EARTHQUAKES AND RELATED CATASTROPHIC EVENTS, ISLAND OF HAWAII, NOVEMBER 29, 1975

A Preliminary Report

GEOLOGICAL SURVEY CIRCULAR 740

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By Robert I. Tilling, Robert Y. Koyanagi, Peter W. Lipman, John P. Lockwood, James G. Moore, and Donald A. Swanson

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ABSTRACT

The largest earthquake in over a century—magnitude 7.2 on the Richter Scale—struck Hawaii the morning of November 29, 1975, at 0448. It was centered about 5 km beneath the Kalapana area on the southeastern coast of the island (lat 19°20.1′ N., long 155°01.4′ W.). The earthquake was preceded by numerous foreshocks, the largest of which was a 5.7-magnitude jolt at 0336 the same morning, and was accompanied, or closely followed, by a tsunami (seismic sea wave), massive ground movements, hundreds of aftershocks, and a volcanic eruption.

The tsunami reached a height of 12.2–14.6 m above sea level on the southeastern coast about 25 km west of the earthquake center, elsewhere generally 8 m or less. The south flank of Kilauea Volcano, which forms the southeastern part of the island, was deformed by dislocations along old and new faults along a 25-km long zone. Downward and seaward fault displacements resulted in widespread subsidence, locally as much as 3.5 m, leaving coconut palms standing in the sea and nearly submerging a small, near-shore island. A brief, small-volume volcanic eruption, triggered by the earthquake and associated ground movements occurred at Kilauea's summit about three-quarters of an hour later. The earthquake, together with the tsunami it generated, locally caused severe property damage in the southeastern part of the island; the tsunami also caused two deaths. Damage from the earthquake and related catastrophic events is estimated by the Hawaii Civil Defense Agency at about $4.1 million.

The 1975 Kalapana earthquake and accompanying events represent the latest events in a recurring pattern of behavior for Kilauea. A large earthquake of about the same magnitude, tsunami, subsidence, and eruption occurred at Kilauea in 1868, and a less powerful earthquake and similar related processes are believed to have occurred in 1823. Indeed, the geologic evidence suggests that such events have been repeated many times in Kilauea's past and will continue. The 1975 events serve as a critical, though tragic, reminder of the dynamic nature of the volcano and point up the need for careful land-use planning and adequate building codes to minimize damage and loss of life from similar events in the future.

Detailed scientific study of the cause and effects of the November 29, 1975, event will take many months. This report summarizes information available in February 1976.

NARRATIVE

At 0336[1] on Saturday, November 29, 1975, a sharp earthquake, foreshock to the largest in over a century, woke most residents on the island of Hawaii, including 32 people camped near the beach at Halape, a coconut palm grove on the southeastern coast (fig. 1). This quake, 5.7 on the Richter Scale, was centered about 8 km beneath the south flank of Kilauea Volcano, approximately 5 km inland of Kamoamoa (fig. 1).[2] In the dim predawn light, the campers at Halape near the base of 320 m-high Puu Kapukapu (Forbidden Hill) saw dust clouds rising from rockfalls that the earthquake sent crashing down its steep face. Instinctively, some of the campers moved their sleeping bags away from the area of the falling rocks, closer to the beach. One young boy told his father that he felt something bad was going to happen and that he wanted to leave. He was reassured, and most of the campers went back to sleep.

About an hour later, at 0448, a second, much stronger, earthquake struck the island. Unlike the earlier one, this quake, centered about 5 km beneath Kilauea's south flank near Kamoamoa, did not quickly subside in intensity. The violent ground shaking caused electrical power outages in many parts of the island, and seismographs at the Hawaiian Volcano Observatory went off scale. Scientists at more distant locations, as at stations in North America, Japan, and New Zealand, where seismographs did not go off scale, later calculated a Richter magnitude of 7.2. The

[1]All times Hawaiian standard time (H.s.t.) unless otherwise noted.
[2]All measurements given in metric units.

last previous earthquake of similar magnitude occurred in 1868.

At Halape, about 25 km west of the epicenter, the campers were able to stand during initial periods of the violent shaking but were soon thrown to the ground if they did not cling to trees or large rocks for support. A deafening roar rose from Puu Kapukapu as numerous rockfalls rumbled down its south cliff face. Many campers, frightened by the noise, moved still closer to the beach, away from the falling rocks. Some thought about the possibility of a tsunami and ran toward the beach to check the sea. Their flashlights shone on a slowly but noticeably rising sea. Within a minute or so, sea level began to rise faster, causing the campers to run back toward the rockfalls at the base of Puu Kapukapu. The rising water, now a breaking, surging wave, knocked many of the campers off their feet, briefly submerging some as they fled for higher ground. They had barely time to catch their breath before a second wave struck, far more turbulent and higher than the first, carrying every loose object in its path as far as 100 m inland.

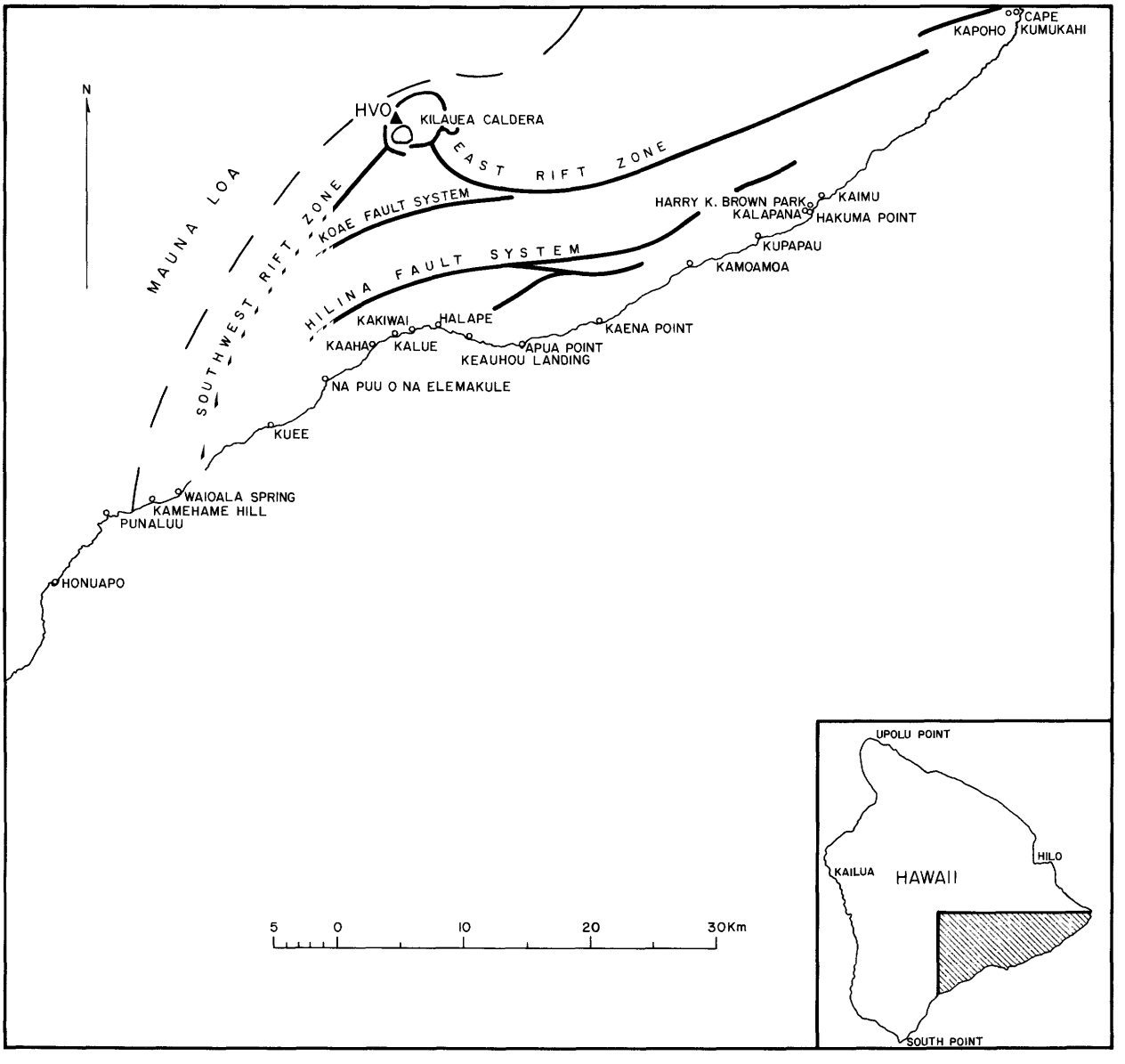


FIGURE 1.—Index map of the island of Hawaii showing the location of the Hawaiian Volcano Observatory (HVO) and other places on the island affected by the events of November 29, 1975.

Trees, debris from the Halape shelters, rocks, horses, and people were washed into a large, pre-existing crack in the ground, 5–7 m deep and 10 m or more wide, churned by the surging wave. One survivor said he felt like he was "inside a washing machine." Several smaller waves repeatedly washed over the exhausted victims stranded in the crack. One person was drowned or battered to death during the terrifying ordeal; another was swept out to sea and is presumed dead. Nineteen people were injured at Halape; seven required hospitalization. Four of ten horses were lost.

The large waves that wreaked havoc at Halape were caused by sudden nearby earth movements. These waves reached Halape within 30 seconds after the strongest shaking had ended, spreading outward from their source at speeds of several hundred kilometers per hour.

At Punaluu (fig. 1), 30 km southwest of Halape, the disastrous quake woke the several families camped near the beach and others sleeping in nearby houses, but few suspected that a tsunami was moving swiftly toward them. Sea level began rising rapidly within a few minutes after the earthquake, forcing campers and residents to wade quickly to higher ground. The largest wave arrived about 10 minutes later, destroying seven homes and two vehicles and causing interior damage of nearly $1 million as it swept through a large beachfront restaurant and gift shop; the structures remained standing. No injuries were reported. Farther southwest, at Honuapo, the spreading tsunami damaged a fishing pier, destroyed park facilities and a warehouse, then continued to Kaalualu Bay, 21 km southwest of Punaluu, where it damaged vehicles, ravaged a campsite, and badly frightened seven campers.

In Hilo (fig. 1), the main population center on the island, the major earthquake toppled some chimneys, damaged structures, shattered windows, and shook merchandise from shelves. Civil Defense authorities sounded a tsunami watch, and much of the low-lying coastal area was evacuated. At about 0510, when the water level dropped with the recession of the first tsunami, crew members of the U.S.S. *Cape Small*, a Coast Guard cutter moored in Radio Bay in Hilo Harbor, watched their ship settle to the muddy bottom and begin to list to one side. A series of waves surged in and out of the bay at approximately 15-minute intervals, smashing some small boats and washing others onto docks; four boats were sunk and three damaged. One of the waves washed a car from the pier into the harbor; another threw a man from his boat onto the pier, then washed him back into the water and onto his boat as the wave receded.

At 0532 lava began to fountain from a 500-m-long fissure on the floor of Kilauea Caldera and continued to erupt sporadically until about 2200. No injuries or property damage resulted from this small eruption, but the earthquake and tsunami had already taken a heavy toll in Hawaii.

THE EARTHQUAKE

Data from seismometers operated by the Hawaiian Volcano Observatory (HVO) placed the 7.2-magnitude earthquake about 5 km west-southwest of Kalapana on Hawaii's southeastern coast (lat 19°20.1′ N., long 155°01.4′W.) at a depth of about 5 km (fig. 2). The earthquake was strong enough to be felt on the neighbor island of Maui and on Oahu, more than 400 km from the epicenter.

During and immediately after the earthquake, intense bursts, glows, or flashes of white to bluish light, lasting from a few seconds to about a minute, were observed by a number of people, including some of the campers at Halape. Such "earthquake lights" have been observed before, during, and after major earthquakes, mostly in Japan and California. Although there is no generally accepted scientific explanation for their occurrence, earthquake lights apparently result from earthquake-induced oscillations or distortions of the atmosphere.

STRUCTURAL DAMAGE

The main earthquake caused structural damage estimated at about $2.7 million. A preliminary survey conducted by various governmental agencies showed minor to moderate damage to 5 churches (4 in Hilo, 1 in Opihikao), 11 commercial buildings (10 in Hilo, 1 in Mountain View), and 80 homes (51 in Hilo, 23 in Puna, 2 in Hamakua, 3 in Ka'u, and 1 in Kona). Five poorly constructed or old houses were reported completely demolished (4 in Hilo, 1 in Ka'u) (fig. 3).

All available sources of information were used to estimate relative intensities of the November 29 earthquake in different parts of the island (table 1). Earthquake *intensity* is defined in terms of observed physical effects and damage related to

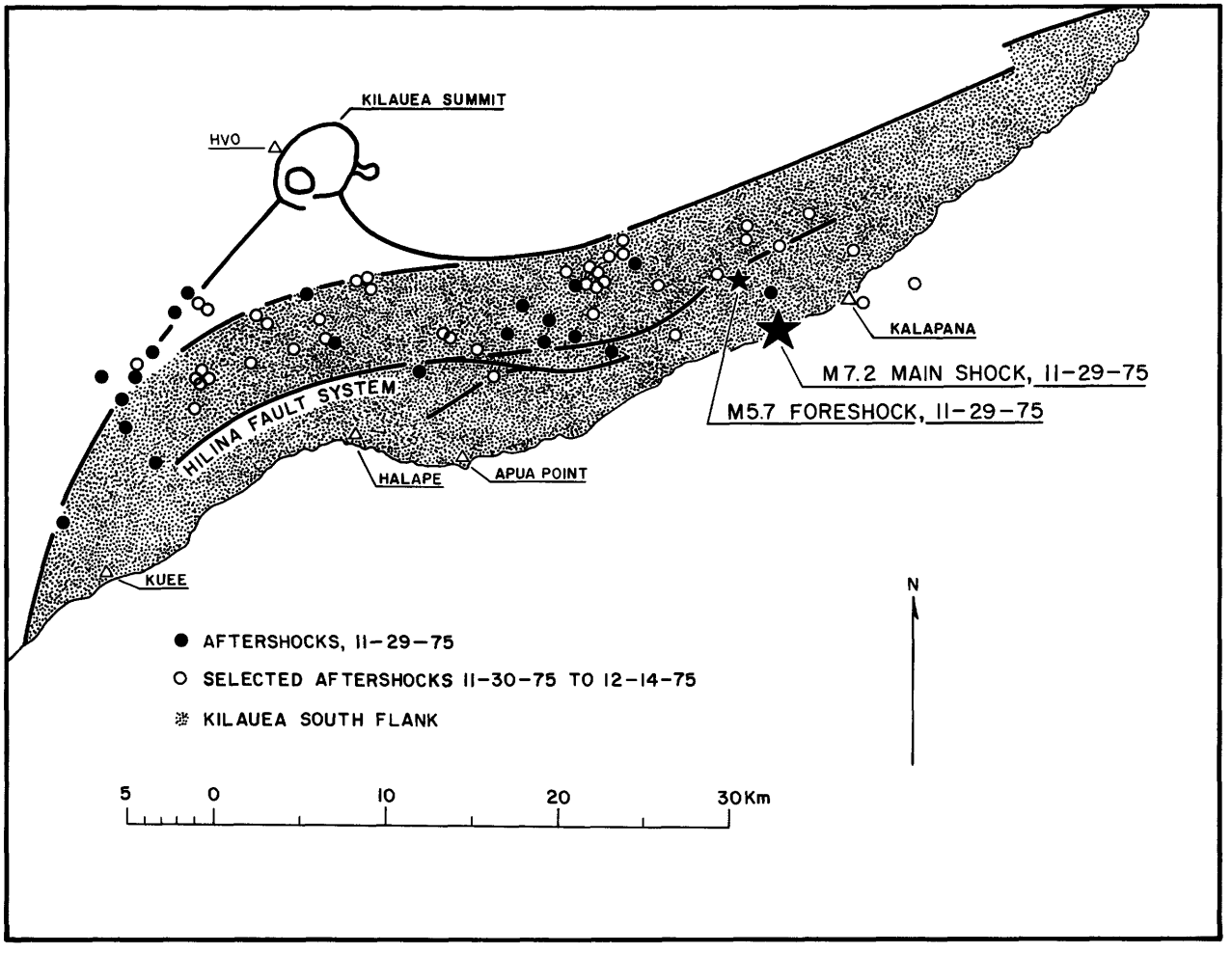


FIGURE 2.—Epicenters of the November 29, 1975, magnitude-7.2 earthquake, its largest foreshock (magnitude 5.7), and selected larger aftershocks. The fault systems and rift zones are as shown in figure 1.

local ground shaking (table 2); it differs from *magnitude,* which is calculated from data obtained by seismic instruments. Earthquake-intensity variations may be contoured to produce isoseismal maps commonly used by seismologists and civil engineers to assess patterns of earthquake damage and effects.

As much of Hawaii is unpopulated, direct observations of ground shaking and its effects are not known for large areas; for this reason, the intensity map for the main earthquake (fig. 4) is based on irregularly distributed, statistically inadequate, data. Nonetheless, observations do show most buildings within 20 km of the earthquake epicenter sustained no significant structural damage from the ground shaking, whereas buildings in Hilo and at the summit region of Kilauea Volcano, far from the epicenter, showed extensive damage. The building at the Wahaula Visitor Center of Hawaii Volcanoes National Park, located almost directly at the earthquake epicenter, was virtually undamaged. The apparent offset of the zone of maximum damage (intensity VII-VIII; fig. 4) from the epicentral region poses an enigma for which there are no ready solutions at present.

EARTHQUAKES PROBABLY RELATED TO MAIN EARTHQUAKE

The general level of seismicity on the south flank of Kilauea increased somewhat during the month preceding the main earthquake (fig. 5), and several of the larger (magnitude 4–5) shocks were felt islandwide. A number of these earthquakes, which in hindsight may be called foreshocks, were located near the Kalapana area. The

TABLE 1.—*Intensities and description of damage from the magnitude 7.2 earthquake, November 29, 1975*
[Intensities are based on the Modified Mercalli Scale, table 2]

District (towns, villages)	Intensity	Description of damage
Hilo	V–VIII	Extensive damage in downtown area. Minor cracks in road, water pipes, concrete walls and floors, plaster. Minor cracks and floor-to-wall separations a few millimeters wide and bowing of the walls were observed in steel-reinforced concrete structures at the hospital, several schools, and libraries. Some of these buildings 5 to 10 mm vertical drops in some floor sections. Churches in Hilo reported damage to a pipe organ, cracks in hollow tile blocks, breaks in a swimming pool, and water lines. Hotels, apartments, and business buildings suffered structural and equipment damage. Shelved items in markets fell or tumbled over. Fifty-one home owners in Hilo reported loss due to broken water pipes, windows, plate glass, water gutters; cracks in concrete walls and steps; cupboards torn away from walls and breakage of chinaware; collapse of stone walls and fences; plumbing damage and cesspool cave-ins; house and garage shifting from foundation; doors and doorways distorted; leaks in roofs; minor ground cracks, chipping of ceramic tile floors; collapse of stairways; cracking or crumbling of brick fireplace chimneys.
Puna (Volcano, Hawaii Volcanoes National Park)	VII–VIII	Extensive ground cracking caused heavy road damage in the National Park. On the Crater Rim Road, damage was reported in Waldron Ledge, Kilauea Military Camp, Halemaumau, and Keanakakoi sections. Damage was noted on the Chain of Craters, Ainahou, and Hilina Pali Roads. A water tank at the Youth Conservation Corps and Kipuka Nene was damaged. Waterlines in several areas broke. Fireplace chimneys at Kilauea Military Camp and at a residential home in Volcano collapsed. About three wooden water tanks were destroyed, and several others were partially damaged at Volcano. At the Volcano Observatory, violent ground motion lasted about half a minute, many loose objects moved or turned over, sounds were heard from rockfalls in crater and water sloshing in water tank.
Puna (Kalapana)		A wood frame house shifted 1 m from foundation. One water tank damaged. Many small road cracks. Residents report strong shaking; that loose objects fell off shelves.
(Kapoho)		Minor cracks and small rockfalls from walls of cinder cones.
(Kurtistown)		Damage in seven residential homes—cracked concrete steps, house and garage moved from foundation, 10-cm wall separation, roof separation, chinaware broken from falling out of cupboards. Rock wall damaged.
(Opihikao)		Two water tanks at a church destroyed.
(Pahoa)		Three homes moved from foundation. Other damage included a broken waterline, collapsed water tank, and toolshed.
(Glenwood)		Loose objects fell off shelves, water splashed out of fish bowl.
(Mountain View)		Floor of water tank cracked; plexiglass cracked; television set shifted off stand and fell to the floor; rock wall damaged.
(Hawaiian Paradise Park)		One house shifted off foundation; cabinets toppled off walls.
(Black Sands Subdivision)		Damage reports from two homes. One house dropped 7.5 cm; walls cracked, loose objects fell. At other residence, water tank fell and house beams cracked.
(Hawaiian Beaches)		A garage concrete slab cracked.

TABLE 1.—*Intensities and description of damage from the magnitude 7.2 earthquake, November 29, 1975*—Continued

District (towns, villages)	Intensity	Description of damage
Ka'u	IV–VII	In Naalehu, foundation to one ranch house cracked and roof damaged. One homeowner in Pahala reported doors distorted, house moved from concrete foundation, furniture and stereo fell.
Kona	IV	Loose objects fell off shelves; strong shaking, rockfalls in Kealakekua.
Hamakua	IV–VI	Landslides on coast road at Laupahoehoe and Honomu; loose objects fell off shelves. Heavy rolling ground motion.
Kohala	III–IV	Some loose objects moved; shaking felt by many people.

largest foreshock at 0336, 5.7 magnitude, occurred about 4 km northwest of, and 72 minutes before, the 7.2-magnitude quake (fig. 2).

A thousand or more earthquakes per day (fig. 5), some felt and heard by local residents, continued to shake the region for 2 weeks following the November 29 event. These earthquakes, termed aftershocks, were distributed primarily north of the inland margin of the Hilina fault system west of the epicenter of the main earthquake. Most occurred at depths of 5–7 km. During the same time, the frequency of earthquakes increased beneath the southwest flank of Kilauea, suggesting possible migration of magma into the southwest rift zone as the summit area deflated after the brief summit eruption. Aftershock activity continues (mid-February 1976), though at a steadily declining level. Extrapolation of the present rate of diminution of activity (fig. 4) and comparison with previous well-documented major earthquakes in Hawaii suggest that aftershocks will continue into the late summer of 1976, when seismic activity on the south flank may return to its normal level, like that of August-October 1975.

Studies of past seismicity beneath the south flank of Kilauea show some similarities of earlier events to the present activity. The largest earth-

TABLE 2.—*Modified Mercalli Scale (1956 version) of earthquake intensity*

[From Charles F. Richter, 1958, Elementary Seismology: San Francisco, W. H. Freeman and Co., 768 p. Annotated by Richter (CFR)]

I. Not felt. Marginal and long-period effects of large earthquakes.

II. Felt by persons at rest, on upper floors, or favorably placed.

III. Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.

IV. Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV wooden walls and frame creak.

TABLE 2.—*Modified Mercalli Scale (1956 version) of earthquake intensity*—Continued

V. Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.

VI. Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken (visibly, or heard to rustle—CFR).

VII. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments—CFR). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII. Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

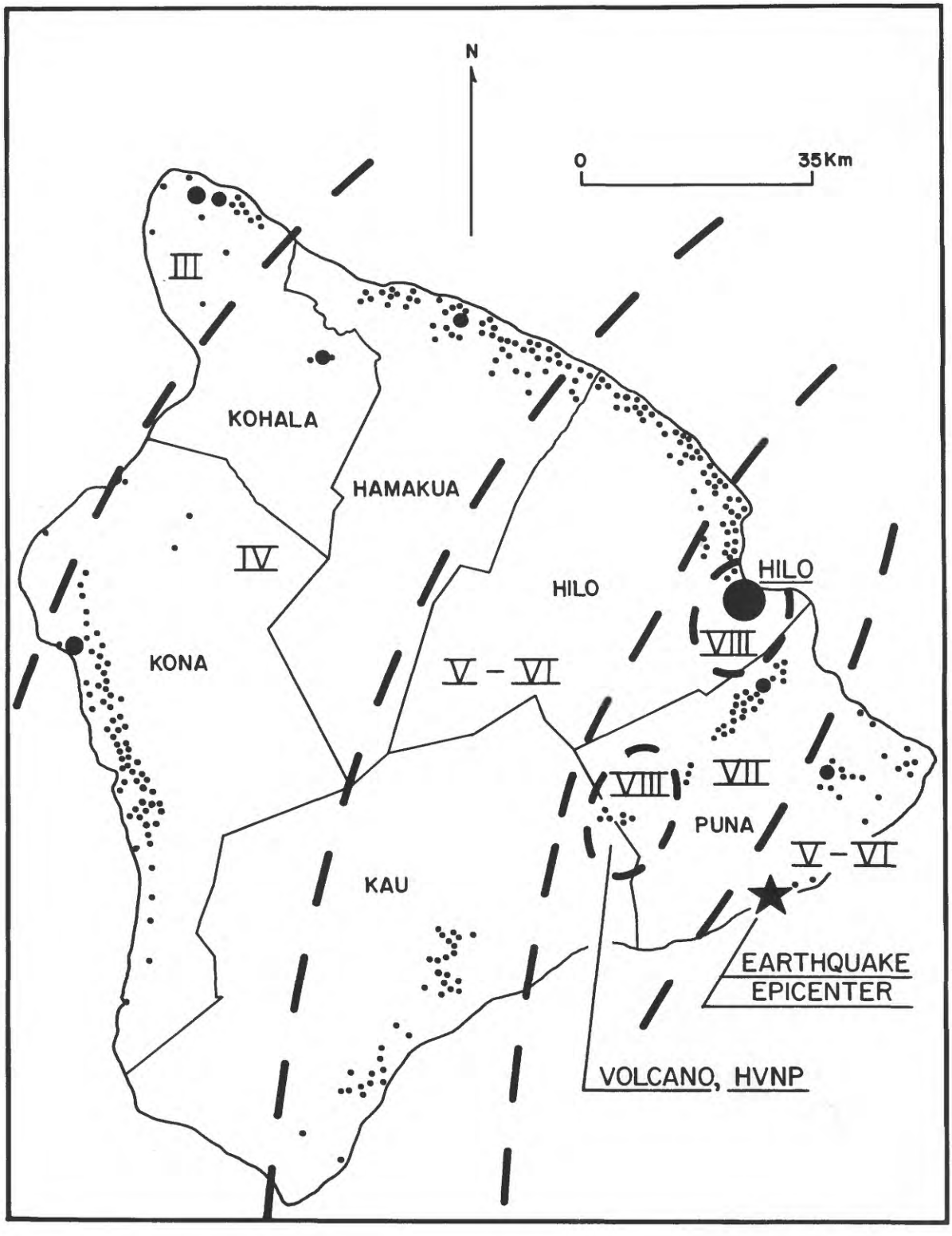
IX. General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. (General damage to foundations—CFR.) Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, and craters.

X. Most masonry and frame structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI. Rails bent greatly. Underground pipelines completely out of service.

XII. Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

FIGURE 3.—Damage caused by November 29, 1975, earthquake. *A*, Two children were trapped in this damaged home about 7 km north of Hilo. *B*, Spilled merchandise in Hilo supermarket. *C*, Collapsed chimney that fell through roof, dining room, Kilauea Military Camp, Hawaii Volcanoes National Park. *D*, Volunteers replace 300-lb granite headstone toppled by earthquake at churchyard, Kurtistown, 14 km south of Hilo. *E*, Fallen ceiling plaster and cinder blocks, Hilo High School. (Photographs: *A*, UPI; *B*, *C*, *E*, Larry Kadooka, *Hawaii Tribune-Herald; D*, George Abe, Hawaii Island Chamber of Commerce.)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quake to occur near Kalapana during this century was a 6.5-magnitude shock in March 1954. Unfortunately, the seismic network and coverage before 1955 was limited, and earthquake determinations were far less precise than at the present time. Nonetheless, some critical comparisons can be made.

The 6.5-magnitude earthquake on the morning of March 30, 1954, located about 4 km west of Kalapana, was preceded by a 6.0-magnitude foreshock nearly 2 hours before and a few kilometers inland (fig. 6). The main shock was followed by intense aftershock activity, probably clustered in an elongate belt along much the same part of the Hilina fault system as the aftershock area related to the 1975 earthquake (fig. 6). In the time between 1954 and 1975, several other moderate (magnitude 4–5) earthquakes within the Hilina fault system west of the main 1954 earthquake were accompanied by aftershock activity. In each instance, if the principal earthquake was located in the eastern part of the Hilina fault system, the aftershock area was offset or elongate west of the main epicenter, whereas if the main earthquake originated in the central part of the fault system, the aftershock area was offset or elongate eastward.

From October 1961 until November 29, 1975, no earthquakes larger than magnitude 4.5 occurred in the Kalapana area. During this time, most earthquakes within the Hilina fault system occurred in a zone extending eastward from an area northwest of Apua Point nearly to Kalapana, and in the more recent activity (1971–74), in the western end of the system. No moderate or large earthquakes have struck the part of the Hilina system between Apua Point and Na Puu O Na Elemakule (fig. 6) for more than 20 years. It is significant that this part of the fault system is the area in which 1975 ground breakage was minimal. Equally significant, aftershock activity in Kilauea's south flank from 1950 to 1975 was restricted to a 6-km-wide belt bounded on the south by the northern edge of the Hilina fault system; the virtual absence of aftershock activity farther south (fig. 2) is not yet understood.

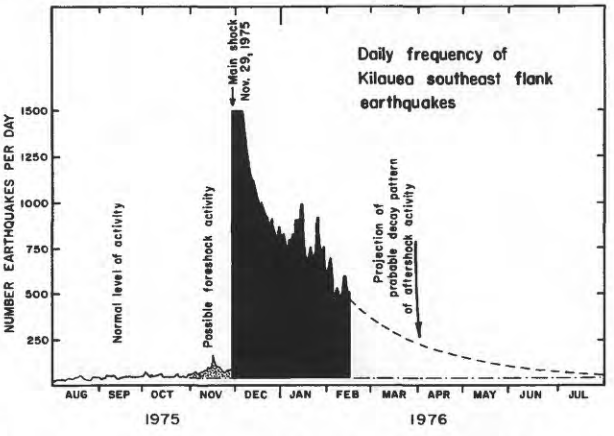


FIGURE 5.—Daily frequency of earthquakes within the south flank of Kilauea from August 1975 through mid-February 1976. Most of these earthquakes were much too small to be felt.

THE TSUNAMI

The tsunami was generated by sudden ground motion associated with the main earthquake. It produced one of the largest waves recorded in Hawaiian history and the only destructive one generated locally in the 20th century, killing two people and causing property damage of about $1.4 million. Had the tsunami not expended much of its energy on the sparsely populated southeast coast of the island, it probably would have caused considerably more property damage, injuries, and deaths.

CHRONOLOGY

The 32 campers at Halape (fig. 1) were the first to experience the tsunami. The sea began slowly and quietly rising within 10–30 seconds after ground shaking had diminished. No withdrawal of water was observed before this initial rise. The rising water rapidly developed into a rushing wave, followed by at least two more large waves. The major part of the tsunami was over a scant 10 minutes after it had begun, and the highest wave reached 14.6 m above the postsubmergence

FIGURE 4.—A preliminary isoseismal map of the island of Hawaii for the 7.2-magnitude earthquake, November 29, 1975 (compiled from damage reports summarized in table 3 and other sources). Intensities (III–VIII) are based on the Modified Mercalli Scale, 1956 version (table 2). Areas in Hilo, Volcano, and Hawaii Volcanoes National Park (HVNP) generally were most damaged (intensity VIII). Approximate population density of the island shown by dots; each small dot represents 100 people; larger dots represent principal towns containing from a few hundred to several thousands of people.

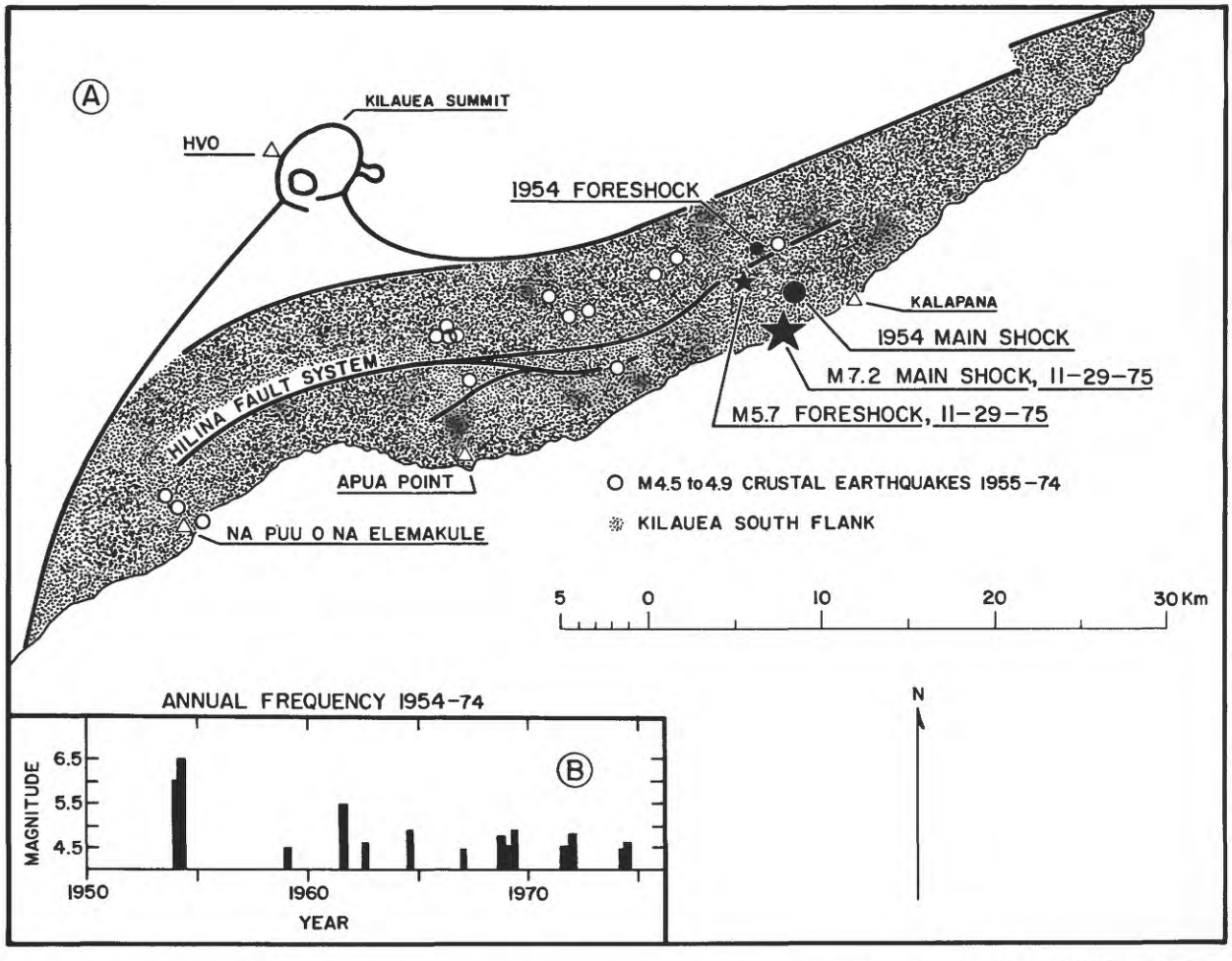


FIGURE 6.—*A*, Epicentral distribution of moderate to large earthquakes beneath Kilauea's south flank, 1950 to 1974. Fault systems and rift zones as shown in figure 1. *B*, Distribution by time and magnitude (M) of earthquakes plotted in *A*. With gradual expansion and upgrading of HVO seismic network since 1954, the uncertainty in earthquake locations has improved from about 5-km radius of error to about 1-km radius of error or better.

shoreline (fig. 7). Observations at other places indicate that the tsunami consisted of five or more distinct waves.

The waves spread east and southwest from their source near Halape at approximately 300 km per hour. At about 0508, the tsunami struck Hilo Bay, where the first effect was a 0.5-m rise of water, followed by a larger recession; the second and largest wave, about 2.5 m high, crested at approximately 0530. Moving southwest from its source, the tsunami struck Punaluu shortly before 0500; the first wave was relatively small, but the second surged several hundred meters inland and reached 5.5 m above sea level. The spreading tsunami damaged the park area at Honuapo 6 km to the southwest, rounded South Point, and struck the highly developed west (Kona) coast of Hawaii at about 0515. At Keauhou Bay, some fishing boats were sunk and others damaged by a 2.5-m wave that crested over the pier, crashed through a house, and left one fishing boat stranded on the dock. At Kailua-Kona, the wave crested at 2.1 m, piled debris against a newly completed hotel, sank one boat, and damaged three others (fig. 8).

Along the Kona Coast, the tsunami caused wide oscillations in sea level for more than an hour. At 0521, water receded 1.2–1.5 m at Napoopoo, at 0527 water receded 1.5–2.4 m at Kahaluu, and at 0528 water receded 2.4 m at Kailua; at 0535 water rose at Maniui beach, at 0536 high waves were reported at Kahaluu, at 0545 the

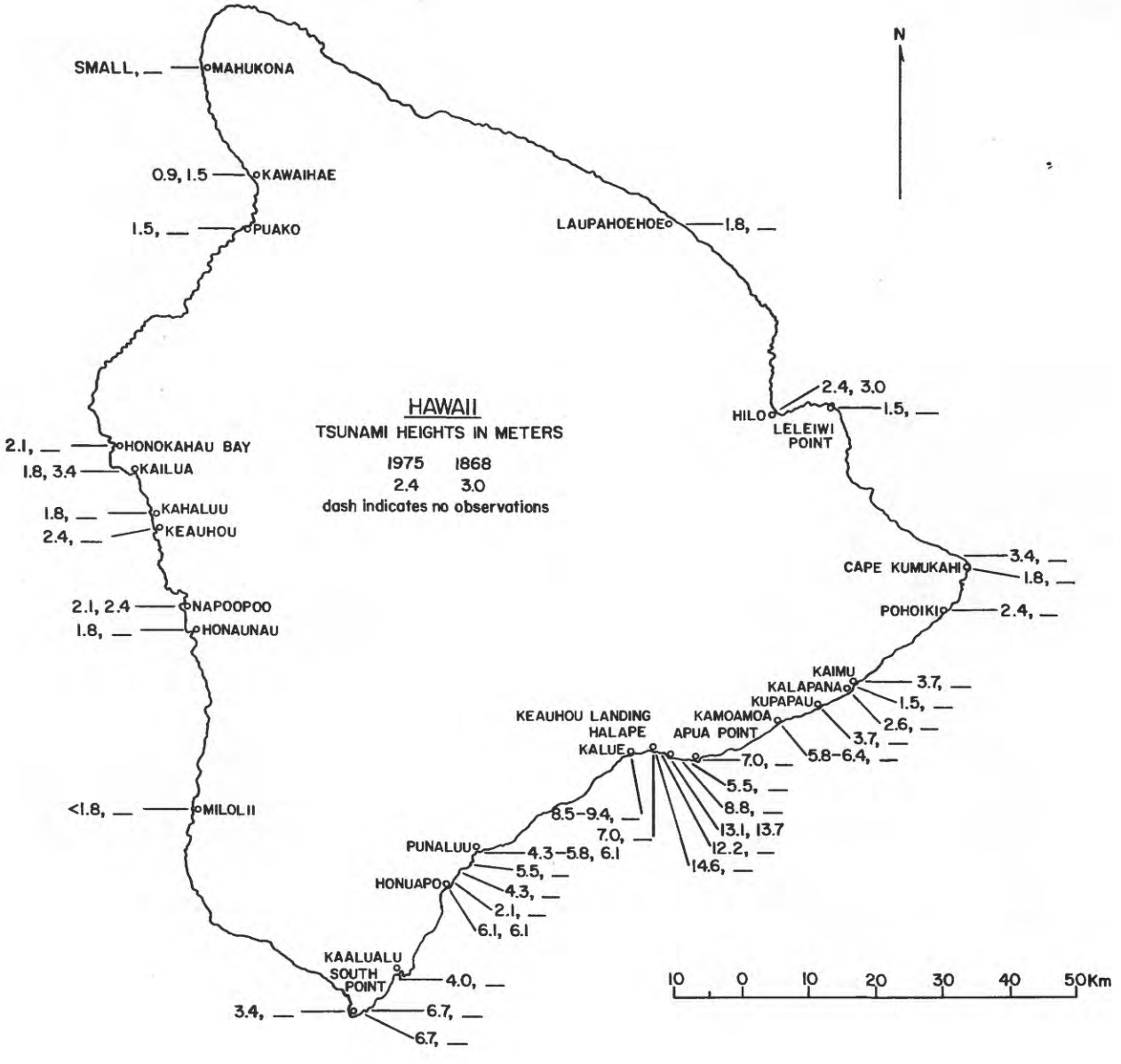


FIGURE 7.—Maximum heights of the two locally generated tsunamis (April 1868 and November 1975) on the shore of the island of Hawaii in historic time. All wave heights are given in meters relative to present, that is, postsubsidence, mean lower low water.

Kailua pier was under water, at 0650 water was over the Alii Drive roadway in Kailua, and at 0658 wave action continued in Keauhou Bay.

The wave was recorded by tide gages throughout the Hawaiian islands and elsewhere (table 3), but did no serious damage west of the Island of Hawaii. At Hana, Maui, a fisherman, noting an unusual recession of water at about 0530, waded out through the surf with a throw net before water rising neck-high drove him back. Tide gages on Oahu and Kauai registered the passage of the tsunami only a few centimeters high. Tide gages along the coast of California, Alaska, and some Pacific islands registered the tsunami 4–6 hours later. The wave caused minor damage to floating dock facilities at Catalina Island off the California coast.

FIGURE 8.—Damage caused by earthquake-related tsunami, November 29, 1975. *A*, Collapsed concrete finger pier, Wailoa River estuary, Hilo. *B*, Overturned boat, Wailoa River small-boat harbor. *C*, House shoved 25 m inland off its foundation, Punaluu, *D*, Foundation remains of a warehouse destroyed at Honuapo. *E*, Piano washed out of restaurant, Punaluu. *F*, Tables and chair (on branch) from restaurant deposited near pond, Punaluu. *G*, Demolished home, Punaluu. *H*, Car com-

pletely turned around and smashed, Punaluu. *I*, Powerboat washed onto dock, Keauhou Bay, Kona. (Photographs: *A, B,* Hugh Clark, *Honolulu Advertiser; C,* Paul Miyasaki, *Hawaii Tribune-Herald; D, H,* Andy Badig, *Ka'u News; E, F,* George Garcia, Kilauea Military Camp; *G,* David Shapiro, *Star-Bulletin; I,* Leigh Critchlow, *Hawaii Tribune-Herald.)*

CHARACTERISTICS

The tsunami reached its maximum height of 14.6 m above mean lower low water about 1.5 km east of Halape (fig. 7), where it was channeled against a low cliff trending about normal to the coast. Generally the tsunami rose highest on the low ground within the Halape-Keauhou Landing area, where it averaged about 9 m above low water. This part of the coast subsided 3–3.5 m during and immediately after the earthquake; it is not known whether the wave swept the coast before or after the subsidence was complete.

The scouring action of the tsunami was most extensive in this region. Coconut palm trees were rarely felled by the wave, but most other trees, particularly keawe, were totally uprooted, shattered, and carried up to the high splash mark (fig. 9). One 9-m-high casurina tree (iron-wood) at Keauhou Landing remained standing off the submerged coast but was badly scarred 3 m above sea level by debris carried by the wave. The high splash mark is marked on land by a pile of trees, bagasse, rocks, and other debris and by the inland margin of a zone of withered leaves and grass killed by salt water.

The tsunami deposited great numbers of small fish, crabs, and other sea life up to the high splash mark, but rarely were large water-worn beach cobbles and coral heads carried this far. The stench of rotting marine life was strong for many days afterward. Angular blocks of lava picked up on land were commonly piled at the high splash mark by the tsunami. Blocks about 30 cm in size were most numerous in these piles; some were 1 m in greatest dimension.

The speed at which tsunamis travel is a function of water depth—the deeper the water, the greater the speed. In deep water (6,000 m or more) where there are no islands nearby, a tsunami may move as fast as 950 km/hr; whereas in shallow water (180 m or less), it may move as slowly as 150 km/hr. The average velocity of the November 29 tsunami, as determined from time-distance relations (table 3; fig. 10), varies within

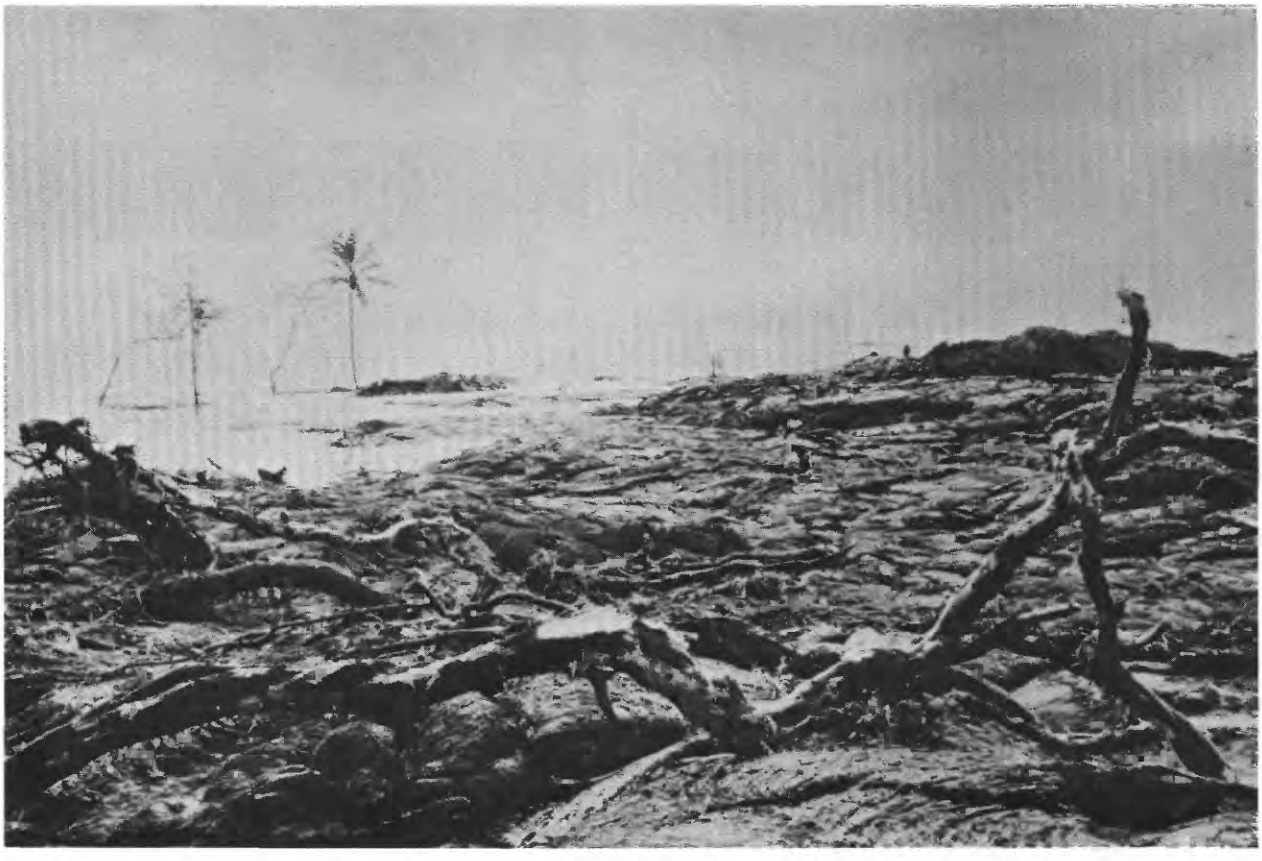


FIGURE 9.—Part of a keawe tree toppled and scarred by wave action at Keauhou Landing. Note coconut palms standing in the sea.

TABLE 3.—*Tsunami characteristics as recorded by some Pacific tide gages, supplemented by visual observations*

Source[1]	Site	Approximate arrival time, G.m.t.[2]	Approximate traveltime[3] (hr. min.)	First motion	Maximum amplitude (m)	Distance[4] (km)	Average velocity (km/hr)
	Hawaii						
VO	Punaluu, Hawaii	14:58	0:10	Rise?		57	342
VO	Honuapo, Hawaii	15:00	0:12	Rise?		65	325
TG	Hilo, Hawaii	15:08–15:11	0:20–0:23	Rise	1.7	43	130–112
VO	Kailua-Kona, Hawaii	15:15	0:27	?		108	240
TG	Kahului, Maui	15:28	0:40	Rise	.9	280	489
VO	Hana, Maui	15:30	0:42	?		190	271
TG	Honolulu, Oahu	15:37	0:49	Rise	.2	368	449
TG	Moku o Loe, Oahu (Kaneohe)	15:39–15:42	0:51–0:54	Rise	<.1	371	436–412
TG	Nawiliwili, Kauai	15:44–15:48	0:56–1:00	Rise	.3	535	575–573
	California						
TG	Bodega Bay	19:55–20:17	5:07–5:29	?	.4	3734	729–681
TG	Imperial Beach	20:30	5:42	Rise	.4	4042	709
TG	Long Beach	21:33	6:45	Rise	.2	3974	589
TG	Los Angeles	21:33	6:45	Rise	.3	3965	587
TG	Newport Beach	21:05	6:17	Rise	.2	3992	636
TG	Port San Luis	20:04	5:16	Rise	.8	3793	720
TG	San Francisco (Fort Point)	20:28	5:40	Rise	.2	3752	662
TG	San Diego	20:44	5:56	Rise	.1	4033	680
	Alaska						
TG	Sitka	21:12–21:25	6:24–6:37	Rise?	.2	4495	702–679
TG	Yakutat	21:47	6:59	Rise	<.1	4626	663
	Pacific						
TG	Johnston Island	16:58–17:11	2:10–2:23	?	.1	1558	719–654
TG	Wake Island	20:18–20:29	5:30–5:41	?	<.1	4017	730–707
TG	Pago Pago, American Samoa	20:33	5:45	?	.2	4154	722

[1]TG, tide gage; VO, visual observation. All tide gages operated by National Oceanic and Atmospheric Administration, U.S. Dept. Commerce.
[2]Reported as hours and minutes, Greenwich mean time (G.m.t.); to obtain Hawaiian standard time (H.s.t.), subtract 10 hours. Range of time indicates indefinite beginning of wave: no wave measurable before first time given, and definite wave measurable after second time given.
[3]Reported as hours and minutes after the start of 7.2-magnitude earthquake (14:48, G.m.t.).
[4]All distances are direct great circle routes from earthquake epicenter at lat 19°20′ N., long 155°02′ W.

the expectable range. Tide-gage data clearly show retardation of the wave velocity in shallow water or where islands impeded the direct movement of the wave front. The tsunami velocity for passage between and along the Hawaiian islands was typically about 500 km/hr or slower, but the open-ocean velocity was about 700 km/hr (fig. 10). The wave was delayed about 1 hour at Long Beach and Los Angeles, and one-half hour at Newport Beach, probably because of retardation related to shallow water adjacent to the Channel Islands fronting these shore sites.

The islandwide pattern of wave heights for the November 1975 tsunami is similar to that for the April 1868 tsunami, generated locally by a large earthquake off the south coast (fig. 11). In 1868 as in 1975, the highest waves affected the island's southeast coast from Cape Kumukahi to South Point. In contrast, patterns for tsunamis generated by crustal disturbances originating near the North and South American continents, as in 1946, 1957, and 1960, show maximum heights along the northeast and west coasts (fig. 11). The 1946 wave was produced by a tectonic event in the Aleutian Islands accompanied by a magnitude 8 earthquake. The 1960 tsunami was generated by a disturbance in Chile accompanied by a magnitude 8.2–8.5 earthquake.

Tide gages at all locations where the first arrival of the November 29 tsunami was well defined recorded an initial rise of sea level (table 3). This would be expected if the south flank of the volcano slumped seaward, as indicated by observations and geodetic data. The slumping of a large part of Kilauea's south flank would produce a decrease in the volume of the ocean basin and a local upward displacement of the seawater column to produce the tsunami. An alternative explanation would require an overall rise of the ocean floor, again decreasing the volume of the ocean basin.

THE ERUPTION

About half an hour after the main shock, seismographs near the summit of Kilauea began to record shallow, high-amplitude harmonic tremor, a distinctive type of seismicity associated with movement of magma. At 0532 the sky over Kilauea glowed yellow-orange as fluid, gas-rich lava began to fountain from a N. 85° E.-trending fissure about 500-m long on the caldera floor, just

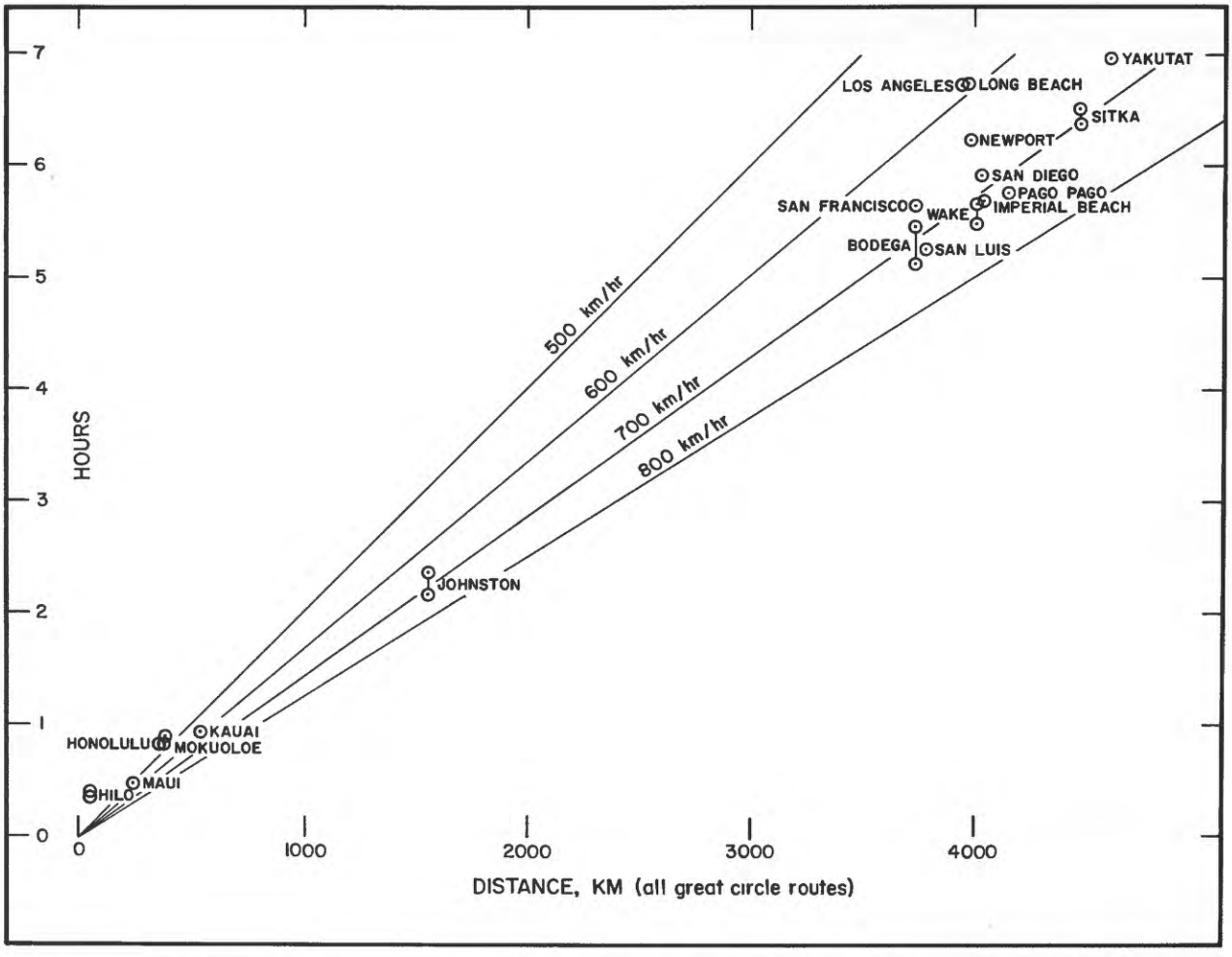


FIGURE 10.—Plot of approximate tsunami arrival times relative to distance from point of generation (data of table 3).

northeast of Halemaumau (A, fig. 12). The new lava issued from a continuous line of fountains as much as 50 m high. Within 15 minutes, the fountains decreased to 5–10 m high (fig. 13), eventually dying out about 0700. The fountains fed a small basaltic pahoehoe flow that spread mainly north from the eruptive fissure, eventually covering an area of about 0.25 km^2 on the caldera floor (fig. 14). As fountaining abated, emission of gases became increasingly vigorous. After eruption of lava had ceased, jetlike, noisy degassing continued from the vents.

Weak eruptive activity resumed at 0830 with copious fuming from a point on the northeast wall of Halemaumau, 21 m above the crater floor (B, fig. 12). The rate of fume emission increased rapidly, and within a few minutes lava began to erupt in 4–5 m high fountains that fed narrow, sluggish rivulets moving slowly down the sides of a low spatter cone built around the vent. A small pool of lava gradually accumulated on the floor of Halemaumau at the base of the cone, while jetlike emission of gas continued at the vent.

At 0953 another vent (C, fig. 12) opened on Halemaumau's northeast wall 18 m above the crater floor, 107 m southeast of vent B. The activity at vent B diminished somewhat as lava began to spurt to 3–5 m heights at vent C. The proportion of gas to lava emitted by both vents gradually increased, and after 1100 the material erupted was mostly incandescent blocks sporadically thrown nearly 100 m high during loud gas bursts. The ejecta largely fell back into the vents, and by 1330, molten lava was no longer visible and the rate of degassing had greatly decreased.

At about 2005 eruption resumed intermittently in Halemaumau from these same two vents, producing lava fountains at times 100 m high

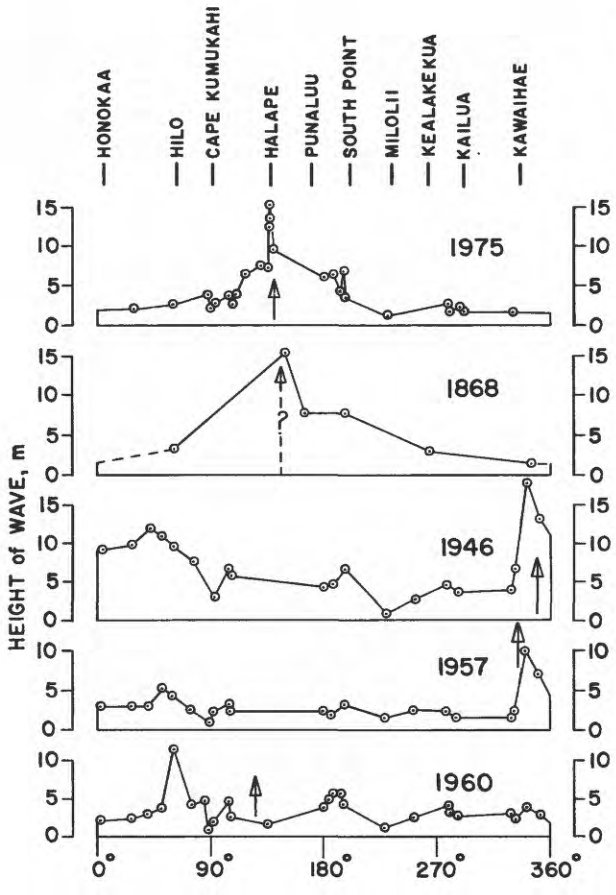


FIGURE 11.—Height of tsunamis (in meters above mean lower low water) on the island of Hawaii for five major events; 1868 and 1975 tsunamis were generated locally. Coastal points are located by their azimuth from a point in the center of the island at lat 19°30'N., long 155°30' W. Azimuth of arrival path of waves shown by arrow. Arrival path for 1868 tsunami (dashed arrow) not known exactly. Data for 1946, 1957, and 1960 tsunamis from Eaton, Richter, and Ault (1961); data for 1868 tsunami from several sources, chiefly Wood (1914). See Suggested Reading for complete references.

and accompanied by vigorous degassing. By 2200 the eruption had ended, but noisy degassing continued until 0200 on the morning of November 30.

The lava from vents B and C in Halemaumau, judged by its high viscosity, probably was erupted at a relatively low temperature, perhaps from a body of magma trapped in a pocket high within the volcano. The total volume of lava produced during this short-lived eruption was small, approximately 250,000 m^3 from vent A, 3,200 m^3 from vent B, and 300 m^3 from vent C (fig. 12).

The eruption was not unexpected, as tiltmeter and other geodetic measurements had indicated that Kilauea had been inflating steadily since its last eruption in December 1974. The amount of inflation caused by gradual accumulation of magma at shallow depths within the volcano had reached a level approaching that of several recent eruptions. The November 29 eruptive activity was apparently triggered by the 7.2-magnitude earthquake. The small volume and brief duration of the eruption suggest that the shallow magma might not have reached the surface under its own buoyant energy without a triggering mechanism apparently provided by the violent ground shaking.

GROUND MOVEMENTS

On November 29, the summit and south flank areas of Kilauea were severely deformed by vertical and horizontal displacements of several meters forming numerous ground cracks and faults. At Halape, ground subsided as much as 3.5 m, and 20 km to the east, the inhabited Kalapana area sank nearly a meter. Inland, a nearly continuous zone of ground cracking and faulting, with vertical offsets as much as 1.5 m, formed for about 25 km along the Hilina fault system. Smaller scale slumping, sliding, and rock falls occurred widely as a result of ground shaking; such movements extensively damaged roads and trails in Hawaii Volcanoes National Park. Precise determination of the magnitude and patterns of ground displacements will be possible only after an extensive geodetic survey now under way.

SUBSIDENCE OF THE SOUTH COAST

At Halape, the subsidence left a grove of coconut palms standing in water averaging 1.2 m deep and 100–150 m landward of the presubsidence shoreline (fig. 15). Halape's old rocky beach is submerged, but a larger, sandy beach had formed by mid-December 1975. Broad areas of the peninsulas at Kakiwai and Kalue, 2 and 3 km respectively west of Halape, are now submerged beneath crashing surf. A shallow, tranquil lagoon covers 2.2 hectares (1 hectare=2.47 acres) of what formerly was a sand-covered flat above a low sea cliff at Kaaha, 1.5 km west of Kalue. At Keauhou Landing, 2.3 km east of Halape, a brackish Hawaiian water well is submerged, the narrow beach destroyed, and its fringing thicket of keawe trees swept away.

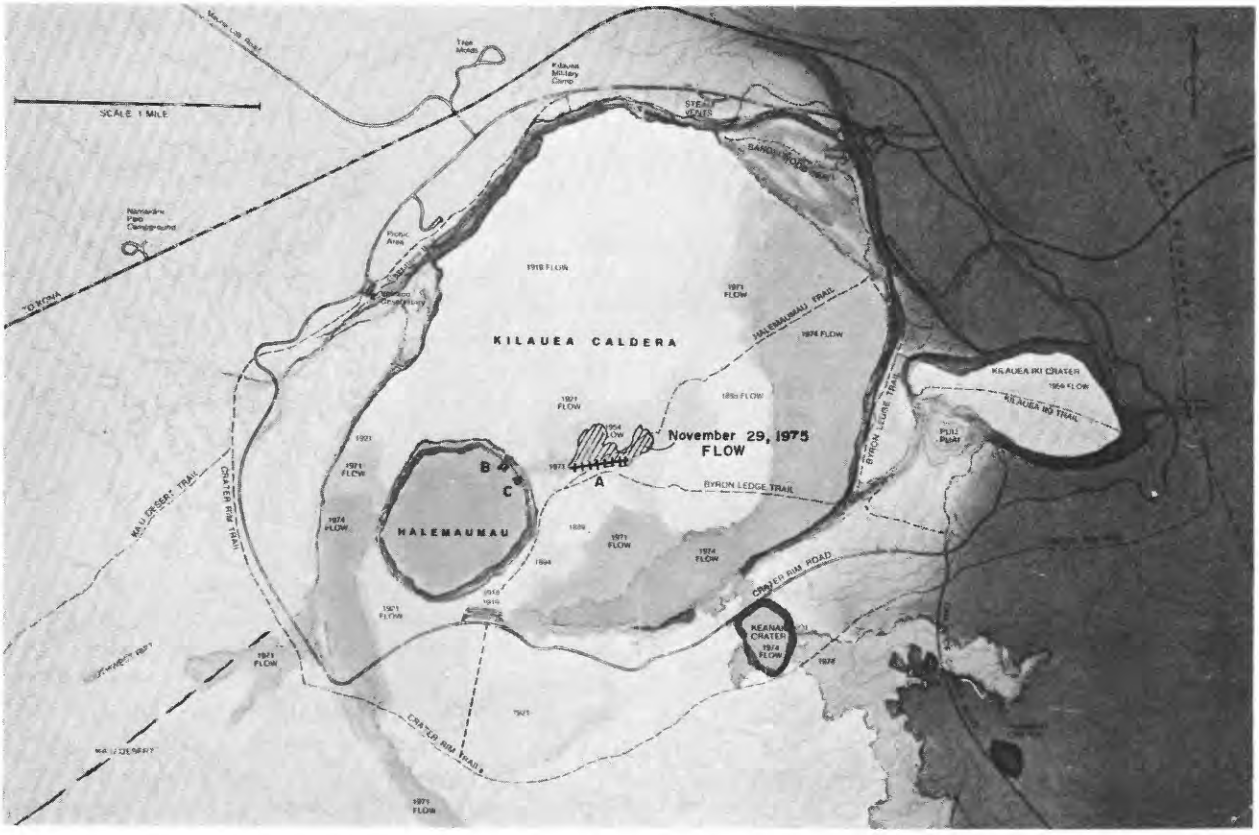


FIGURE 12.—Sketch map of recent vents and lava flows, Kilauea Caldera and vicinity. Approximate area covered by the November 29, 1975, flow shown by hachures; principal fissure (A) by heavy black line. The two minor vents (B and C) are at the base of the northeast wall of Halemaumau Crater. (Base map from *Halemaumau Trail,* 1975, Hawaii Natural History Association.)

Few landmarks against which the amount of subsidence could be visually estimated occur between Keauhou Landing and Kalapana, nearly 20 km farther east, but several small black-sand beaches formed in 1970–72 near Apua Point are now underwater.

At Kalapana, a broad shallow lagoon now occupies an area between Kalapana and Hakuma Point that was previously muddy or even dry during low tide. Two segments of the highway between Kalapana and Harry K. Brown Park were regularly flooded at high tide after the subsidence; they have since been built up. At the renowned Kaimu black-sand beach, 1 km northeast of Kalapana, wave swash now enters the coconut grove fringing the beach, eroding the sandy platform in which the palms are rooted.

The amount of subsidence was measured at several localities along the coastline from Honuapo to Kaimu shown in figure 16; further data will become available in the area northeast of Kaimu once level lines have been reoccupied. Most measurements were made directly from postsubsidence sea level to points of previously known elevation, including benchmarks, triangulation stations, topographic control points, and tide gages. All measurements were adjusted to mean sea level using the tide tables to determine the absolute subsidence of the land. Estimates of precision indicated on the profile (fig. 17) are based on the method of determination and the quality of the observation.

The maximum measured subsidence, about 3.5 m, took place in the Halape-Keauhou Landing area, about 25 km west of the epicenter of the main earthquake. Kalue may have subsided by a comparable or even somewhat greater amount, as suggested by relations near a previously established tidal reference point that was not found and was possibly dislodged by the earthquake. The amount of subsidence decreases in both directions from this central area. Toward the south-

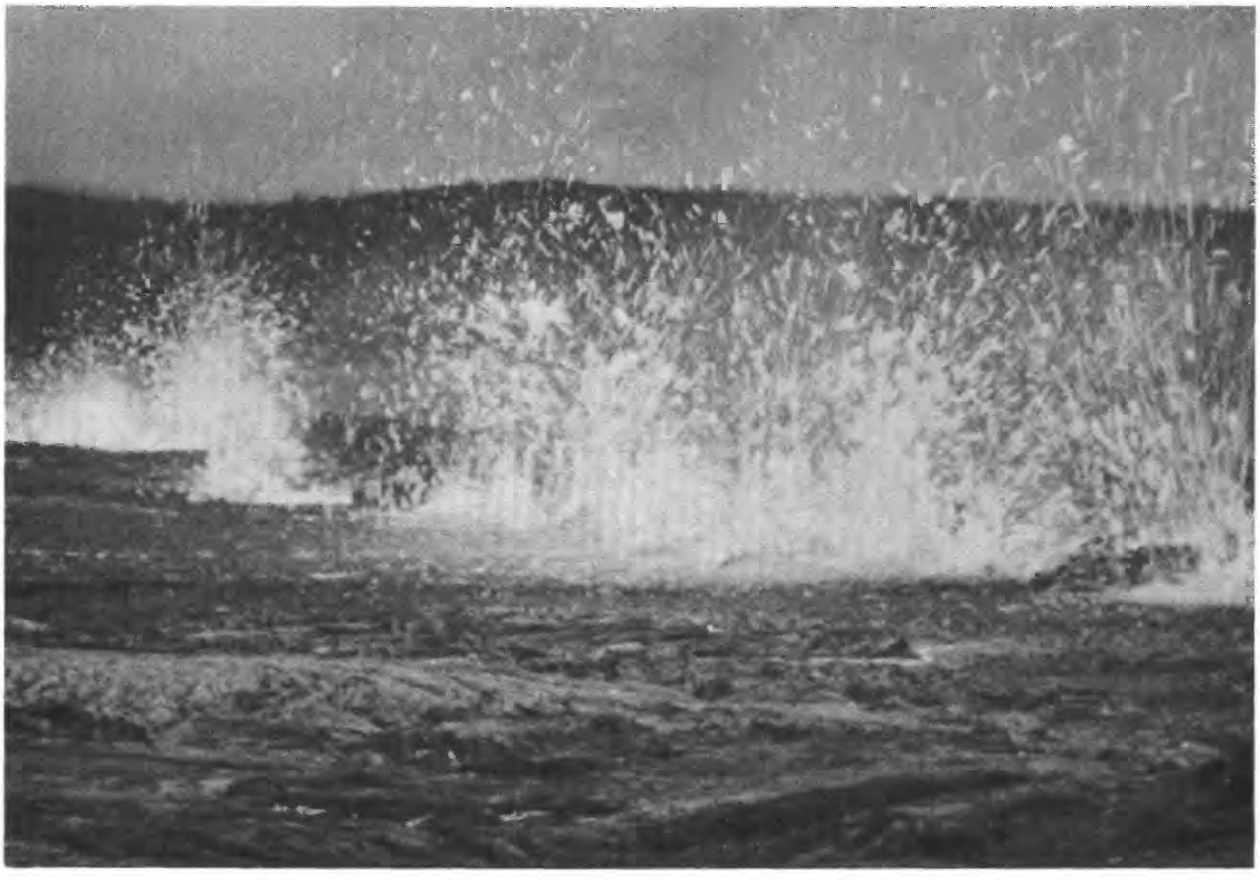


FIGURE 13.—Lava fountains on floor of Kilauea Caldera at about 0600, November 29, 1975. View from near west end of eruptive fissure; fountains are about 10 mm high.

west, measurements indicate definite subsidence at Na Puu o na Elemakule and Kuee but not in the vicinity of Kamehame Hill (figs. 1 and 16). Continuously recorded water-level data for a well at Punaluu indicated about 0.1 m uplift of land, and the Honuapo area showed no detectable change with present measurements. Toward the east, the amount of subsidence decreases from Keauhou Landing to Kaena Point, then remains at about 1–2.2 m to Kupapau; releveling of a short section along the highway near Kaena Point indicates westward tilting of nearly 10 cm/km. Subsidence was about 75 cm at the Kupapau tide gage. The Kalapana area sank a maximum of about 85 cm; releveling suggests that about 64 cm of this amount results from the regional subsidence and that 21 cm is accounted for by differential dropping or abrupt northward or eastward tilting of the previously known Kalapana graben (fig. 17). As seen in figure 17, the zone of subsidence is asymmetric, terminating more abruptly on the west than on the east side.

The subsidence of the south coast disturbed the equilibrium of shoreline processes. Wave erosion of cliffs and headlands, particularly during storm periods, will be more vigorous because deeper water permits higher energy waves to attack them. Old beaches will be eroded and redistributed rapidly until a new quasi-equilibrium is established. New beaches may develop, as at Halape.

FAULTING IN THE HILINA SYSTEM

Apparently concurrent with the subsidence, a nearly continuous zone of ground breakage formed along the Hilina fault system, a zone characterized by south-facing, normal fault scarps as high as 500 m (fig. 18). The new breakage along the Hilina fault system consists of a series of steep normal faults, mostly along preexisting fault traces, with displacements systematically down to the south. In places, the new fault displacement is obscured by extensive slumping and landsliding which occurred along all of the steep scarps.

FIGURE 14.—Oblique aerial view to southwest showing floor of Kilauea Caldera, and distribution of lava flow of November 29, 1975. Fume rises from the main vent fissure, which cuts across fissure of 1954 eruption. Halemaumau in background.

The new faulting extends for about 25 km along the trend of the Hilina system and has vertical offsets of as much as 1.5 m. In detail, the new faults are discontinuous and en echelon in pattern; individual breaks extend a few ten to a few hundred meters. Overall, they define a nearly continuous zone of normal faulting between more coherent blocks, whereas elsewhere on Kilauea, the pattern is widespread landsliding and slumping of relatively incoherent material from steep slopes.

In the past lava flows have cascaded over most of the "palis" (Hawaiian for cliffs or scarps) of the Hilina fault system (fig. 18*A*), gradually building them southward toward the sea. The new ground rupture took place near the top of the palis, presumably along the buried faults that originally created the cliffs. Some palis, such as the seaward flank of Puu Kaone (figs. 18*B*), have not been built seaward by draping of younger flows, but rather have retreated northward through erosion; hence, ground rupture took place near the base of these scarps (fig. 19).

Most of the new faulting occurred along the northern parts of the Hilina system; several old faults near the coast show no new ground rupture. The most continuous zone of breakage and the largest vertical offsets are along the northern edge of the system 5 to 10 km north and northeast of Halape (fig. 16), where vertical displacements of 0.5–1.5 m occur for a distance of more than 15 km. To the south and southwest of this zone of maximum faulting, vertical displacements of as much as 0.5–1.0 m along other faults are common. Accordingly, the cumulative observed fault displacement is at least as much as 2.5 m landward of the Halape area and accounts for about 70 percent of the maximum measured coastal subsidence in Kilauea's south coast.

Along the southwestern part of the Hilina fault system, new ground breakage is evident along several northeast-trending zones over an extent of at least 5 km (fig. 16), with vertical displacements locally as much as 1 m. Much of the ground movement in this area, however, seems to have resulted in only slight readjustment along preexisting fractures.

In addition to the main faults, many cracks opened within the Hilina system, indicating a component of horizontal extension. Most cracks are old, but freshly broken rocks and torn vegetation indicate renewed movement on many of these during the November 29 events. Small new cracks in dirt and soft sediment, with opening of as much as a few centimeters, are common near the larger bedrock cracks, suggesting net extension across the Hilina system.

Geodimeter[3] measurements of lines across the Hilina fault system indicate that horizontal changes of 1 m or more were common; one 5.5-km-long measurement line extended 5.8 m, another 5.5-km-long line contracted 3.0 m. These measurements, though not yet tied to stable reference stations, suggest a significant seaward shift of Kilauea's south flank during the November 29 events. As part of the overall seaward and downward movement, fault blocks in some areas apparently tilted north, as leveling surveys near Kaena Point and Kaimu (fig. 1) indicates landward downtilting of about 1 cm/100 m and 1.5 mm/100 m, respectively.

POSTEARTHQUAKE ADJUSTMENTS

Following the catastrophic ground movements on November 29, a systematic monitoring program was initiated to detect and document continued deformation in the inhabited Kalapana area. Geodimeter measurements of selected lines across the Hilina fault system indicated cumulative postearthquake extensions of as much as 8 cm during December 1975. Similarly, precise leveling during December indicated postearthquake relative subsidence of 9 mm localized in the Kalapana graben. Geodimeter measurements January-February 1976 show that all monitor lines had nearly stabilized by mid-February. Leveling data for the same time period indicate continuing subsidence. At this time (February 1976), available information suggests that Kilauea's south flank has largely stabilized, even though relative sinking persists in the immediate Kaimu area at an average rate of about 1 cm per month. How much longer this rate of localized relative subsidence will continue is not known. The measured changes cannot be related to sea level until the entire leveling network of Kilauea has been reoccupied and the results referenced to tide-gage data.

LANDSLIDES AND GROUND CRACKS

The intense ground shaking of the main earthquake produced numerous rockslides and

[3]Laser-beam electronic instruments for precise measurement of horizontal distances.

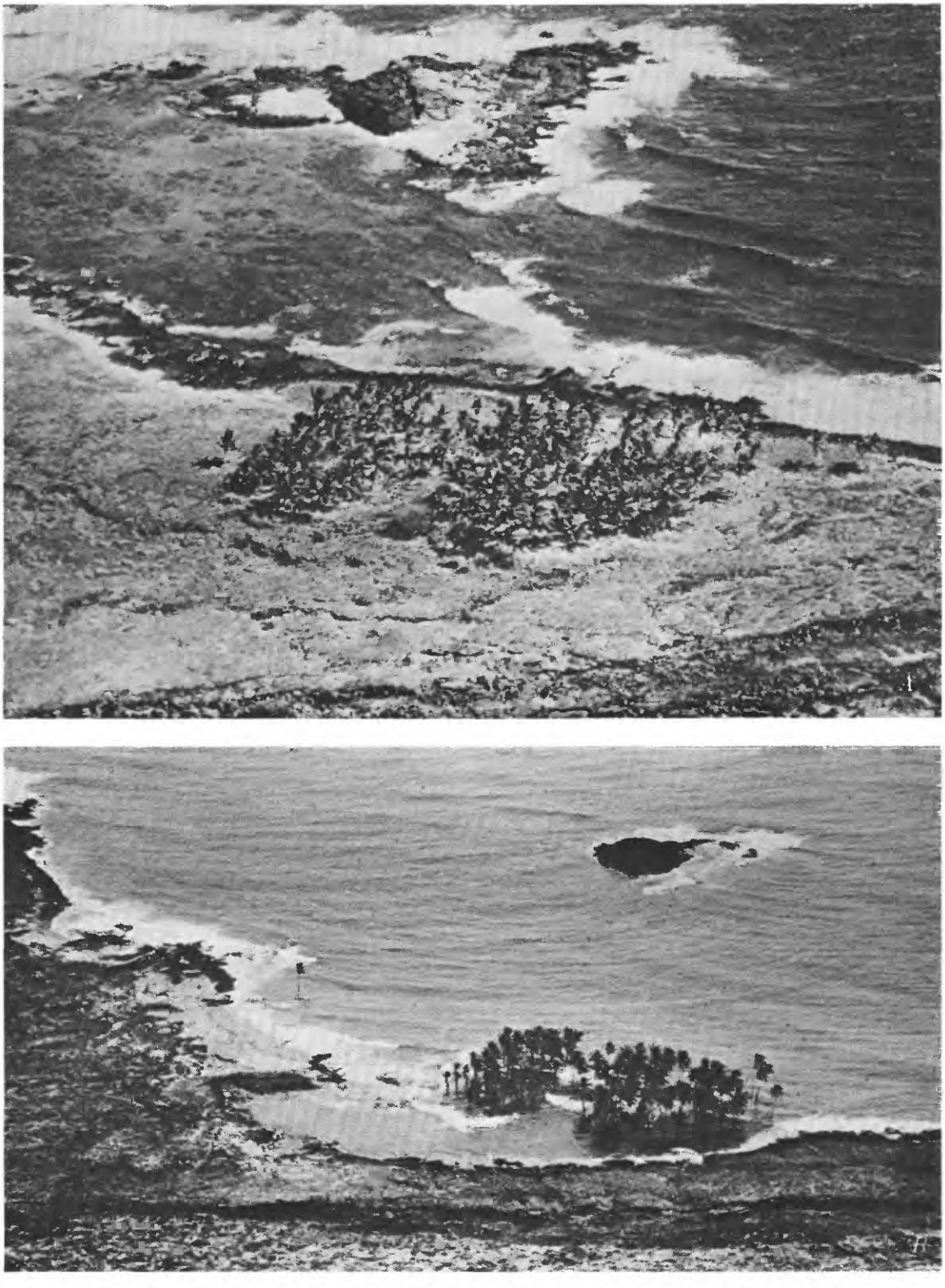


FIGURE 15.—Preearthquake and postearthquake views of coast illustrating subsidence. *A*, Preearthquake view of Halape area from Puu Kapukapu. *B*, Postearthquake view of Halape from Puu Kapukapu showing the palm grove standing in the sea and the offshore island nearly submerged as a result of 3.5 m subsidence; on November 29, 1975, campers were swept by the tsunami into the crack behind the palm grove. *C*, After subsidence, surf surges through the palm grove at

Halape. *D*, Preearthquake aerial view of Keauhou Landing; note shelter and trees. *E*, Postearthquake aerial view of Keauhou Landing; the shelter and nearly all of the keawe trees have been washed away by the tsunami; palm trees now stand in the sea. (Photographs: *A*, Don Reeser, National Park Service; *C*, *E*, Boone Morrison; *D*, Robin Holcomb, U.S. Geological Survey.)

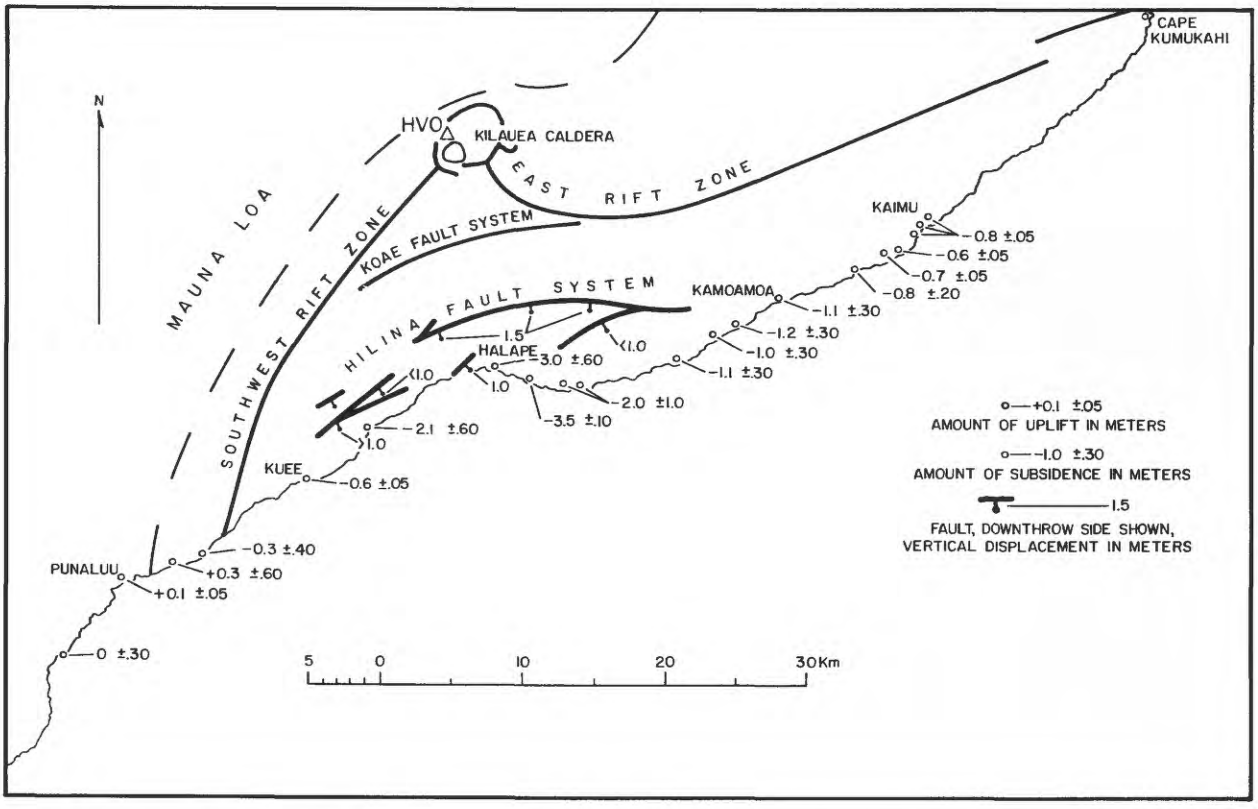


FIGURE 16.—Zones of major faulting in the Hilina fault system and amounts of subsidence along the south coastline related to the main November 29, 1975, earthquake.

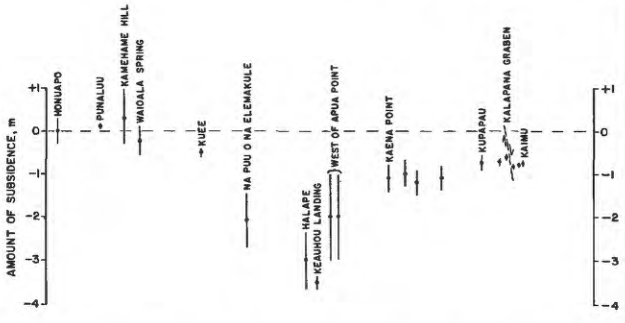


FIGURE 17.—Amount of subsidence at points along the coast line from Honuapo to Kaimu. Bars indicate estimated error limits given in figure 16; dashed horizontal line, zero change. Note disruption of profile along west edge of Kalapana graben, suggesting dropping or abrupt tilting of graben. (See fig. 1 for geographic locations.)

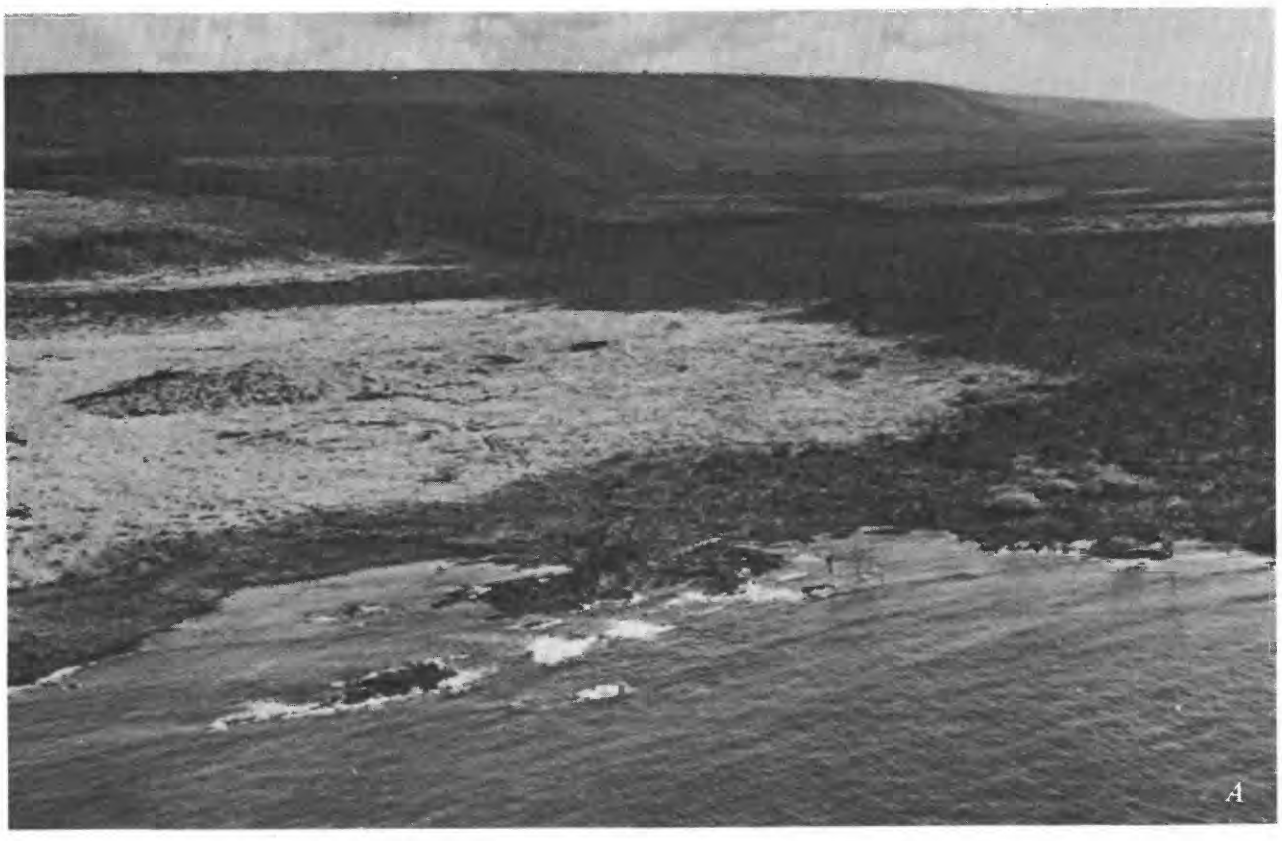
ground cracks, especially in areas of preexisting steep slopes such as fault scarps, crater walls, and road cuts.

Rockfalls and landslides occurred along every major cliff in the Hilina fault system, and new open cracks are conspicuous in soil within 50–100 m of the tops of the cliffs, suggesting local lurching of the ground toward the free cliff face during the shaking.

Some of the largest ground cracks and rockslides occurred along the rims of Kilauea Caldera and the pit craters of the upper east-rift zone. These dislocations caused more than $675,000 damage to roads, trails, and viewing overlooks in Hawaii Volcanoes National Park. Visitor overlooks at Keanakokoi, Pauahi, and Puhimau Craters slumped downward and outward; parts of them crashed into the craters, and gaping cracks as wide as 25 cm formed in the parts still left, rendering them too unstable for continued use by park visitors (fig. 20).

Cracks as wide as 1 m opened in the Waldron Ledge area on the northeast side of Kilauea Caldera, destroying a 1-km segment of the Crater Rim Road (fig. 21). Extensive new cracking damaged the Crater Rim Road near Kilauea Military Camp and blocked the Chain of Craters and

FIGURE 18.—Hilina fault system. *A*, Postearthquake, low-angle aerial view of Kilauea's south flank looking northeastward. Background shows some lava-draped "palis" (cliffs) of the Hilina fault system. Foreground shows the coast at Keauhou Landing (note the palm trees in water and the dark swath indicating the area washed by the tsunami). *B*, Preearthquake, high-angle aerial view of part of the Hilina fault system. Halape area upper right-hand corner; Puu Koae is top of cliff at left center.



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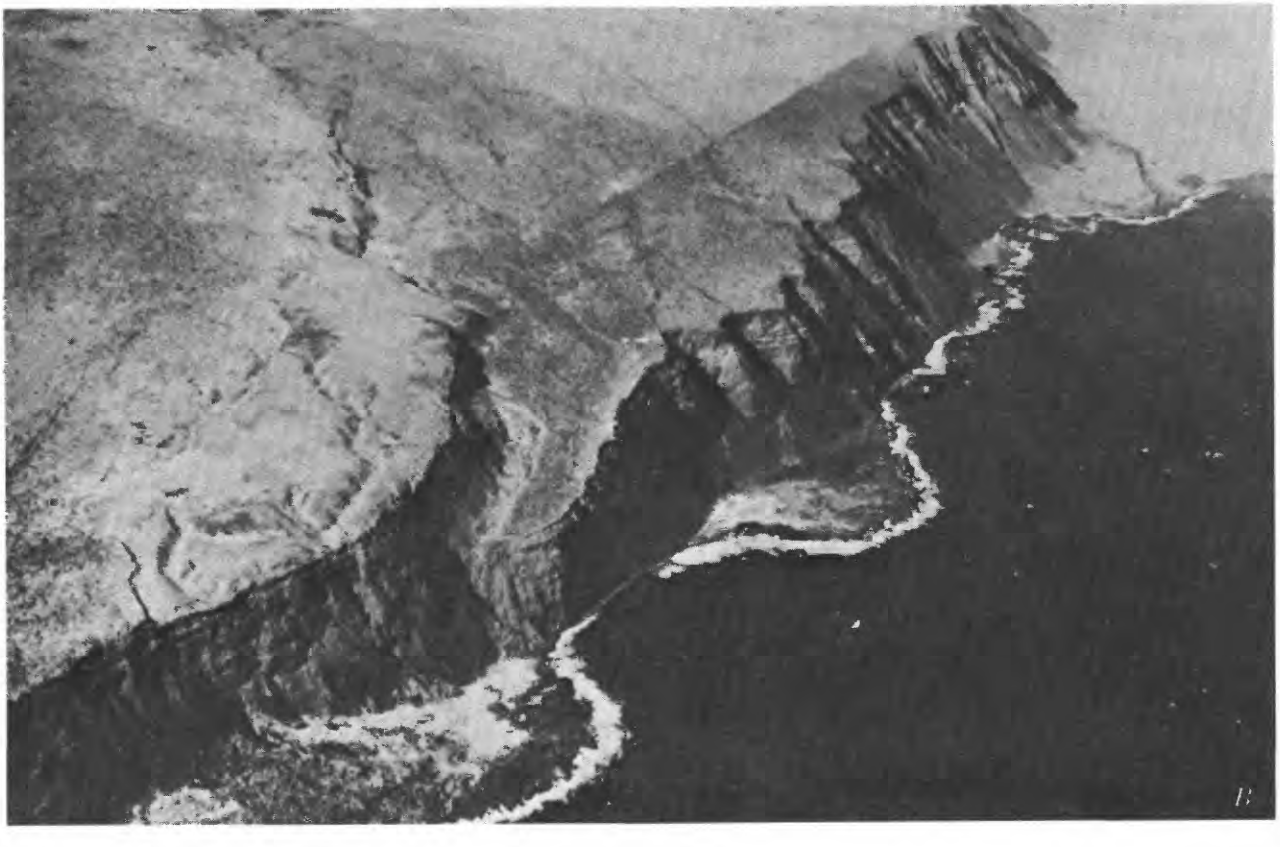

B

FIGURE 19.—Vertical offset of about 1.5 m along new fault, south face of Puu Kaone (see fig. 18*B*).

Hilina Pali Roads (fig. 12). While most of the ground breakage was extensional, producing new or widened cracks, local compressional features formed where slices of ground swayed between bounding open fractures and ended on one side or the other. A 5-cm partial closing of one crack in this manner produced a striking chevron fold across a road on the southeast side of Kilauea Military Camp (fig. 22). In a few places, movements along cracks produced apparent lateral offsets of as much as 10 cm (fig. 23).

Conspicuous cracking occurred along the Koae fault system south of Kilauea Caldera. In this area characterized by numerous open fissures, some old cracks opened, others closed, and in many sand-covered areas, small new cracks are evident. Limited geodimeter and leveling data indicate that horizontal extensions of as much as 2 m and significant southward tilting occurred across the Koae fault system. Much and perhaps all of the cracking had formed by a few hours after the earthquake.

DEFORMATION RELATED TO MAGMA MOVEMENT

Kilauea's summit area began to deflate as soon as the eruption began. The rate of deflation, measured by a tiltmeter in a vault near the Hawaiian Volcano Observatory, was 2–3 microradians[4] per hour during the early part of the eruption, gradually increased to 4–5 microradians per hour later in the morning, continued at this high rate for about 30 hours, then at lower rates for more than a week (fig. 24). Total deflation recorded was about 241 microradians, the largest deflation in the summit area since the 1960 Kapoho eruption.

Leveling data indicate that the maximum subsidence in the summit area is at least 1.2 m, centered about 2 km south-southeast of Halemaumau (fig. 12). The volume of deflation is computed to be at least 68 million m^3, about 270 times the volume of lava erupted on November 29 (0.25+million m^3) The large ratio of volume of deflation to volume of erupted lava suggests that

[4]One microradian represents a tilt of 1 mm in 1 km.

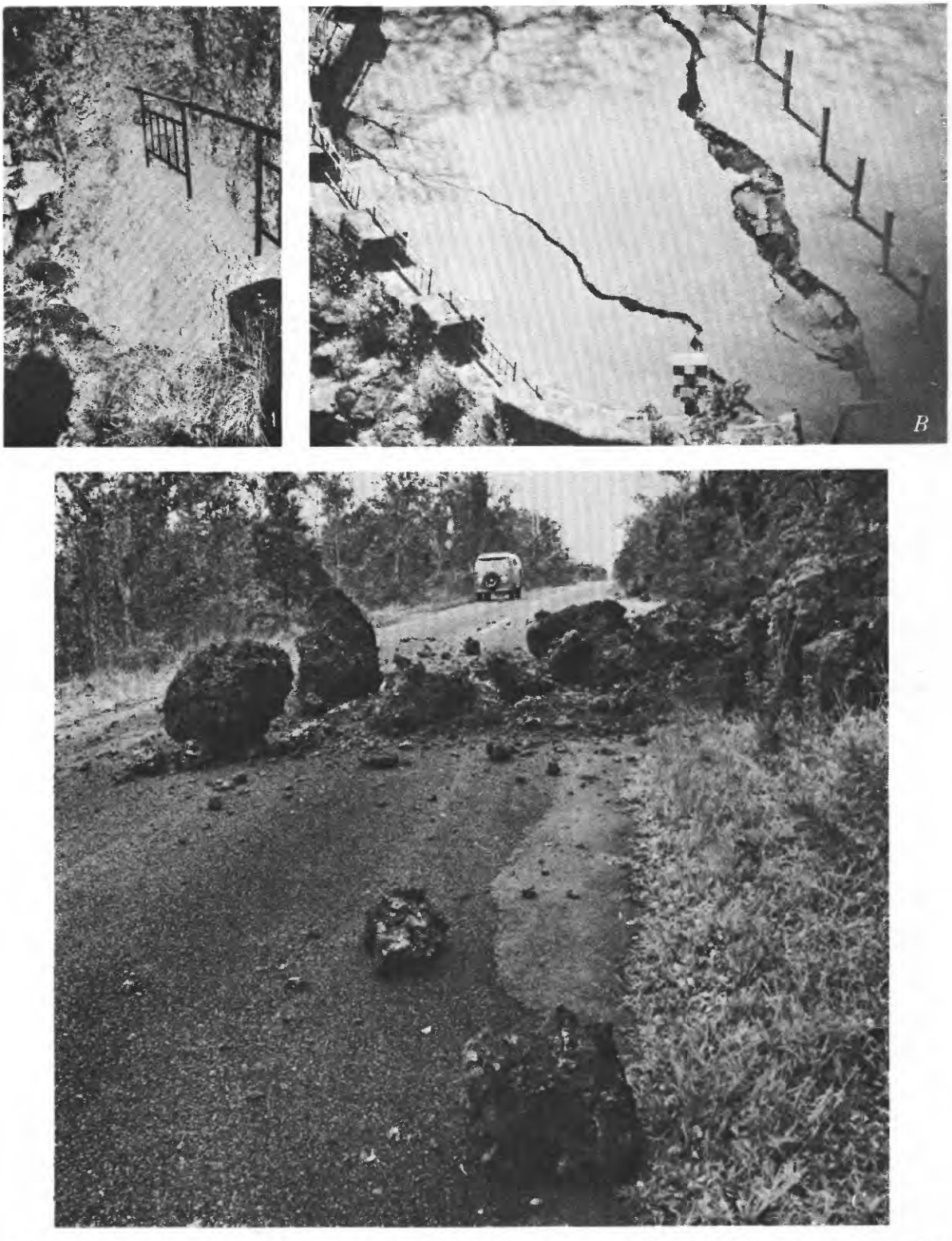

FIGURE 20.—Ground cracking and landslides in Hawaii Volcanoes National Park. *A*, Back part of viewing overlook area at Puhimau Crater slumped completely into the crater, leaving guardrail projecting into space. *B*, Aerial view of large cracks in viewing overlook area of Pauahi Crater. *C*, Small landslide from spatter and cinder cone partially blocking Chain of Craters Road (Photographs: *B*, Hugh Clark, *Honolulu Advertiser; C*, Boone Morrison.)

FIGURE 21.—Large crack in Crater Rim Road, Hawaii Volcanoes National Park. Cracking resulted from slumping of rim block toward caldera, the edge of which is a few meters to right of road.

the deflation was caused primarily by subsurface migration of magma beneath the summit area to unknown sites within the rift zones.

CAUSE OF EARTHQUAKE AND GROUND MOVEMENTS

Some of the catastrophic events of November 29, 1975, were caused by ground shaking or subsidence along the south coast. The tsunami was generated either by the sudden downward and seaward movement of a large segment of the south flank of Kilauea, which literally pushed a large wave into motion, or by the sudden uplift of the sea floor at the base of the volcano's slope, where a pronounced bulge (fig. 25) may reflect similar events in the past. The brief eruption at Kilauea's summit may have been triggered by opening of earthquake-induced fractures above the swollen magma storage reservoir. Subsidence and some ground cracking of the summit area apparently resulted from movement of magma from beneath the summit into the rift zones and possibly elsewhere in Kilauea's flanks. Landslides on steep slopes and cracking of roads were clearly surficial effects caused by ground shaking.

What caused the 7.2-magnitude earthquake

FIGURE 22.—Small compressional chevron fold across road on southeast side of Kilauea Military Camp, Hawaii Volcanoes National Park.

and the massive movements of Kilauea's south flank, during which a large slab, several thousand square kilometers in extent, apparently broke loose along the north edge of the Hilina fault system and moved downward and seaward several meters? Some scientists argue that the earthquake triggered the catastrophic ground movements, while others argue that the ground movements triggered the earthquake. Definitive answers to this fundamental but controversial question will require careful study of the seismic and geodetic data, much of which is still being collected. At this time (February 1976), only a few percent of the expected total number of aftershocks have been instrumentally recorded and analyzed. Seismic data thus far studied define a 5- to 9-km-wide belt of aftershock activity bounded on the south by the northernmost faults of the Hilina system (fig. 2). Most of the aftershocks occur at a depth of 5–7 km. Yet, the zone of major ground dislocations is *south* of this well-defined belt of aftershock activity. The reason for the apparent absence of aftershocks in the part of Kilauea's south flank most deformed is not known at present.

One fact seems clear, however. Regardless of which came first, the earthquake or the massive ground shifts, the sudden movement of such a large block of ground was caused ultimately by gravitational stresses on an unstable part of the volcano. The surface of Kilauea's south flank

FIGURE 23.—Collapse offsetting center line of Chain of Craters Road, just south of Pauahi Crater, Hawaii Volcanoes National Park.

slopes about 8° to a depth of about 4.5 km below sea level. The flank is unstable because (1) it is almost completely detached from the rest of the volcano along fractures of the two rift zones and the Koae fault system (fig. 1); (2) it consists in part of loose, poorly coherent debris formed earlier in Kilauea's growth; and (3) it is subject to seaward shoving by magma injected into the rift zones. Piling up of lava flows on the surface of the south flank further increases the gravitational instability. Eventually, when some critical threshold is exceeded, part of the flank tears loose along the Hilina fault zone, and a mammoth block of ground lurches downslope (seaward). In a sense, the Hilina fault system marks the heads of giant landslides (fig. 25).

The sudden ground movements on November 29 were doubtless similar to those that have formed the Hilina fault system, and the event is almost certainly the latest in a series of many similar episodes that have built the palis to their present heights. As long as Kilauea remains active, gravitational and magma-induced stresses will inexorably build up, and the mobile south flank will shift seaward and downward episodically and abruptly, providing stress relief. Then the cycle will begin anew. Consequently, if Kilauea's prodigious eruptive activity persists, such events as occurred on November 29 will recur, perhaps at a tempo suggested by the earthquakes and associated subsidence of 1823(?), 1868, and 1975.

COMPARISON WITH 1868 EVENTS

The events of November 29, 1975, and April 2, 1868, are comparable in many respects, although

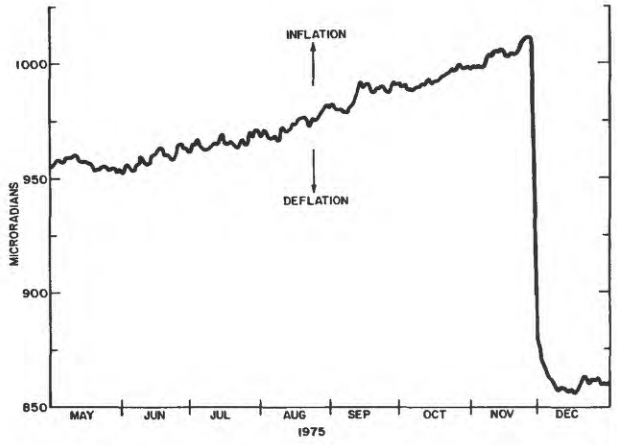

FIGURE 24.—Changes in tilt May-December 1975, as recorded on E-W component of water-tube tiltmeter located in vault near Hawaiian Volcano Observatory. Plot shows E-W component of deflation associated with November 29 events to be about 145 microradians. N-S component of deflation (not shown), approximately 193 microradians, resulted in total deflation of about 241 microradians.

the 1868 earthquake was apparently stronger, estimated to be between magnitude 7.5 and 8.0 from damage effects (intensity). During both episodes, the south coast of Kilauea subsided, a tsunami occurred, Kilauea erupted a small volume of lava, and the summit area of the volcano collapsed. A brief summary of the 1868 events is given below:

March 27, 1868

(a) Numerous small earthquakes were felt; the swarm continued until April 2.

(b) A small eruption occurred on the summit of Mauna Loa.

(c) Eruption in Kilauea Caldera, characterized by active lava lakes continued.

April 2, 1868

(a) At 1600, a very large earthquake occurred that caused great damage and was felt as far away as Kauai, 500 km to the northwest. Stone buildings were destroyed or damaged throughout the south half of Hawaii, especially in the Ka'u District. Large ground cracks opened on the south and southwest flanks of Kilauea.

(b) A mudflow triggered by the earthquake swept across Wood Valley, Ka'u District, killing 31 people. Landslides and rockfalls were dislodged from steep cliffs throughout the island, killing two people near Hilo.

(c) The southeastern coast of Kilauea subsided as much as 2.1 m.

(d) A tsunami destroyed all coastal villages on the southeastern side of the island, killing 46 people. The tsunami reached 18 m above sea level (fig. 7).

(e) A small eruption occurred on the side of Kilauea Iki Crater, while lava lakes in Kilauea Caldera continued activity. Much of the floor of the caldera subsided nearly 100 m. A small volume of lava was extruded on the southwest rift zone of Kilauea, 15 km southwest of the caldera.

LESSONS FOR THE FUTURE

In the 20th century, 21 earthquakes greater than 5.5 in Richter magnitude have occurred in Hawaii (1918, 1919, 1929 (3), 1933, 1938, 1940, 1941, 1943, 1944, 1950, 1951, (2), 1952, 1954 (2), 1955, 1962, 1973, 1975). Earthquakes of this magnitude were probably fairly frequent in past centuries, before the days of quantitative seismic recordings. Large earthquakes in Hawaii have caused millions of dollars in damage, but relatively few injuries and deaths. Tsunamis have been the most disastrous natural hazards on Hawaii, causing considerable bodily injury and loss of life as well as property damage; since the beginning of the 19th century, more than 350 people have been killed by tsunamis.

The Pacific Tsunami Warning System, which covers the Hawaiian Islands, is geared to alert residents of the impending arrival of tsunamis generated on distant shores around the Pacific. Waves produced by tectonic movements in Alaska and Chile require about 5 to 15 hours respectively to reach Hawaii, ample time to activate the Civil Defense warning system. However, the time between a locally generated earthquake and the resulting tsunami is generally too short for such a warning. The November 29, 1975, wave arrived at Hilo only 20 minutes after the earthquake. The tsunami warning siren first sounded in Kona approximately 30 minutes after arrival of the first wave.

The only practical warning system for such local events is an educated and informed populace. The basic warning of a possible tsunami is the earthquake itself. If ground shaking makes standing difficult, produces significant rockfalls, and damages structures, one should immediately

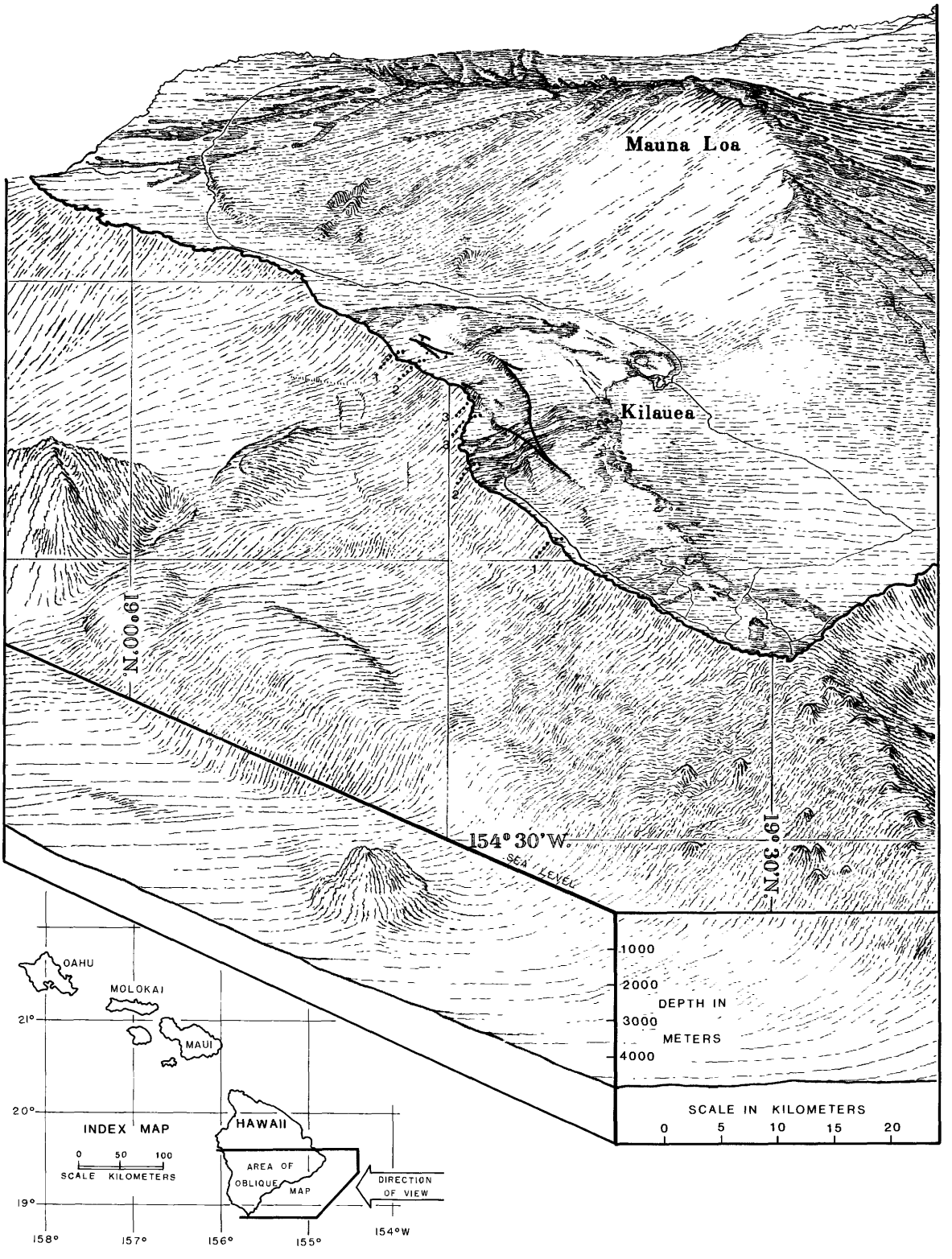

FIGURE 25.—Oblique map of the south half of the island of Hawaii as viewed from the east showing submarine topography. Heavy lines define new faulting, and dotted lines indicate amount of coastal subsidence in meters during the 1975 earthquake. Physiographic drawing by Tau Rho Alpha.

move to high ground. Experience from the 1975 tsunami suggests the following:

(1) In historic times, tsunamis affecting Hawaiian coastal areas have attained maximum heights of nearly 17 m locally; however, past tsunami heights have rarely exceeded 12 m above sea level. Obviously, any inhabited coastal areas below 12 m are particularly subject to possible tsunami damage. Beach campers are especially vulnerable to tsunamis, because they are close to the sea and often in remote areas not covered by warning or communications systems. In such remote beach areas, it would be advisable to locate overnight shelters 12 m above sea level, if at all possible. As only large earthquakes are preceded by foreshocks, campers should be instructed to move to high ground if they experience any felt earthquake. Not all large earthquakes produce tsunamis, but it is more prudent to have a few false alarms than tragedies.

(2) A reliable warning system for locally generated tsunamis should be established, utilizing strong-motion seismic instruments (accelerometers). Such a system would provide at most only 25 minutes of advance warning for Hawaii Island residents, but even a few extra minutes might save lives. Such a system would potentially be more important for population centers, such as Honolulu, on the other islands in the state; which probably would have a longer warning. Since 1868, 12 of the 13 local earthquakes of intensity VII or greater that might generate a tsunami have been centered around the Big Island; the other occurred near Maui. Thus, Honolulu might expect 45–55 minutes of advance warning of a tsunami generated near Hawaii Island.

At this time (February 1976), Hawaii Civil Defense officials have announced a plan to develop a warning system using strong-motion instruments.

(3) According to established Civil Defense procedures, waterfront hotels should move guests immediately to upper floors rather than risk evacuation across wide areas of low ground.

(4) Residents should be reminded periodically of the procedures to take in the event of a locally generated tsunami. Such reminders need to be given at fairly frequent intervals, because many years may pass before any of the Hawaiian islands is again hit by a locally generated tsunami.

(5) The generally unstable nature of Kilauea's south flank should be considered in any land-use decisions for that area.

ACKNOWLEDGMENTS

Gathering of data and preparation of this report were facilitated by the efforts of many individuals and governmental agencies. George Pararas-Carayannis, Director, International Tsunami Information Center, and Harold Loomis, Joint Tsunami Research Effort (NOAA), provided tide-gage and other information concerning the tsunami that filled in some gaps in our observations. Wayne Hall and Dorothy Radbruch-Hall, U.S. Geological Survey, furnished observations of tsunami and ground-movement effects. Patrice de St. Ours, guest investigator at the Observatory from the University of Orsay (France), made important observations of the Kilauea summit eruption. Robert Crosson, University of Washington, assisted in the seismic studies.

We greatly appreciate the aid and cooperation of various agencies of the County of Hawaii, in particular the Civil Defense Agency and Fire and Police Departments, and the assistance of the officials of Hawaii Volcanoes National Park. Kenneth Ellard and Ronald Thrash, helicopter pilots for Hawaii County, skillfully provided a critical service. The Federal Disaster Assistance Administration (Region IX) provided some logistic support for the postearthquake monitoring of the Kalapana area. We thank the Halape campers, and many other residents of Hawaii County, especially Herbert and Doris Mann of Volcano, for useful first-hand descriptions of earthquake and tsunami effects, and our colleagues of the Hawaiian Volcano Observatory for their long hours of work during the hectic time following the catastrophic event of November 29, 1975.

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Wood, H. O., 1914, On the earthquakes of 1868 in Hawaii: Bull. Seismol. Soc. America, v. 4, no. 4, p. 169–203. (The largest earthquake in Hawaii's history struck in 1868. The events of November 29, 1975, were in many ways similar to, but less destructive than, the events of 1868.)