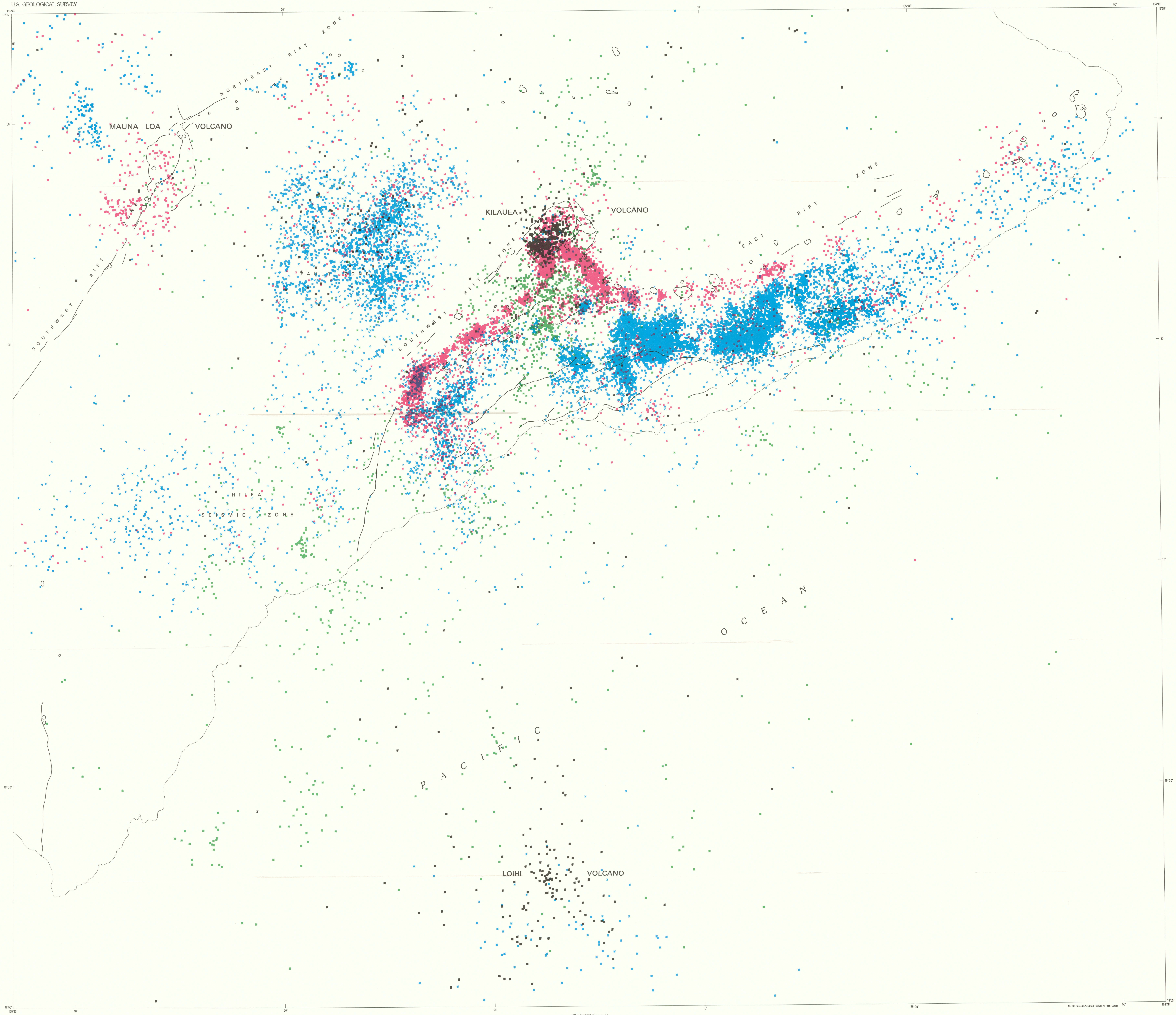
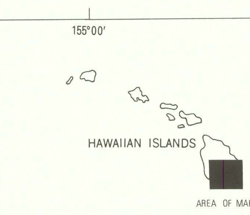
DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

MISCELLANEOUS INVESTIGATIONS SERIES
MAP I–1611



SCALE 1:100 000 (Approximate)



EXPLANATION

Earthquake depth in kilometers

- 0- 5 km
- 5-13 km
- 13-20 km
- 20-60 km
- Caldera or pit crater
- Fault

Kilauea is one of the most active volcanoes in the world, having erupted 31 times during the period 1952-1982, and 17 times during the 1968-1981 period covered by this map. Mauna Loa volcano has also been very active historically, although the only eruption during 1951-1983 was in 1975. Loihi was first recognized as an active volcano during the 1970's on the basis of two significant earthquake swarms (Klein, 1982) and detailed marine geologic studies (Malahoff and others, 1982; Moore and others, 1982). These three volcanoes account for nearly all of the contemporary eruptions and seismic activity in the Hawaiian Islands.

Mauna Loa, Kilauea and Loihi are the youngest and southernmost volcanoes in Hawaii. The passage of the Pacific plate over the Hawaiian hot spot at a speed of about 13 cm/yr (Dalrymple and others, 1973) formed a chain of mostly extinct volcanoes and seamounts. The three volcanoes on the map are also examples of different stages in the development of a Hawaiian volcano. They range from Mauna Loa (oldest, largest, and northernmost), through Kilauea to Loihi (youngest, smallest, and southernmost). Apart from the topographic edifice, the most prominent feature of each volcano is a summit caldera underlain by a magma storage reservoir within the upper five km of crust. The magma reservoirs are fed by vertical magma conduits having roots at a depth of at least 60 km in the mantle. The reservoirs in turn feed eruptions or intrusions either directly above in the summit caldera, or laterally into conduits within rift zones radial to the caldera. On Kilauea and Mauna Loa, rift zones consist of eruptive fissures, cracks, pit craters, and small lava shields. Each volcano has two rift zones whose orientations strongly influence the visible seismic pattern: Mauna Loa's rifts trend northeast and southwest from the caldera, Kilauea's trend southwest and east, and Loihi's are roughly north-south.

The network of seismic stations operated by the Hawaiian Volcano Observatory (HVO) to monitor the volcanoes has gradually expanded since the late 1950's (Klein and Koyanagi, 1980). Seismic stations are densest on Kilauea, and several stations were added on Mauna Loa in the mid 1970's. The number of stations within the map area grew from 22 in 1968 to 48 in 1981. In 1982 the station spacing was roughly 7 km on Kilauea and about 25 km on the rest of the island. Improvements in station coverage, timing precision, and location precision in 1967 mean that the plotted data for 1968 and later are significantly better in quality.

The data analysis procedures can be found, along with a complete list of all earthquakes located, in the annual HVO summaries (for example Nakata and others, 1982). The earthquakes on this map were uniformly located with the HYPOINVERSE program (Klein, 1978) using a linear gradient crustal model (Klein, 1981). The calculated errors (one standard deviation) in earthquake locations are typically several hundred meters on Kilauea, a kilometer or so on Mauna Loa, and about 2 km or less in areas of poor station coverage such as Loihi. The close agreement between most epicenter locations and the geologic structures with which they are associated means that the actual location errors seldom exceed the calculated errors.

The magnitude cutoff of 1.5 chosen for the plotted earthquakes eliminates most events of low significance and poor location quality. It also reduces the number of plotable earthquakes from more than 60,000 to about 20,000. The network sensitivity and analysis procedures are such that very few events larger than magnitude 1.5 were missed within about 5 km of Kilauea caldera. On Kilauea's flanks and Mauna Loa, however, the earthquake catalog may not be complete below a magnitude of about 2.3. The plotted sample of earthquakes in these regions is therefore incomplete above the magnitude 1.5 cutoff of the plot, but there are enough events to define active areas and tectonic structures.

DISCUSSION

The depth boundaries used to plot earthquakes in different colors were chosen to separate events into different tectonic categories. Earthquakes between 0 and 5 km depths are plotted as red dots and primarily represent "volcanic" earthquakes. The distinction here between "volcanic" and "tectonic" earthquakes is based on their association in space and time with observed eruptions and intrusions of magma. Even though Hawaiian "tectonic" earthquakes occur beneath a volcano, they are indirectly coupled to magmatic processes. On Kilauea, the shallow "volcanic" events mostly underlie the summit caldera and the two rift zones. They occur episodically and in rapid swarms, mainly in response to magma movement within Kilauea volcano. Shallow earthquake swarms generally accompany eruptions and intrusions of magma within the rift zones, and earthquakes migrate downrift in response to magma movement (Koyanagi and others, 1976). Shallow events also occur above the summit magma reservoir beneath Kilauea caldera during periods of inflation while the reservoir fills with magma from below. Shallow caldera seismicity thus anticipates eruptions by months or weeks, and reveals magma movement and a possible eruption within hours when a rapid swarm occurs.

Earthquakes in the 5 to 13 km depth category are plotted as blue dots and are primarily "tectonic" in nature. These events concentrate adjacent to but not directly below Kilauea's active rift zones. Most active is the south (seaward) flank of Kilauea adjacent to the westward half of the East Rift Zone. The plotted south flank earthquakes consist both of a continually-occurring background of seismicity and aftershocks of magnitude 5 and larger events, such as the November 1975 Kalapana earthquake (magnitude 7.2). South flank earthquakes sometimes show a moderate increase during or just following the larger Kilauea eruptions, but generally respond sluggishly to adjacent volcanic activity. Both their temporal pattern (Koyanagi and others, 1972) and focal mechanisms (Ando, 1979; Crosson and Endo, 1982) indicate that earthquakes result from north-south compressive stresses generated by repeated dike intrusion in the rift zones.

The second major seismic zone active between 5 and 13 km depths is the Kaoiki fault zone between Kilauea's Southwest Rift Zone and Mauna Loa. Like Kilauea's south flank, seismicity consists of both mainshock-aftershock sequences and a continuous background (Koyanagi and others, 1966). Focal mechanisms are generally right-lateral strike-slip on northeast trending planes, and apparently relieve compressive stresses generated at Kilauea's and Mauna Loa's rift zones (Endo and others, 1978). The Kaoiki and south-flank seismic zones merge into the Hilea seismic zone, a diffuse east-west band of earthquakes located 30 km south of Mauna Loa's summit. This zone was the site of two magnitude 5+ earthquakes in January 1982, whose occurrence, focal mechanism, and aftershock zone suggest a tectonic regime very similar to Kilauea's south flank (F. W. Klein, unpub. data, 1982).

The seismic and volcanic activity of Mauna Loa during the period covered by the map is far less than on Kilauea: most earthquakes resulted from periods of gradual inflation during 1973-75 and 1980-81, and the eruption of July 1975. By analogy with Kilauea, then, most Mauna Loa events are "volcanic" and magma-related. Since Mauna Loa's earthquakes locate both above and just below 5 km depth, that depth does not separate "volcanic" and "tectonic" seismicity as it does under Kilauea. The earthquakes beneath Mauna Loa's summit caldera and Northeast Rift are related to obvious magma conduits, and the seismicity to the northwest may represent a buried rift-like structure. Mauna Loa has no obvious "tectonic" flank seismicity, with the possible exception of the Kaoiki fault zone to the southeast and the Hilea seismic zone to the south. The low seismicity of Mauna Loa relative to Kilauea is probably a result of its low volcanic activity in recent years.

Few events occur in the next depth category between 13 and 20 km. One prominent zone, however, is directly beneath Kilauea Caldera. Earthquakes under the caldera span most of the depth range from the surface to about 55 km, and define the vertical magma conduit (Ryan and others, 1981). The conduit feeds Kilauea's shallow storage reservoir from mantle sources. Earthquakes from this conduit consist both of rapid swarms and background seismicity, and do not closely correlate with episodes of shallow volcanic or seismic activity. The resupply of magma to Kilauea's shallow reservoir from depth thus appears to be a process detached from rapid expulsions of magma during eruptions and intrusions.

The other zone active between depths of 13 and 20 km is Loihi submarine volcano. Loihi's major earthquake swarm during 1971-72 consisted both of rapid swarms in concentrated zones beneath the summit, and subsequent diffuse and continuous seismicity on the southwest flank (Klein, 1982). The seismicity of Loihi thus is very analogous in pattern to that of Kilauea. The occurrence at Loihi of summit followed by flank seismicity was easily recognized because the swarm was one episode isolated in time: the cause and effect relationship of summit and flank activity is less obvious on Kilauea because volcanic events are so numerous and seismicity is so high. Earthquake depths at Loihi may be in error by about 10 km because there are no offshore seismic stations and the crustal velocity model in the vicinity of Loihi is somewhat uncertain. Depth thus cannot be used to discriminate volcanic and tectonic earthquakes as on Kilauea, nor is it certain that most events actually are below 13 km depth as plotted.

Earthquakes with depths below 20 km are plotted as green dots. The densest concentration of deep earthquakes is below and slightly south of Kilauea Caldera at a depth of about 30 km. This cluster is part of the vertical magma conduit mentioned earlier, which dips slightly southward at this depth. Kilauea's seismic root also fans out, becomes diffuse, and joins a seismic zone which is mostly between the Kilauea, Mauna Loa and Loihi summits at a depth of about 40-50 km (see the cross-section in Klein, 1982). The deepest earthquakes on the map are roughly equidistant from the three volcanic summits, are at depths of 45-55 km, are associated with deep harmonic tremor and therfore magma flow, and are an expression of the contemporary Hawaiian hot spot.

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EARTHQUAKE MAP OF SOUTH HAWAII, 1968–1981

By
Fred W. Klein and R. Y. Koyanagi

1985

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