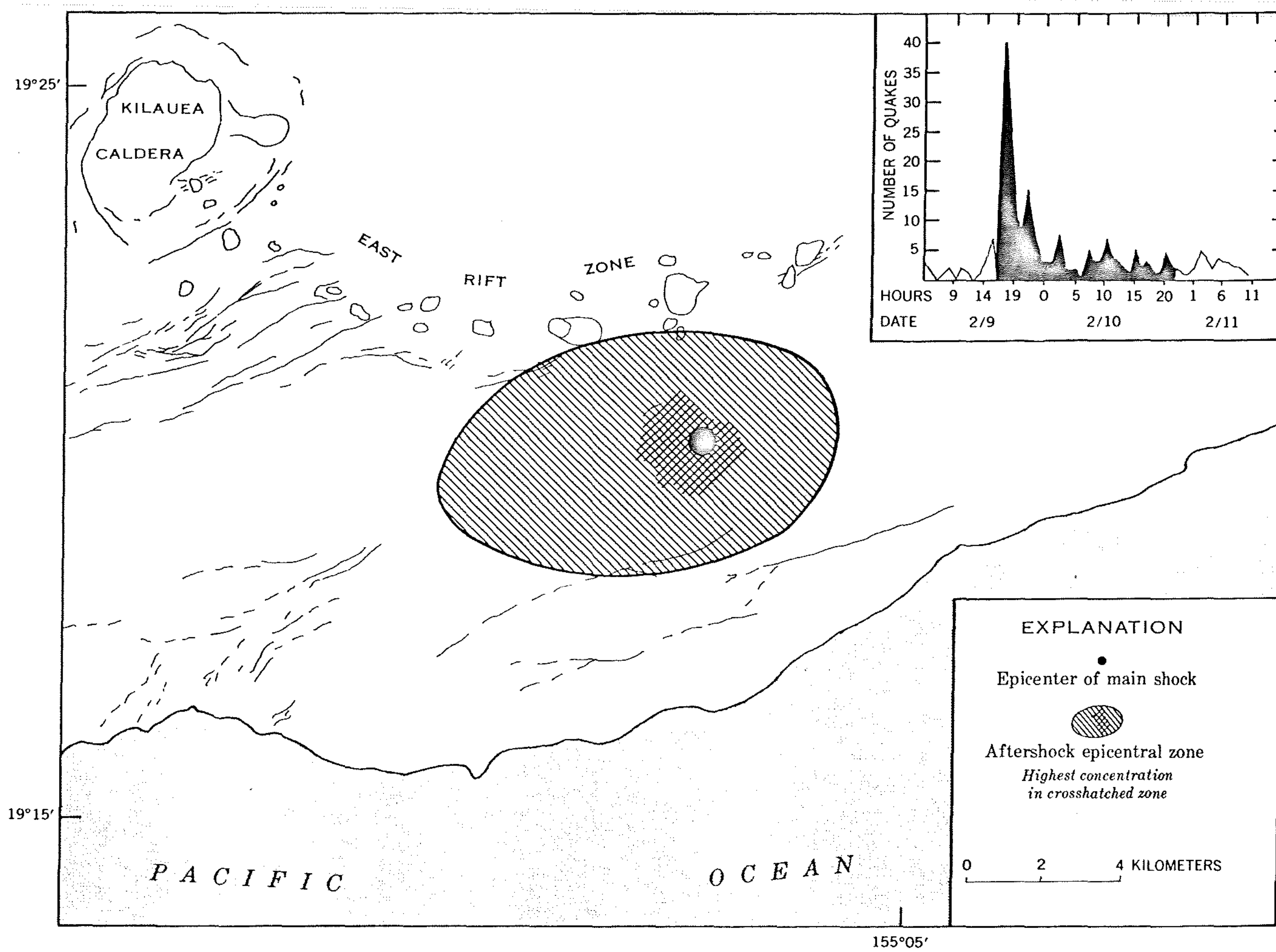

Figure 9.— Aftershock sequence from a magnitude-4.1 earthquake on February 9, 1969, located on the south flank at a depth of about 10 km. Map shows location of the main shock, the zone of concentrated aftershock activity, and the extent of the epicentral zone in relation to conspicuous structural features. Inset shows hourly frequency pattern; the darkened area indicates the period of aftershock activity.

Geodetic studies (Swanson and others, 1971a, b) indicate that the azimuth of displacement of the south flank is approximately at right angles to the trend of the east-rift fissures and Koae faults. The maximum stress axes (fig. 10) are generally within 10° to 20° of this direction. This approximate agreement in direction is surprising, considering the preliminary nature of the focal mechanism study. At present, however, the consistency of orientation of the stress axes, rather than their exact azimuth, is probably of most significance.

The south-flank earthquakes reach depths of 10 to 12 km (8 to 10 km using Hill's [1969] model), which is approximately the depth of the old sea floor on which Kilauea is built (Hill, 1969). These depths suggest that the entire south flank down to the old sea floor is being displaced away from the rest of the volcano.

A general model relating earthquakes to south-flank deformation can be suggested. With vigorous diking, probably by a process similar to hydrofracturing, rocks within the rift zone are rapidly strained beyond elastic limits, and swarms of small earthquakes exhibiting a narrow range of magnitudes are recorded. The intruding magma finally stops splitting the wallrock when magmatic pressure is relieved sufficiently, and conduits slowly widen to allow smoother passage; the earthquake swarms and, eventually, harmonic tremor diminish. To accommodate the new magma within the rift system, that part of the south-flank block adjacent to the intrusion is displaced seaward. In the subsequent stages of activity, stresses resulting from this displacement spread outward and deeper within the mobile south flank (Moore and Koyanagi, 1969), leading consequently to displacement of the entire south-flank block. The late-stage stresses are distributed over a wider area, and

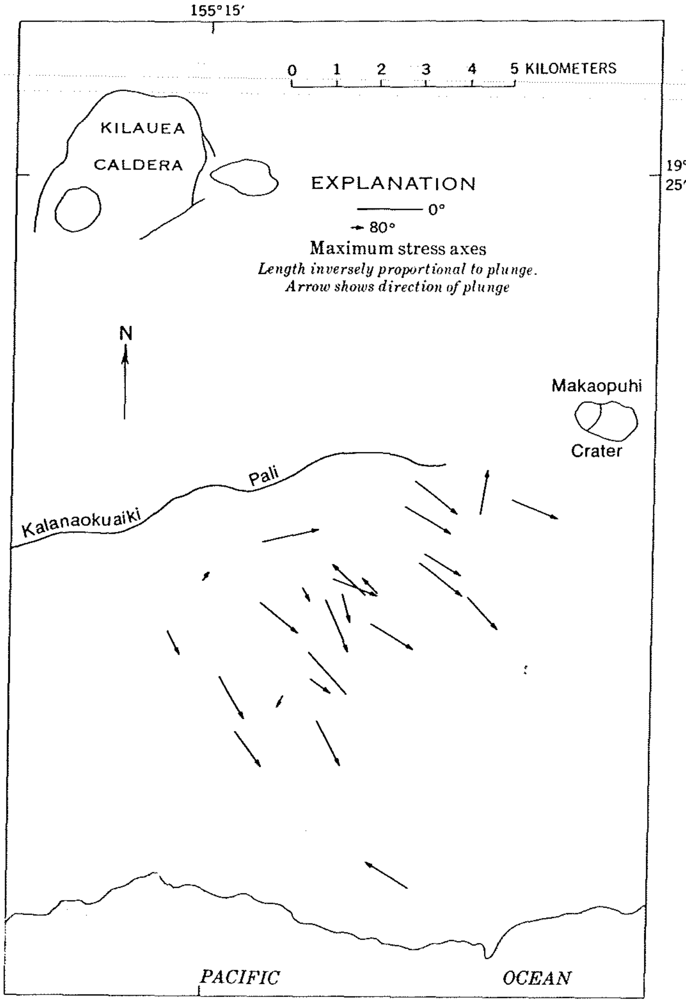

Figure 10.—Maximum stress axes for well-located south-flank earthquakes from October 1969 to March 1970 inclusive. Most axes plunge very gently southeastward. Kalanaokuaiki Pali is a cliff bounded by the southernmost fault in the Koae fault system, and Makaopuhi Crater is a conspicuous pit crater on the east rift.

the intensity of the activity is relatively reduced, so that rocks within the south flank begin to strain at slower rates. In the postmagmatic period, the earthquakes assume behavior more commonly observed in tectonic regions, displaying a wider range of magnitudes and occasional aftershock activity.

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