



STRUCTURAL DAMAGE AND GROUND FAILURES FROM THE NOVEMBER 16, 1983, KAOIKI EARTHQUAKE, ISLAND OF HAWAII

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ABSTRACT

On November 16, 1983, at 0613 (H.s.t.), a magnitude 6.6 earthquake occurred on the Island of Hawaii at a depth of 12 km midway between the active volcanoes of Mauna Loa and Kilauea. The right-lateral strike-slip faulting was probably generated by compressional stresses caused by inflation of the crustal magma reservoirs of both volcanoes. The earthquake shaking was felt for nearly one minute and caused substantial damage to structures in the southeastern part of the island. Landslides occurred on steep slopes throughout the island and, together with cracking of the ground and vibrational settling of subsurface materials, caused temporary closure of some roads. Fortunately, only a few people received minor injuries as a result of the earthquake; this was most likely because it struck at an early hour, when most people were still in bed.

INTRODUCTION

At 0613 Hawaii standard time (H.s.t.) on Wednesday, November 16, 1983, most residents of the Island of Hawaii were awakened by a magnitude 6.6 earthquake. The shaking from this earthquake was felt for nearly one minute and caused substantial damage in the southeastern part of the island, throwing houses from foundations, toppling water tanks, and causing electrical power and telephone outages in the epicentral area. Instruments at the U.S. Geological Survey's Hawaiian Volcano Observatory (HVO) were rendered temporarily inoperative. Landslides occurred on the steep caldera and crater walls in Hawaii Volcanoes National Park and on steep slopes elsewhere on the island. These landslides together with ground cracking and failure of subsurface materials made some roads impassable.

Only four or five people were injured in the earthquake and their injuries were slight. This was probably because it occurred at an early hour, when most residents were still in bed. However, financial losses from the earthquake were estimated at \$7 million (Harry Kim, Hawaii Civil Defense Director, oral commun., 1983).

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Wood Valley, Kapapala Ranch and parts of Volcano were supplied by Elliot T. Endo, USGS, Vancouver, Washington, who was also kind enough to review the manuscript. Harry Kim, Hawaii Civil Defense Director, Hilo, supplied much of the information on locations of road and structural damage, both public and private, in the Hilo area. I thank David K. Keefer for thorough and thoughtful review of the manuscript. Discussions with Robert Y. Koyanagi and Norman G. Banks provided many helpful insights that contributed to this research.

THE EARTHQUAKE

The earthquake was located in the Kaoiki region between the centers of Hawaii's most active volcanoes, Mauna Loa and Kilauea, at a depth of nearly 12 km (fig. 44.1). Inflation of the summit regions of both Mauna Loa and Kilauea apparently caused sufficient horizontal compressional stress between the two crustal magma reservoirs to generate the faulting. A *P*-wave first-motion analysis from local seismic data indicates a strike-slip mechanism with a northeast-trending nodal plane (see fig. 44.1, inset); right-lateral motion is preferred on the basis of the pattern of ground cracking from this and previous seismic events in the Kaoiki region (Koyanagi and others, 1984, p. 1). Ground cracking indicating right-lateral faulting included a system of left-stepping echelon extension fractures found at about the 1,900-m elevation on Mauna Loa Road. The fractures were traced 4.5 km to either side of the road. Extension of 20–30 cm was common across the longer fractures (Endo, 1985, p. 67).

Detailed analysis of the mainshock and aftershock sequence, however, did not substantiate a simple strike-slip mechanism. There were several discrepancies: (1) The distribution of aftershocks did not define a fault plane that substantiated the mechanism derived from the mainshock. (2) Most aftershocks occurred at shallower depths than the mainshock. (3) Teleseismic fault-plane solutions from other locations were slightly, but significantly, different (Endo, 1985, p. 186–187, 211–213). To explain these discrepancies Endo suggests that the initial right-lateral strike-slip movement was immediately followed by southeastward low-angle slip of part of the southeast flank of Mauna Loa (Endo, 1985, p. 213–215). Such slip would relieve the compressional stresses in the epicentral area, thereby altering the pattern and depth of the aftershocks, and would account for the differences in teleseismic solutions.

KAOIKI EARTHQUAKES

Seismic events called Kaoiki earthquakes occur in a region midway between the summits of Mauna Loa and Kilauea Volcanoes. Although the region takes its name from the Kaoiki fault system, a prominent geologic feature on the southeast flank of Mauna Loa, the seismically active area lies more than 5 km northwest of the Kaoiki system. The Kaoiki fault system probably developed as a result of gravitational stresses induced by forceful intrusions of magma along the southwest rift zone of Mauna Loa before Kilauea was large enough to provide a buttress (Swanson and others, 1976, p. 32). Radiocarbon dating of lava flows and stratigraphic relationships along the fault system, however, indicate that the normal faults of the Kaoiki system have been inactive for tens of thousands of years (Lipman and Swenson, 1984).

The Kaoiki region, on the other hand, is an area of constantly high seismicity with hundreds to thousands of earthquakes recorded by nearby seismographs each year. During the past 25 years, three earthquakes of magnitude greater than 5 have occurred in the Kaoiki region (table 44.1); these events were aligned within the seismic zone in a northeast-southwest direction and were separated from each other by about 3 km (Koyanagi and others, 1984, p. 3). This pattern of seismicity could not be related to any known geologic structure until 1976, when surface fissures probably related to the November 1974 Kaoiki earthquake were discovered (Endo, 1985, p. 42). First-motion data compiled by Endo (1985) for crustal earthquakes from 1959 to 1982 at depths less than 16 km beneath the southeast flank of Mauna Loa and nearby areas of Kilauea confirm a fault system trending predominantly northeast-southwest between Mauna Loa and Kilauea. However, the combination of strike-slip and dip-slip solutions from this compilation also imply a complex tectonic region having both compressional and extensional local stresses (Koyanagi and others, 1984, p. 4).

SEISMIC INTENSITY

The greatest structural damage and abundance of landslides occurred in the epicentral area. Maximum intensity was estimated at VIII to IX (modified Mercalli scale) in parts of Kau and Puna Districts (fig. 44.2). Especially hard hit were the summit area of Kilauea and parts of Hilo. A table of relative intensities for the island was compiled from residents' reports received at the HVO, from information provided by the Hawaii Civil Defense Agency, and from fieldwork (table 44.2; for locations see fig. 44.1).

DESCRIPTION OF DAMAGE

The fault rupture in the epicentral area occurred in an uninhabited part of the island (fig. 44.1) and therefore caused no direct damage to structures. However, the earthquake shaking damaged more than 350 homes and 35 businesses in the southeastern part of the island (Hawaii Tribune-Herald, 1983). A preliminary survey of public buildings conducted by governmental agencies found minor to moderate damage to two health facilities (one in Hilo, one in south

Kona), seven schools (five in Hilo, two in Kau), two libraries (one in Hilo, one in Laupahoehoe), and one church in North Kohala (Hawaii County Civil Defense, written commun., 1983). In addition, there was structural damage to Hilo Hospital, resulting in a reduction in available beds in some units. The new Hilo Hospital under construction at the time of the earthquake was almost undamaged.

In the epicentral area, telephone service, electricity and water supplies were affected (Chiu and others, 1984). Most telephone and electrical services were restored within a few hours. However, residents of the area obtain water from rain-catchment systems; hence the destruction of, and damage to, water tanks and connecting pipes caused great inconvenience and disruption to many people.

STRUCTURAL DAMAGE

Most houses on the island are single-story wood-frame structures with either post-and-pier (fig. 44.3) or concrete slab foundations. In this earthquake, houses with post-and-pier construction sustained greater structural damage, primarily because of lateral displacement of the piers and consequent decoupling of the piers from the houses. The piers often moved with respect to each other as well as to the ground. Most structures with concrete slab foundations, on the other hand, had little damage, generally limited to hairline cracks through the slabs. However, the degree of shaking damage to loose objects inside houses seemed to have little or no relation to the type of foundation.

KAU DISTRICT

KA LAE, WAIHOHINU, NAALEHU, PUNALUU AND PAHALA

There was little structural damage reported from these towns. One house about one mile south of the highway on the Ka Lae Road moved 1.2–1.5 m northward off its foundation (fig. 44.1, locality 1; Vicki and Robert Taylor, oral commun., 1983). The house was supported on cylindrical concrete piers almost 1 m high and about 0.4 m in diameter with a 2.5-cm length of reinforcing steel bar (rebar) protruding through the piers into beams in the subfloor of the house. The rebars penetrated the subflooring when the house landed on them during the ground movement.

WOOD VALLEY

Wood Valley is a sparsely populated agricultural community built mostly on an ash deposit and on deposits of landslides induced by the magnitude 7.5–8 1868 earthquake and earlier earthquakes (Brigham, 1869, p. 574–576; Tilling and others, 1976, p. 29–30; fig. 44.1, locality 2; fig. 44.4). Several houses of post-and-pier construction (two built on ash and (or) landslide deposit) moved more than 0.5 m off their foundations toward the southeast at azimuths 105°–155° (fig. 44.4, vectors a, b, c). The 8-cm by 8-cm posts of one house were connected to the foundation piers with 0.5-cm-thick steel plates. The plates were not always on the same side of the posts, and therefore some posts were snapped at the anchor bolts connecting the post to the plate; other posts were relatively

undamaged, but the steel plate was bent at an angle of about 45° (fig. 44.5A, B). Nearby houses with concrete slab foundations on ash or with post-and-pier foundations on a pahoehoe flow sustained little movement (fig. 44.4, vectors d, e). Greenhouses were moved as much as 0.15 m in a complex pattern toward azimuths anywhere from 67° through 340° (fig. 44.4, vector e). These structures had few central supports or walls, hence the various structural elements may have failed at different times during the shaking, which could account for the range in direction of failure.

The Wood Valley Buddhist Temple had only a few centimeters of displacement with respect to its piers, but the two-story frame dormitory structure situated in the front yard of the temple shifted 0.26 m northeastward (fig. 44.4, vector f). Nearly every headstone in the cemetery was overturned, according to a spokesperson. The pattern of movement was complex: One headstone that had been mortared to a larger base was displaced 0.28 m to the northwest (az 290°), but a similarly constructed headstone fell in a southeasterly direction (az 140°). This divergence in direction of fall may be due to the headstones breaking loose from their mortar at different times during the earthquake shaking. Restoration work was nearly completed when the site was visited eight days after the mainshock, hence no other observations were possible (E.T. Endo, written commun., 1984).

KAPAPALA RANCH

The main house shifted 0.18 m downhill toward the south-southeast (fig. 44.1, locality 3; fig. 44.4, vector g) whereas a ranch house (locality 4 on figs. 44.1, 44.6) located 19 km (12 mi) to the northeast, nearer the epicenter, was displaced about 0.8 m northeastward (az 55°) off its foundation piers (fig. 44.7). A water tank about 100 m uphill from the ranch house had a length of PVC pipe, which was originally connected to the body of the tank, trapped underneath it (fig. 44.8). It seems likely that the pipe was severed early in the shaking, fell to the ground, and then rolled beneath the tank as the tank swayed back and forth. Several wooden water tanks located elsewhere on the ranch, one with a 378,500-L (100,000-gal) capacity and nearly full, were leaning precariously and leaking profusely; they were eventually dismantled.

VOLCANO GOLF AND COUNTRY CLUB SUBDIVISION

Most houses in this subdivision were built on a thin pahoehoe flow that overlies an ash deposit at least 0.5 m thick (locality 5 on figs. 44.1, 44.6). At the time of the earthquake, 48 houses had been built or were under construction in the subdivision. Of these, 18 houses with post-and-pier construction were displaced 0.2–1.2 m southwest from their foundations. Only one of the houses had 2.5 cm of reinforcing rebar protruding through the foundation piers into the posts (fig. 44.9). After the earthquake, this house was southwest of its piers, but the posts were not sheared by the rebar nor were most of the rebars bent, suggesting that the house rocked laterally and slid up along the rebars during the earthquake shaking.

Some houses with post-and-pier foundations had attached garages with concrete-slab foundations. In most such cases, the

house moved farther than the garage, causing a tearing of the shared wall (figs. 44.10A, B). In one case, however, the garage was situated on the southwest side of the house (the general direction of movement) and because of its greater rigidity, may have kept the house on its foundation.

Of the 30 other houses in the subdivision, 9 moved on their post-and-pier foundations and suffered minor damage, and the remaining 21 houses, most of which were on concrete slabs, showed no evidence of movement. However, large metal water tanks adjacent to some of these houses showed 5–9 cm of movement north-northeastward. A few fiberglass water tanks had vertical ruptures in their sides wide enough to allow loss of all the water.

There were reports of extensive breakage inside many houses, regardless of foundation type, and of heavier appliances and furniture displaced more than lighter pieces.

HAWAII VOLCANOES NATIONAL PARK

Although no buildings within the national park moved off their foundations, there was extensive interior damage in some buildings (locality 6 on figs. 44.1, 44.6). At the HVO, a concrete foundation slab was cracked in two places but not offset, and work areas were chaotic with toppled equipment and books (fig. 44.11). Some seismic stations were disabled because of damage to the sensors or recorders, while the operating stations were saturated for several hours with signals from ground oscillations. Tiltmeters could not be reset until there was a substantial reduction in the oscillation of the ground. Within the park residential area just south of park headquarters, damage to houses was minor and seemingly arbitrary. Similarly constructed and situated houses differed greatly in the amount of dishevelment of the interiors. There was no damage nor dishevelment to the park headquarters' buildings. Damage to leaking water pipes and valves in the park amounted to \$16,000.

At Kilauea Military Camp within the national park boundary, buildings moved but stayed on their foundations. In the Short Stop, a grocery store, bottled foods and beverages were broken and the concrete slab floor, supported on piers about 1 m high, was cracked and vertically offset about 1 cm. The Post Exchange also had breakage of glass items. Concrete slabs and walkways were cracked, and some concrete steps were buckled compressively where they abutted buildings. Service pipes from the water storage tanks to the camp were damaged and had to be replaced (Glenn Higa, Foreman, Engineers' Section, oral commun., 1985). Stone chimneys were cracked but could be repaired.

PUNA DISTRICT

UPPER WRIGHT ROAD, VOLCANO

Damage was severe and affected nearly every structure in this part of Volcano, which is underlain by an ash deposit locally as much as 4.7 m thick (locality 7 on figs. 44.1, 44.6). Patterns of movement were complex and are difficult to interpret; many houses in this part of Volcano are older and have combined post-and-pier and slab construction. Houses were displaced off their post-and-pier

foundations as much as 0.7 m, generally in either a southwesterly or northeasterly direction. One three-story-high wood frame house had recently had its original piers replaced with steel-reinforced concrete piers poured as a single unit (fig. 44.12A, B). This house was displaced about 0.3 m northeastward (az 35°) of the piers, and the steel rebar had sheared most of the posts that supported the upper story of the house. The use of rebar alone to connect the posts to the foundation proved inadequate. The superstructure of the house appeared to be undamaged.

More water tanks collapsed or were damaged in this community than elsewhere in the epicentral area; others, though undamaged, were moved as much as 0.8 m southeastward (E.T. Endo, written commun., 1984; fig. 44.13). Wooden water tanks were more severely damaged than those made of fiberglass or metal, probably because the former were less rigid. Many of the collapsed tanks were observed by residents to sway back and forth during the period of shaking before their failure. Evidence of a few centimeters of movement of heavier metal tanks could be seen in the soft ground. Connecting pipes were often severed or damaged.

In this largely agricultural community, financial losses resulted from crop damage when the earthquake shaking caused greenhouses to collapse, shook vegetables off plants (fig. 44.14), and caused vibrational settling of loose earth into adjacent furrows, thereby uncovering seeds and seedlings.

SOUTH HILO DISTRICT

HILO

Major structural damage in Hilo occurred in two main areas, shown in figure 44.15 as areas A and B. There was also structural damage at Hilo Hospital, located near a cliff overlooking the Wailuku River (see table 44.2 for details). Minor structural damage, ranging from collapsed rock stairways to cracked rock walls, was common throughout the Hilo area.

Most of the damaged residences in Hilo were built on a thick ash deposit or near the edges of lava flows overlying an ash deposit (fig. 44.1, locality 8; fig. 44.15, area A). Several houses were damaged when they moved downslope off their post-and-pier foundations in response to the earthquake shaking. Others were severely damaged because of the steeper slopes on which they were built (fig. 44.16A) or their location alongside unbuttressed slopes such as stream channels. A few houses built across steep slopes were structurally damaged by the shaking (fig. 44.16B), although there was no evidence of ground failure. Houses with concrete slab foundations fared better, with only minor hairline cracks in some slabs.

The old part of Hilo, built on an ash deposit locally as thick as 4.7 m (fig. 44.15, area B), was also severely shaken; major structural damage resulted to two buildings (figs. 44.17, 44.18), but most losses were due to breakage of plate-glass windows and damage to goods. A heavy canopy that recently had been installed on a commercial structure fell off during the shaking. It probably had been inadequately connected to the structural elements of the

building. A gas station reported the severing of connecting pipes to an underground gasoline-storage tank, causing the loss of some 11,355 L (3,000 gal) of fuel.

ANALYSIS OF STRUCTURAL DAMAGE

Structural damage was influenced by three main factors: (1) shaking of the ground, (2) lithology of the substrate, and (3) construction practices.

SHAKING OF THE GROUND

Damage to structures in the epicentral area may have been caused by the prolonged, strong ground shaking of greater than one-tenth the acceleration of gravity (0.1 g) for 8.5 seconds (table 44.3). One exception to this may have been the ranch house at location 4 (fig. 44.1). Because of its nearness to the epicenter, it is likely that the *P* and *S* waves arrived there nearly simultaneously, thus causing greatly enhanced first motion at this locality. The block south of the fault on which the ranch house was located, moved laterally to the southwest, decoupling the piers from the house and leaving the house northeast of its foundation.

In Hilo, the shaking damage in the Kaumana area (fig. 44.15, area A) may have been enhanced by the decoupling effect of a thin lava flow from Mauna Loa Volcano overlying a 3- to 6-m-thick ash deposit and deeply-weathered lava flows from Mauna Kea Volcano. That this type of enhancement could be expected was anticipated by Nielsen and others (1977), Wieczorek and others (1982), and Buchanan-Banks (1983).

LITHOLOGY OF THE SUBSTRATE

Structural damage appeared to be worse in areas where buildings were constructed on ash deposits 0.5 m or more thick; however, not every area underlain by ash had structural damage to buildings.

The volcanic ash was originally composed of particles of volcanic glass and crystal fragments, but severe weathering resulting from high average annual temperatures and abundant rainfall has altered most of the original constituents (Bates, 1960; Wieczorek and others, 1982; Buchanan-Banks, 1983). The ash has a large amount of clay-size material and a water content as high as 392 percent (weight of water as a percentage of weight of dry sample). Undisturbed deposits are fairly well indurated and resistant to erosion, forming road cuts at angles often steeper than 60°, even greater than the high angle of internal friction of the material (40°–43°). However, the ash has been found to become plastic after repeated passes of heavy equipment but to subsequently harden again after cessation of the vibrational stress (Hirashima, 1948, p. 485). Although the ash deposits were found to have a sensitivity to slope failure classed as medium to very sensitive (Wieczorek and others, 1982, p. 5), no evidence of large-scale slope failures were

found in the Hilo area. The shear wave velocity of the ash was calculated by Nielsen and others (1977, p. 34) to be between 67 to 142 m/s (219 to 467 ft/s) at strain percents of 10^{-1} – 10^{-3} and an undrained shear strength of 136 kg/m² (300 lb/ft²).

Data on the response of the ground to strong motion from this earthquake was collected and analyzed by the USGS from strong-motion accelerographs scattered throughout the island (Acosta and Maley, unpub. data, 1984; see fig. 44.1 for location of accelerographs and thickness of ash deposits at some recording sites). The amplification of the earthquake waves because of ash deposits is apparent when data from the U.S. Fish and Wildlife accelerograph, located on ash deposits about 3 m thick, and the University of Hawaii, Hilo, accelerograph, located on lava flows, are compared (table 44.3); these two accelerographs are essentially equidistant from the epicenter. The records from the accelerograph situated on ash show peak accelerations that are 5 to 6 times greater than the accelerations recorded on the lava flow, indicating that the amplitude of the earthquake waves was increased in the ash deposits.

In the 1973 Honouliuli earthquake (for data on this earthquake see table 44.1), similar results were found after analysis of a pseudovelocity response spectrum derived from seismic data from a selected aftershock. A simple response peak was obtained from the spectrum from a seismometer sited on lava about 17 km (11 mi) south of the epicenter, whereas a spectrum from a seismometer on ash (located about 14 km (9 mi) south of the epicenter near the U.S. Fish and Wildlife accelerograph that recorded the 1983 earthquake) showed a complex pattern with at least three periods of high response indicating greater wave amplitude on the ash (Nielsen and others, 1977, p. 11-12). Nielsen and others (1977) estimate that the velocity response of the volcanic ash was 5–10 times greater than the response measured on the lava flows. Although the difference in response in 1973 between the ash and lava might be attributed to the closer location of the seismometer on ash deposits to the epicenter, the data are consistent with the 1983 damage pattern.

On the other hand, during the 1975 Kalapana earthquake (for data about this earthquake see table 44.1), data from two seismoscopes at the same locations as the seismometers that recorded the 1973 earthquake do not indicate an increase in velocity response in the ash; the maximum motion of the seismoscope pen was 3.4 cm on the University of Hawaii, Hilo, seismoscope, 43 km (29 mi) from the epicenter, and the seismoscope on ash, 45 km (31 mi) from the epicenter, recorded 3.1 cm displacement (Rojahn and Morrill, 1977, p. 499). It seems likely that the 1975 earthquake did not produce enough energy in a frequency band to cause the ash to respond.

CONSTRUCTION PRACTICES

Few houses with post-and-pier construction had structural ties between the house, the piers, and the ground, and each element was therefore left free to move with respect to the others. In the few cases where structural ties such as rebar and bracing were used between the house and the piers, they appear to have been too few, flimsy, or poorly connected. Neither rebar nor bracing was adequate when used alone. Houses built across steep breaks in slope or near the edges of unsupported slopes generally sustained structural damage.

GROUND FAILURES

For several hours after the earthquake, the air at Kilauea's summit was brown with dust from the initial and continuing landslides off the caldera walls and within Halemaumau Crater (fig. 44.19). Hundreds of landslides, of volume generally less than 3,000 m³, occurred within the epicentral area; rock slides, falls, and topples were the dominant types of failure. These failures caused extensive road and trail damage in Hawaii Volcanoes National Park and temporarily closed the major highway around the island. For many kilometers southwest and northeast of the epicentral area, small rock falls, extensional cracks in the ground, and collapsed lava tubes were evident. Slope failures also occurred at Kealahou Bay, about 50 km from the epicenter, and along the Hamakua Coast, nearly 60 km from the epicenter. The generation of landslides at such distances from an epicenter is in good agreement with the findings of Keefer (1984, fig. 2A, B) for worldwide data on earthquake-induced landslides. Only small failures occurred in the thick and seismically sensitive ash deposits near Hilo and Pahala.

No fatalities or damage to dwellings resulted from the landslides, but two people were injured in rock falls onto the highway along the Hamakua coast about 25 km north of Hilo.

KAU DISTRICT

HAWAII VOLCANOES NATIONAL PARK

Most landslides from the earthquake occurred within Hawaii Volcanoes National Park, where the lava flows of Kilauea Volcano form cliffs as much as 120 m high (locality 6 on figs. 44.1, 44.6). These nearly flat-lying lava flows are a few tens of centimeters to a few meters thick, and thin ash beds occur between some of them. The flows are well indurated and fairly young (0.2–1.5 ka), but are extensively cracked and jointed because of rapid cooling and initial deformation (fig. 44.20). Locally the flows are overlain by about 2 m of loosely consolidated tephra deposits from phreatomagmatic eruptions of Kilauea Volcano.

Hiking trails along the northern edge of the caldera between Kilauea Iki Crater and Uwekahuna Bluff were extensively damaged where perhaps as many as 200 rock slides and rock falls removed sections of trails and covered those at lower elevations with landslide debris (fig. 44.20). A few had volumes greater than 3,000 m³. Some vertical cliff faces failed by toppling, when outward-rocking slabs of coherent material failed at the top because of imbalance; the upper parts of such landslides traveled farthest from the slope.

A reconnaissance survey of damage along Crater Rim Drive was conducted immediately after the earthquake. Although the road pavement was extensively cracked throughout its length, only the zones of greatest damage are shown in figure 44.6. Most of the road cracks depicted in this figure were caused by cracking of the ground beneath the road. The road damage included small apparent offsets in both right- and left-lateral senses, major to minor failures of subsurface material, and extensive compressional and extensional cracking, with the most severe damage where the road crosses

fracture systems related to Kilauea caldera (fig. 44.6, sites *a*, *b*, *c*; St. Ours, 1982). All the damage was attributable to the shaking effects of the earthquake.

At the eastern roadway into Kilauea Military Camp (fig. 44.6, site *a*) vibrational compaction of fill caused the road to collapse where a system of earth cracks lies under the road (fig. 44.21). Earlier failures of this type had occurred periodically along the verge of the road at this location, though on a smaller scale and usually induced by drenching rains removing supporting material. Tilling and others (1976, p. 26) describe compressional damage to a roadway near this locale in the 1975 earthquake.

Highway 11 near the northwestern roadway into Kilauea Military Camp (fig. 44.6, site *b*) was closed for several hours because of failure of subsurface material at a circum-caldera fault.

The southwest rift zone of Kilauea lies parallel to the Kaoiki fault system and is characterized by gaping cracks and fissures. Where Crater Rim Drive crosses the 0.5-km-wide zone (fig. 44.6, site *c*), there was both extensional and compressional damage throughout the zone, with an overall extension of about 4 cm (fig. 44.22A, B).

The roadway cracks at Keanakakoi Crater are subparallel to the west wall of the crater and probably reflect a subsurface zone of fractured rock related to the collapse of the pit crater. The cracks show only small right-lateral offsets and slight upward movement of the northeast side. The viewing overlook had extension cracks approximately 1 cm wide through it, and the rock wall slumped downward and outward toward the crater.

From Keanakakoi Crater, Crater Rim Drive was extensively cracked for 2 km. This earthquake-induced cracking is most likely related to preexisting crack systems in the area (St. Ours, 1982) as well as to settling of uncompacted tephra deposits from the 1959 Kilauea Iki eruption upon which the road was built.

Crater Rim Drive, which is adjacent to Crater Rim Trail between Waldron Ledge and Volcano House, was permanently closed to traffic, and the hiking trail rerouted, because of landslide damage and cracking of the road from vibrational settling of tephra deposits and fill (fig. 44.6, site *d*). This section of road also was badly damaged in the 1975 Kalapana earthquake, when cracks as much as 1 m wide formed parallel to the caldera rim (Tilling and others, 1976, p. 24). The cracks were subsequently filled in and the road repaired; many of the repaired areas failed again in the November 1983 earthquake.

Of the several large landslides that formed on the cliffs, 60–120 m high, along Waldron Ledge, the largest failure was a rock slide with a volume of about 4,600 m³ that occurred at a site that had been identified as an incipient landslide and had been monitored since April 1980 by the USGS (compare fig. 44.23A, B). Details of this monitoring program are included at the end of this section. At the time of the earthquake, a resident of the park housing area, who ran outside after the severe shaking had ceased, heard a whooshing sound that lasted 15–20 seconds and came from the direction of the caldera. This sound was probably generated by the rapid failure of this slide and others along this section of cliff. Judging from the shape of the headwall scarp, the slide probably

began as a block slide and disintegrated as it fell down the cliff face (fig. 44.24A, B). The debris did not travel far from the base of the cliff.

Major to minor arcuate cracking reflecting subsurface movement of material toward a free face also occurred at several locations along the road, from the park residential area to park headquarters and between the headquarters and Sulphur Banks.

South of Kilauea caldera, the Chain of Craters and Ainahou Ranch Roads (fig. 44.1) were extensively cracked by the shaking, and the road cracks in the Hilina Pali Road originally caused by a large intrusion in March 1980 were reactivated by the earthquake shaking. North of the caldera, damage to Mauna Loa Road was particularly severe and increased toward the epicenter and the zone of surface faulting. Some cracks in the epicentral area showed extension of as much as 5 cm, while others showed evidence of the pavement on either side having been repeatedly compressed (fig. 44.25).

MONITORING PROGRAM AT INCIPIENT WALDRON LEDGE LANDSLIDE

Soon after torrential rainstorms in early 1979, a series of cracks appeared in a section of Crater Rim Drive along Waldron Ledge (fig. 44.6, site *d*). These cracks widened in the heavy rains of March 1980. In order to watch for changes that might forecast the failure by landsliding of this part of Crater Rim Drive and Trail, a monitoring program was established by the USGS in April 1980.

Monitor 1 consisted of five nails set out as a quadrilateral centered over the road cracks (fig. 44.26). The distance between the nails was measured with steel tape once a week for the first month, then once a month for the next few months, and thereafter with lessened frequency (table 44.4). Within the first few months, nearly all the lines began showing measurable and cumulative extension, particularly those normal to the cracks (figs. 44.26, lines AE, BC, BD, 44.27A). In addition, the cracks had lengthened at both ends, and vertical offsets had become apparent.

To assess the rate of vertical change, a leveling line was added to monitor 1 in November 1980; it consisted of two lengths of rebar driven into bedrock, rebar 1 and Base, in a line northeast of, and off, the landslide (fig. 44.26). The level gun was placed at point 0 between the rebars to check their respective stabilities (fig. 44.26, right center); the gun was then moved to rebar 1 and the rod to each nail of the quadrilateral to measure its elevation.

Monitor 2 was added to the program in April 1981 to measure horizontal movement on cracks not crossed by the quadrilateral (fig. 44.26). Line X'-X was established northwest of the quadrilateral beyond the zone of visible cracking; it extended 23.7 m from X', a nail in a tree at the caldera edge to X, a nail in the centerline of the road. A second line was established across the quadrilateral and comprised two segments; one segment, line Y'-Z (24.1 m) was measured from Y', a nail in a tree at the caldera's edge to Z, another nail in a tree northeast of the road, and the second segment, line Y' to Y.

The monitors were measured frequently until mid- to late

1982. Measurements were discontinued in January 1983 because of the onset of the prolonged east rift eruption of Kilauea Volcano.

RESULTS OF THE MONITORING PROGRAM

During the period of measurement, all of the monitors normal to the cracks showed lengthening of lines and small vertical offsets indicating that the incipient landslide block was moving slowly outward and downward toward the caldera.

The lines of the quadrilateral were measured 14 times between April 1980 and October 1982 (table 44.4). Cumulative extensions above background level on the lines normal to the cracks (for background level see data for line ED, parallel to the cracks) was detected within a few months of the establishment of monitor 1 (fig. 44.27A). Continued documented movement of the incipient landslide block toward the caldera led to a decision by the Superintendent, Hawaii Volcanoes National Park, to close this section of road to traffic in April 1981 (fig. 44.6, site *d*). Although monitoring frequency decreased after the closing of the road, accelerated movement both laterally and vertically can be seen in the data after July 1981. The largest changes in line lengths within the quadrilateral occurred between July 1981 and July 1982 on lines AC, AD, AE, BC and BD, crossing the cracks (table 44.4, fig. 44.27A). The largest vertical changes also occurred during the same period when nails C, D, and E (the three on the caldera side of the cracks), moved downward with respect to rebar 1 (table 44.4, fig. 44.27B).

Line Y'-Z, which also crossed the cracks curving away from the caldera (see fig. 44.23A, *B*, location B) as well as the cracks monitored by the quadrilateral, extended about 7 mm more than the shorter quadrilateral lines, AE and BD, over the period June 1981 to July 1982 (table 44.4, fig. 44.27C), suggesting that incipient failure was also developing on the cracks curving away from the caldera.

The monitors were destroyed by landslides caused by ground shaking associated with the November 1983 earthquake. Nails A, B and E of the quadrilateral survived the earthquake but E was on a separated block and could not be reached for measurement. The distance between A and B shortened 0.3 m. Lines X'-X, Y'-Y and Y'-Z, could not be remeasured because the trees on the caldera rim holding the nails, and the section of road where nail Y was located, were gone.

SOUTH AND NORTH HILO DISTRICTS

Dozens of soil falls and slides of volume about 15 m³ occurred in the ash deposits near Hilo, and at one location along Kaumana Drive there was evidence of minor subsidence (fig. 44.28). Narrow cracks in asphalt were common.

Small (volume <20 m³) rock falls and soil slumps were observed along the highway from Hilo northward to Ookala, where Mauna Kea ash deposits blanket lava flows of the Hamakua Volcanic Series, also from Mauna Kea Volcano (Stearns and Macdonald, 1946, pl. 1). These flows are deeply weathered and have locally produced saprolite consisting of well-rounded to sub-

angular rock remnants in a clayey matrix. The rocks are in large part soft and frequently slide during periods of heavy rain. Six landslides with volumes less than 500 m³ deposited debris on the highway between Maulua Bay and Kaawalii Gulch causing temporary closure of the road (fig. 44.1, locality 9; fig. 44.29). The debris was removed by midday of November 16 and the highway was reopened (Harry Kim, oral commun., 1983).

In mid-January, when fieldwork was conducted north of Hilo, only four of the six landslides could be located. All the observed failures were rock slides from the steep roadcuts and all appeared to have shallow head scarps, 1–2 m deep. Close examination of the landslides was limited because of the busy, narrow road and the steep slopes. Rock slides could be seen in the roadcuts in each of the highway's large horseshoe bends, with the largest slide occurring in Laupahoehoe Gulch (estimated volume 420 m³) from the near-vertical cliff west of the road. During the next heavy rainstorm, material loosened by the earthquake shaking west of the earthquake-induced slope failure in Laupahoehoe Gulch caused another large landslide in this gulch (fig. 44.30). For several months after the earthquake, similar landslides occurred in this location during rainy periods.

The earthquake-induced rock slide in Maulua Gulch (volume about 6 m³) was the one that caused injury to two people travelling in autos. Another rock slide (volume about 36 m³) covered both lanes of the narrow secondary road to Laupahoehoe Point (fig. 44.31) making it impassable for a short time.

Similar ground failures occurred at these locales as a result of the 1975 earthquake (Tilling and others, 1976, table 1) and the 1973 earthquake (Nielsen and others, 1977, p. 15). Rock and soil falls also occurred on the steep wave-cut cliffs just north of Hilo, about 17 km south of the 1973 earthquake epicenter (Nielsen and others, 1977, p. 14).

KONA DISTRICT KEALAKEKUA BAY

Shortly after the earthquake occurred, a large dust cloud over Kealahou Bay was reported to the USGS as possible volcanic venting from beneath the bay (fig. 44.1, locality 10). Aerial reconnaissance determined the cause of the cloud as dust from several rock slides off the steep slopes around the bay. Currents of brown, cloudy water were observed from the air to extend about one kilometer from the shore (J.P. Lockwood, written commun., 1983).

Several rock slides at Kealahou Bay occurred from about the 120-m elevation on the face of a nearly vertical cliff of weathered Mauna Loa lava flows with intercalated thin ash beds (fig. 44.32; Stearns and Macdonald, 1946, pl. 1). This cliff section has been dated as spanning the interval 2–30 ka by charcoal samples collected from beneath lava flows near the top and at the base of the cliff, respectively (J.P. Lockwood, oral commun., 1985). The largest of these rock slides had a volume of about 5,500 m³. The slides could not be examined closely because of the steep slopes, but the head scarps appeared to be fairly shallow (volume <3 m). Several smaller rock falls also occurred from the steeper lower slopes.

ANALYSIS OF GROUND FAILURES

Ground failures appeared to be influenced by three main factors: (1) proximity to the epicenter, (2) lithology of the substrate, and (3) slope steepness.

PROXIMITY TO THE EPICENTER

The greatest ground cracking occurred in the epicentral area; most landslides also occurred there, the size and abundance of failures decreasing with distance from the epicenter (fig. 44.33). This localization of ground failures is most probably due to the shallow depth of the earthquake and to the generating mechanism. The strike-slip faulting occurred on a near-vertical fault plane that ruptured the ground surface; the seismic energy released along the fault was thereby transferred to the surface as earthquake waves, and the resulting strong ground shaking in the epicentral area caused abundant ground failures.

LITHOLOGY OF THE SUBSTRATE

The lava flows from Hawaii's five volcanoes are typically flat lying, forming broad, shield-shaped volcanic edifices. These gentle slopes are locally modified by faulting, collapse features, and erosional processes, each of which can form steep cliffs. The lava flows, extensively cracked and jointed as a result of cooling and initial deformation, vary in their degree of weathering with the age of the deposit, the density of the rock, and the amount of rainfall to which they have been subjected. The thickness of the flows also varies from a few centimeters to several meters, and they are sometimes interbedded with volcanic ash deposits that are locally as much as 9 m thick (Hirashima, 1948, p. 484; Buchanan-Banks, 1983). In some areas the ash units are the surficial deposits. Landslides and small soil slips frequently occur in the ash and, locally, in the underlying materials following heavy rains. The deeply weathered Mauna Kea lava flows are particularly susceptible to failure induced both by saturating rains and by earthquake shaking.

SLOPE STEEPNESS

Topography was a factor in controlling the location of landslides, and, to a lesser degree, areas of structural damage in the November 1983 earthquake. The largest landslides invariably occurred from the near-vertical cliffs in the epicentral area and from steep slopes elsewhere on the island. Numerous rock falls could be observed along highways where roads were cut through lava flows regardless of the height of the cut. Small soil slumps in ash deposits also occurred where the slope had been steeply cut.

CONCLUSIONS

The 1983 Kahoiki earthquake provided a unique opportunity to examine earthquake-induced structural damage and ground failures in Hawaii. Although the 1975 Kalapana earthquake had a higher magnitude (M 7.2) and hence more seismic energy, its

location near the coast allowed some of this energy to be propagated seaward away from the main cultural centers of the island. The inland location of the Kahoiki earthquake, therefore, resulted in greater structural damage (Koyanagi and others, 1984, p. 4).

Damage to structures was greatest in the epicentral area, where the foundations under some houses moved as much as 1.2 m away from the house. Structures with post-and-pier foundations were more severely damaged in this earthquake than those with concrete slab foundations. In some cases, the posts and piers were joined together with steel plates or rebar reinforcement; these houses nonetheless came off their foundations.

Lithology and topography also seemed to affect the location and degree of structural damage. Houses in Wood Valley, Volcano Golf and Country Club Subdivision, Volcano, and Hilo were damaged where ash deposits at or near the surface were at least 0.5 m thick. Houses built across breaks in slope, on uneven terrain, on sloping ground, or near the edges of unsupported embankments sustained greater damage than those on flat ground.

The regional distribution of landslides resembles the overall pattern of seismic intensity, most failures occurring in the epicentral area. The threshold intensity for triggering small rock falls and soil slumps was IV to V (modified Mercalli scale).

The predominant types of landslide generated by this earthquake were shallow rock slides and falls. They most commonly occurred on the steep slopes and were induced by the earthquake shaking.

Virtually all large landslides occurred in extensively cracked and jointed lava flows. Small soil failures and extensional cracks also occurred in the thick ash deposits in the epicentral area and in Hilo.

Because of the relatively sparse population in the epicentral area and the early hour at which the earthquake occurred, there were few injuries from the landslides. However, landslides along the Hamakua coast slightly injured two people and caused closure of the circum-island highway for a few hours until debris was removed. Compactional failure of road fill also closed the circum-island highway in the epicentral area for a few hours.

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FIGURE 44.1.—The Island of Hawaii showing epicenters of November 16, 1983, Kaoiki earthquake and two earlier damaging earthquakes; also shown are areas of 1983 structural damage and earthquake-related ground failures discussed in text. Additional text figures cited where applicable. Inset shows focal-mechanism solution for 1983 earthquake from Endo (1985, p. 186): *P*-wave first motions plotted on lower hemisphere equal-angle stereonet; open squares, down first motions; solid squares, up first motions. Topography from U.S. Geological Survey Hawaii Island series W532, 1975, 1:250,000.

EXPLANATION

Earthquake epicenters

⊙ Kaoiki earthquake, November 16, 1983

* 1973 and 1975 earthquakes

1 Areas of structural damage or ground failure during 1983 earthquake: 1, Ka Lae Road; 2, Wood Valley; 3, Kapapala Ranch house; 4, Ranch house at east end of Kapapala Ranch; 5, Volcano Golf and Country Club Sub-division and Keauhou Ranch house; 6, Hawaii Volcanoes National Park; 7, Upper Wright Road; 8, Hilo; 9, North Hilo District; 10, Kealekekua Bay

□ Ash deposits

△ Accelerograph location and ash thickness, in meters

— Fault trace, from Stearns and Macdonald (1946, pl. 1) and Lipman and Swenson (1984)

— District boundary

FIGURE 44.1.—Continued.

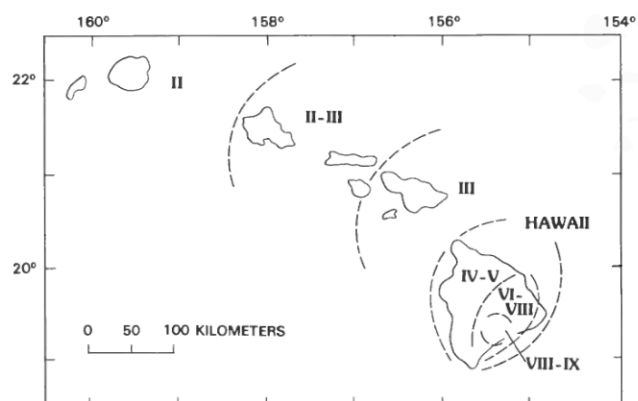


FIGURE 44.2.—Isoseismal map for November 16, 1983, earthquake prepared from observations of damage and felt reports from residents compiled by Hawaii County Civil Defense Agency. Numbers indicate intensity on modified Mercalli scale (from Koyanagi and others, 1984, fig. 3).

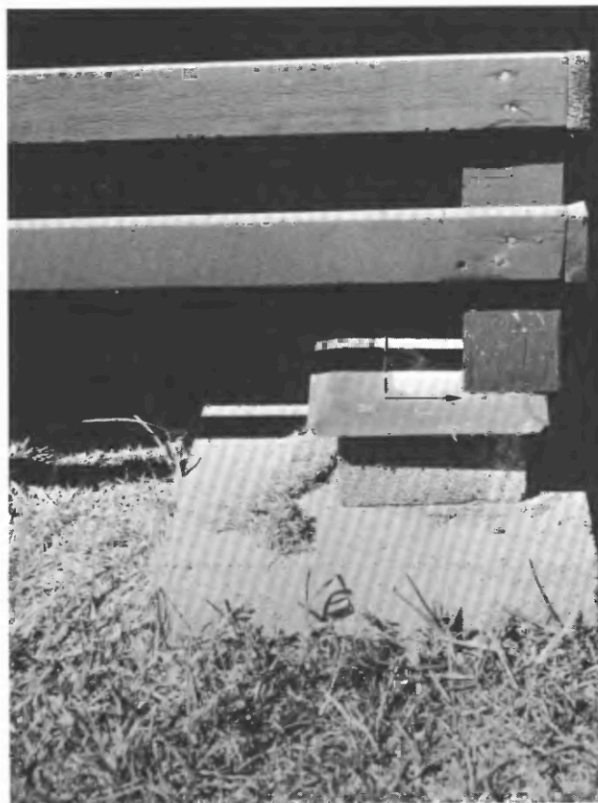


FIGURE 44.3.—Post-and-pier house support displaced in November 16, 1983, earthquake. In this type of construction, two concrete blocks form pier and a vertical wooden 10-cm by 10-cm post supports house. Larger block is resting on ground; smaller is placed on top of this and usually not connected to it. Between upper block and post is a termite shield of thin metal. At this locality, both post and upper foundation block have moved several centimeters to right on their respective supports. Dashed line indicates original position of post; arrow shows direction of movement.

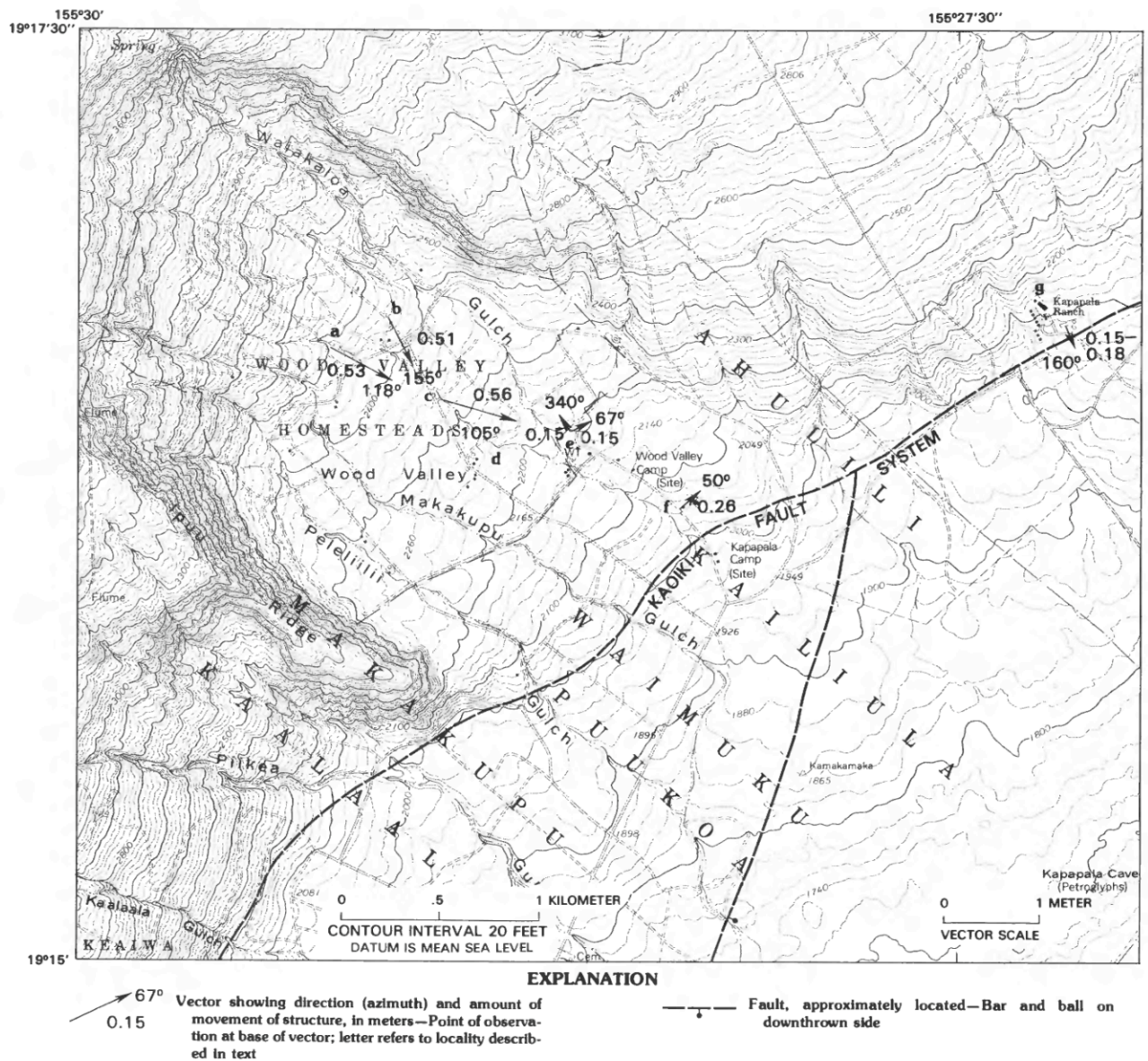


FIGURE 44.4.—Earthquake-related movement of structures in Wood Valley and western Kapapala Ranch, November 1983 (fig. 44.1, localities 2, 3). Topography from U.S. Geological Survey Wood Valley 7.5-minute quadrangle, 1981, scale 1:24,000. Location of faults from Stearns and Clark (1930, pl. 1) and Lipman and Swenson (1984).



FIGURE 44.5.— Damage to a wood-frame house with post-and-pier construction in Wood Valley (fig. 44.4, locality b). **A**, Northeast corner post fractured where anchor bolts connected it to 0.5-cm-thick steel plate positioned on southwest side of post (away from the viewer). Concrete foundation block appears to have been poured as single unit around the steel plate. Post also was torn loose from house and from diagonal bracing when ground, pier, and post moved southeastward. **B**, Northwest corner post with steel plate on south side of post. The 0.5-cm-thick steel plate is bent at 45° angle. Photographs by E.T. Endo.

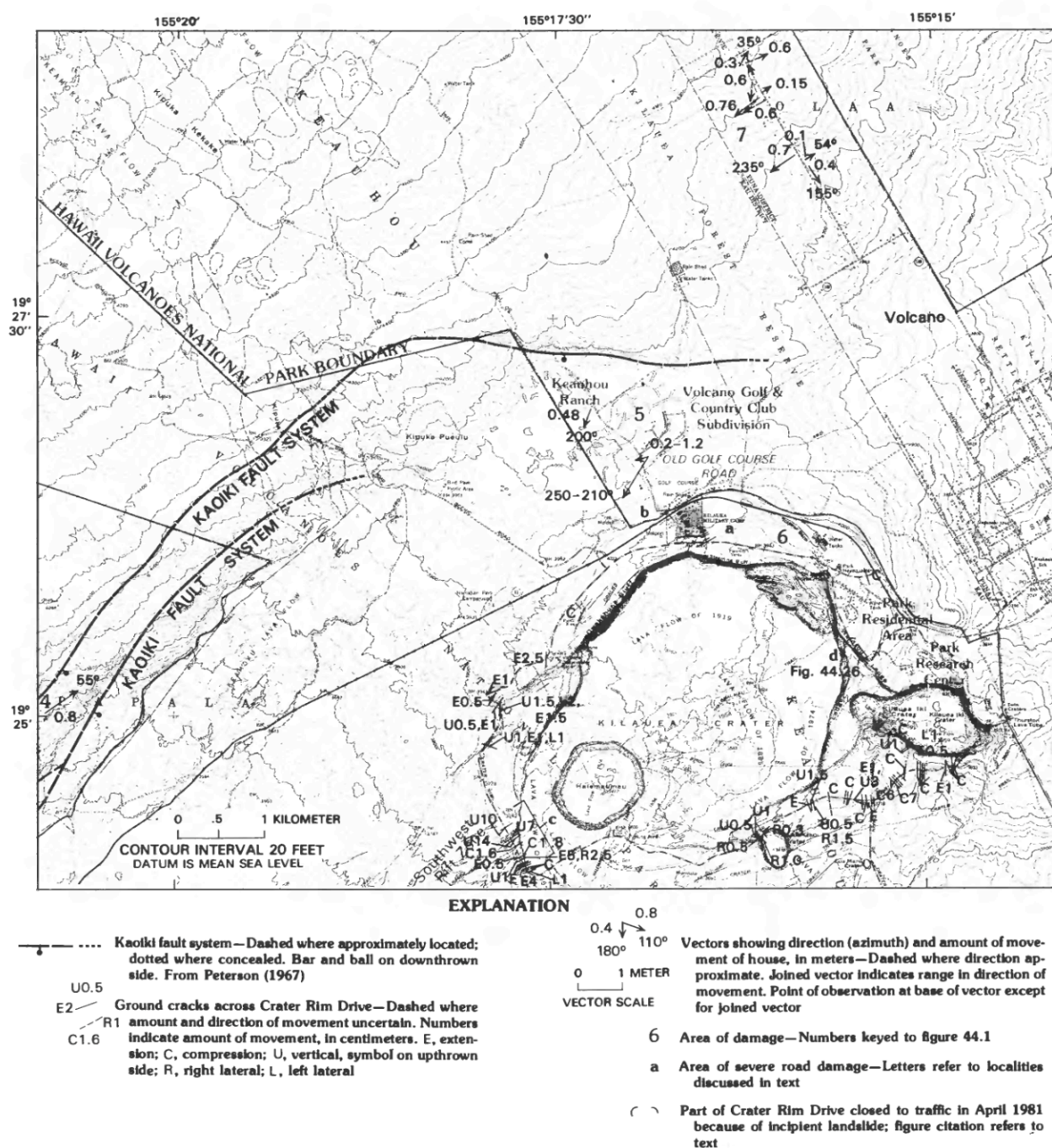


FIGURE 44.6.—Earthquake damage in epicentral region near Kilauea summit (localities 4–7, fig. 44.1). Some of the worst structural damage occurred in this area. Topography from U.S. Geological Survey Kilauea Crater and Volcano 7.5-minute quadrangles, 1981, scale 1:24,000.



FIGURE 44.7.—House on Kapapala Ranch about 12 km east of epicenter was displaced 0.8 m northeastward during earthquake. Most supporting posts remained vertical, but those used to frame a basement room were tilted. Concrete foundation piers, partly obscured by grass, behind figure in dark jacket. Windows broken during earthquake are covered with plastic. Near clump of trees on hill behind house, small soil slips can be seen and broken branches strew the ground.

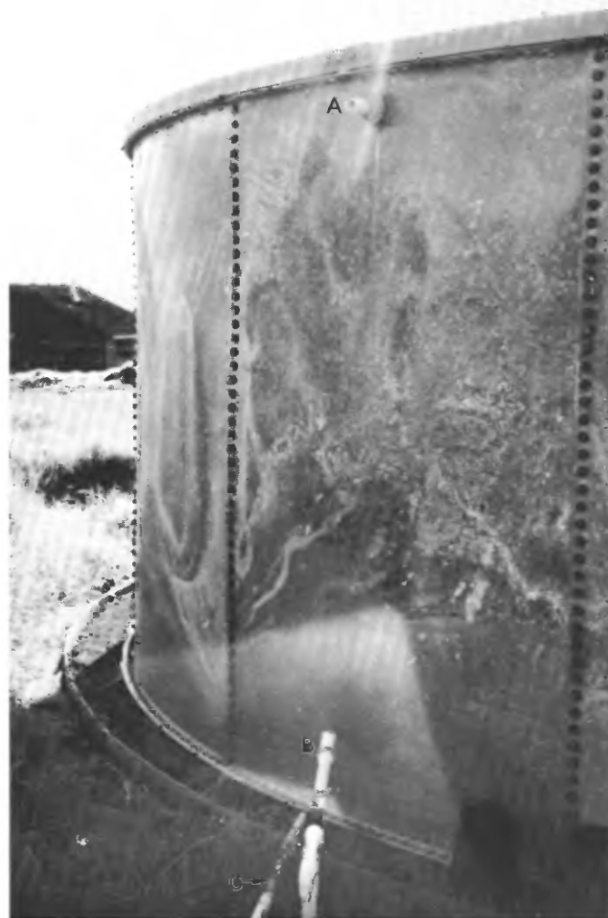


FIGURE 44.9.—North corner pier of damaged two-story frame house in Volcano Golf and Country Club Subdivision. Although house is now 1.2 m southwest of its foundation, rebar protruding through piers is still straight. Termite shield from atop pier can be seen on ground. House subfloor was originally 1 m above ground, but most supporting posts collapsed.

FIGURE 44.8.—Water tank that may have moved as much as 0.12 m southward (to right in photograph) during November 1983 earthquake. The 1.8-m length of pipe that originally extended from A to B now lies under tank at C. First motion apparently snapped pipe, which rolled under tank as tank tilted back and forth.

**A****B**

FIGURE 44.10.—Damaged frame house in Volcano Golf and Country Club Subdivision. **A**, View of attached garage (with concrete foundation) and house (post-and-pier foundation). House moved farther than garage, breaking a 10-cm by 10-cm upright and causing a tear in southwest wall at electric meter. Photograph by R.Y. Hanatani. **B**, Detailed view of right side of house; to right of drainpipe, a supporting post can be seen resting on ground southwest of pier on which it originally stood. Photograph by J.B. Stokes.



FIGURE 44.11.—Main meeting room and library at Hawaiian Volcano Observatory after 1983 earthquake. Bookcases were torn from back wall and fell onto table; storage cabinets were moved as much as 0.5 m. Preearthquake location of cabinets is documented by dust marks on floor behind and to right of plastic waste bin. Smoked-drum seismographs (obscured by easel) located under windows to right were temporarily out of order because their drive mechanisms jammed. Photograph by J.D. Griggs.

**A****B**

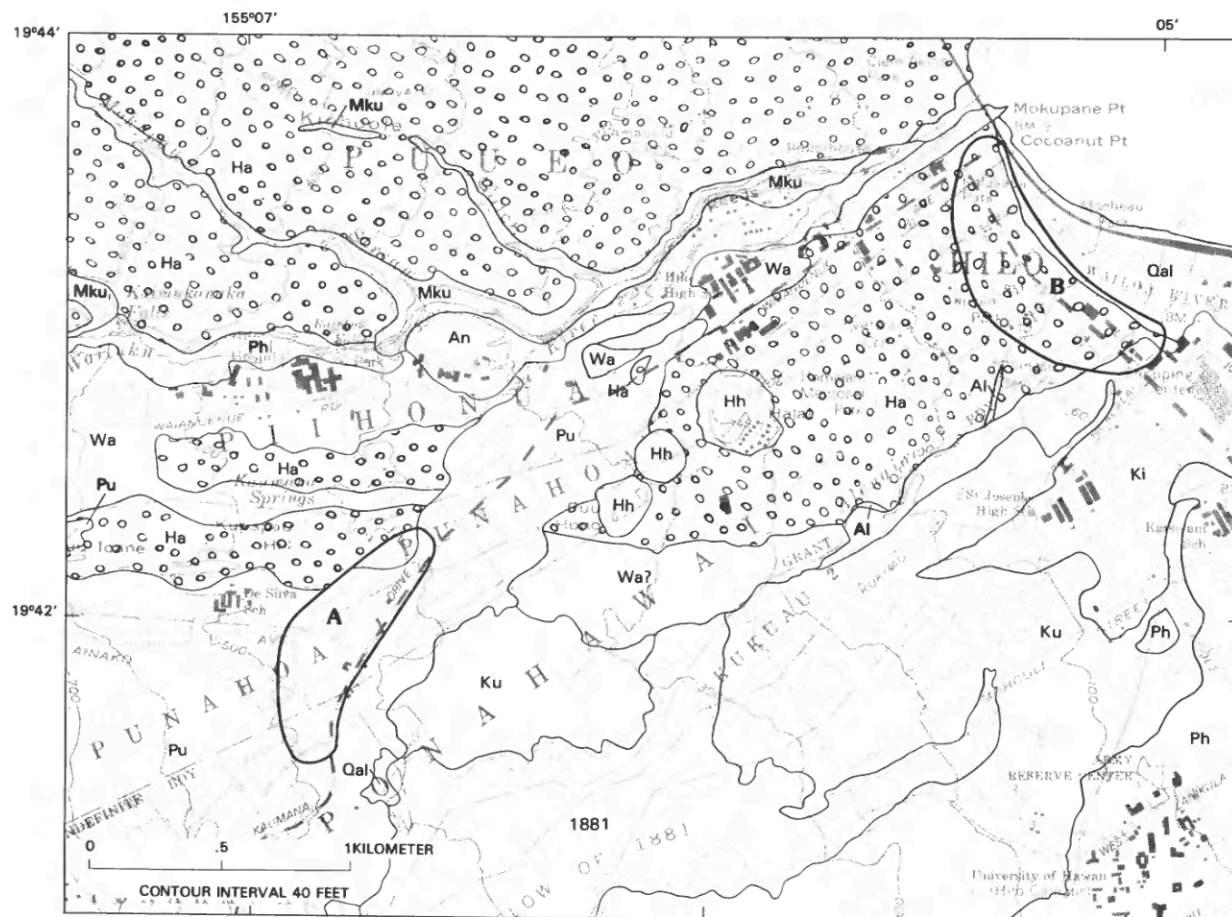
FIGURE 44.12.—Barnlike three-story-high frame house in Puna District that was moved off its foundation about 0.3 m toward northeast in 1983 earthquake. **A**, View of house showing position of one of sheared support posts (circled). **B**, Close-up of footing circled in **A**. The 14-cm by 14-cm wooden post was sheared by rebar that extended from base of footing upward into post as much as 11 cm; most other posts supporting upper story were similarly sheared. House has been replaced on piers.



FIGURE 44.13.—Water tanks in Volcano affected by 1983 earthquake. Most water tanks here were constructed like one standing at right rear. Tank in foreground has collapsed, while other appears little damaged although displaced southwestward 0.7 m. This difference in response to earthquake may be because of a difference in water level in tanks at time of earthquake, or because of a difference in age or condition of tanks. Photograph by E.T. Endo.



FIGURE 44.14.—Greenhouse on Upper Wright Road leaning to southwest after earthquake; view to southeast. Crop loss in this area was severe because of collapse of some greenhouses and uncovering of planted furrows. Crop shown here is tomatoes. Photograph by E.T. Endo.



EXPLANATION

A Area of earthquake damage— Letters refer to discussion in text

CORRELATION OF MAP UNITS

Surficial deposits

Qal Quaternary alluvium

Mauna Loa Volcano

1881	1881 pahoehoe
Ku	Kukuau pahoehoe Age —1.35 ka
Pu	Punahoa pahoehoe Age —3.5 ka
Ki	Kinoole aa Age <8.0 ka
Ph	Malaal picrite Age —9.7 ka
An	Anuenue aa Age —10.6 ka
Wa	Waihanuue pahoehoe Age —14.2 ka

Mauna Kea Volcano

Homelani ash
Age >14.2 ka

Al Alenalo Stream
picrite
Age >14.2 ka

Hh Halal Hills
spatter
Age >14.2 ka

Mku Lavas of Mauna
Kea, undivided

FIGURE 44.15.—Geologic map of Hilo and vicinity showing areas of structural damage from November 1983 earthquake (fig. 44.1, locality 8). Adapted from Buchanan-Banks and Lockwood (1982). Topography from U.S. Geological Survey Hilo 7.5-minute quadrangle, 1981, scale 1:24,000.


A

B


FIGURE 44.17.—Damaged commercial building in old part of Hilo. Side wall separated from main structure, leaving a gap at roof level of about 21 cm.

FIGURE 44.16.—Damage to houses in South Hilo District. **A**, Wood braces have been emplaced to prevent second story of this house from moving farther downslope. Broken and twisted drain pipe gives an indication of amount of distortion this house has undergone. **B**, Living area of this wood-frame house extends across break in slope from street level, marked by vegetation on left, to above four-car garage. Concrete blocks of garage level are broken both through and between blocks. Upper story is warped and has moved toward back of house (toward viewer) and to right. New uprights and cross bracing behind garage doors (not visible in this photograph) have been added to support weight of upper story. Drainpipe has been reattached at street level with rope. A decorative rock wall has collapsed and rocks rolled downhill.

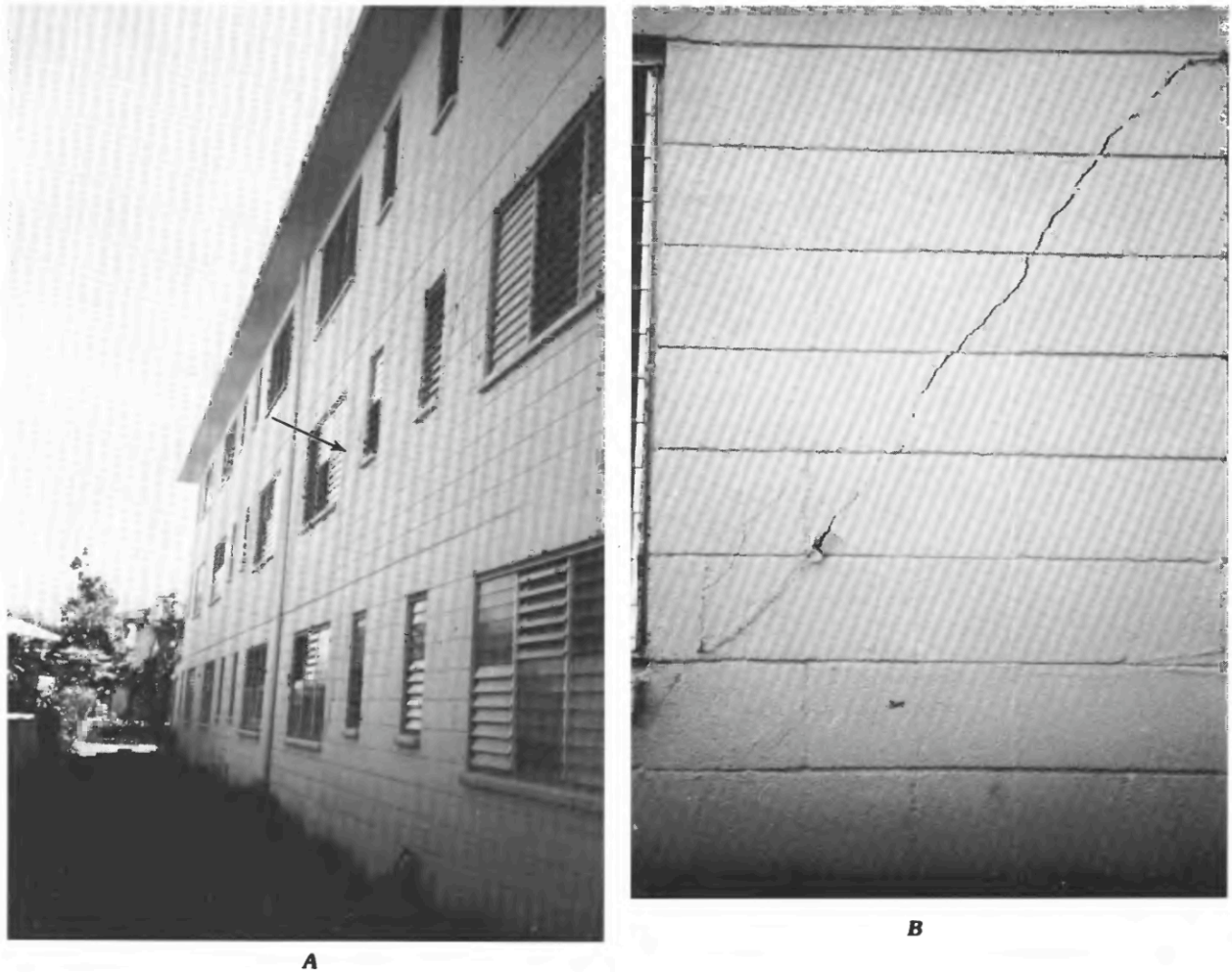


FIGURE 44.18.—Apartment building in Hilo damaged in November 1983 earthquake. **A**, View along two-thirds of length of building, which was difficult to photograph because of steep slope down to left. Cracked cinder block can be seen between most of windows of first and second floors; less structural damage was apparent at third floor. Arrow indicates area shown in detail in **C**. **B**, Detail of damage to a part of first floor not shown in **A**. Along longest and widest crack, smeared texture and flaking paint indicate an old crack that had been repaired and repainted. As a result of earthquake, there is renewed cracking along this feature as well as some new cracks through cinder blocks. This building probably was damaged originally by the 1973 Honouliuli earthquake and (or) by 1975 Kalapana earthquake. **C**, Detail of damage indicated by arrow in **A**. Some blocks were broken in such a way that pieces of them protruded from block or spalled off.



C

FIGURE 44.18.—Continued.



FIGURE 44.19.—View of Uwekahuna Bluff in Kilauea caldera, taken from Crater Rim Trail a few hours after November 1983 earthquake. Dust plumes mark rock falls that were still occurring along this section of caldera wall. Hawaiian Volcano Observatory is just out of photograph to right. Photography by J.D. Griggs.



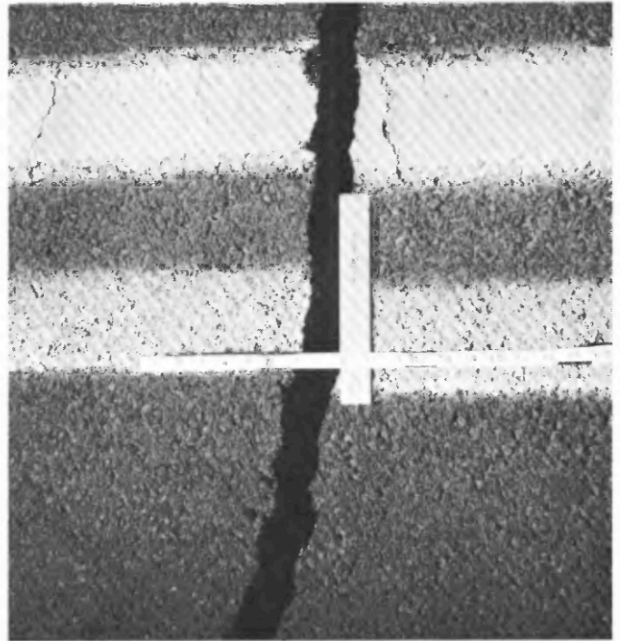
FIGURE 44.20.—Typical section of cliff in Kilauea caldera composed of flows from Kilauea Volcano. View looking up from Halemaumau Trail below Volcano House toward Crater Rim Trail; guardrail (arrow) can be seen suspended over 60-m-high cliff where a rock slide has removed part of trail.



FIGURE 44.21.—Section of Crater Rim Drive at eastern entrance to Kilauea Military Camp that collapsed in November 1983 earthquake along a system of cracks trending at az 60°. Earthquake shaking caused subsurface material to settle, thus undermining road. Note pavement patch from repair of earlier failure at same place.



A



B

FIGURE 44.22.—Compressional and extensional features produced by November 1983 earthquake where Crater Rim Drive crosses southwest rift zone of Kilauea Volcano. **A**, A compressional fold 12 cm high; far end of fold has been collapsed by passage of vehicle. **B**, An open extension crack 5 cm wide, which shows apparent right-lateral offset of about 2 cm, and vertical offset up to north (left) of about 1 cm.

**A****B**

FIGURE 44.23.—Ground failure in November 1983 earthquake along Crater Rim Drive between Waldron Ledge Overlook and Research Center turnoff. **A**, Photograph taken in March 1980, looking northwest, showing road cracks curving toward caldera (left) and outlining incipient landslide (A, C, D). Along the right edge of pavement, additional cracks curving away from caldera (B) mark west side of graben-like depression that runs parallel to roadway for nearly same length as incipient landslide cracks. **B**, Photograph of same section of road taken in October 1984. Slope failed along preexisting cracks (A, C, D) during earthquake shaking. A graben about 2 m deep by 1–2 m wide has formed along cracks at right side of road (B) and caused trees to tilt.

**A****B**

FIGURE 44.24.—Details of failure of Waldron Ledge landslide. Labelled points (A, B, C, D) are same as in figure 44.23. **A**, View southeast at head scarp of landslide and of parallel graben on other side of road. Headwall scarp was approximately 14 m high and 30 m long; landslide removed 11-m-wide section of road and trail. **B**, View downward from road of jumbled mass of rock resulting from disintegration of slide block; mass did not travel far from base of cliff.



FIGURE 44.25.—Earthquake-produced crack across road at northwest entrance to Waldron Ledge Overlook. Chips of broken pavement indicate sides of crack were bashed together repeatedly. Photograph by J.B. Stokes.

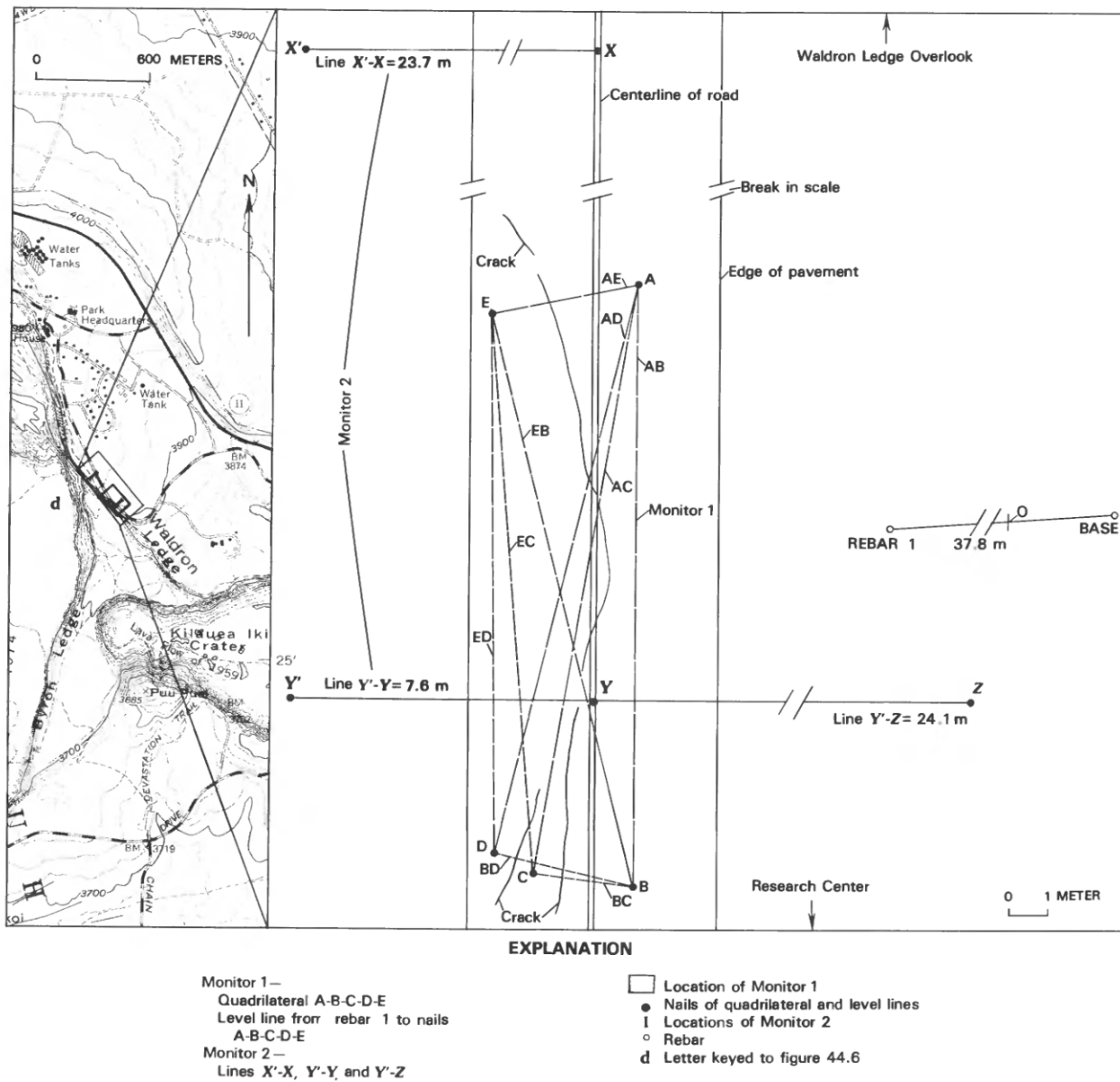


FIGURE 44.26.—Location map and plan of monitors established by USGS across series of cracks in Crater Rim Drive near Waldron Ledge. Topography from USGS Kilauea Crater 7.5-minute quadrangle, 1981, scale 1:24,000.

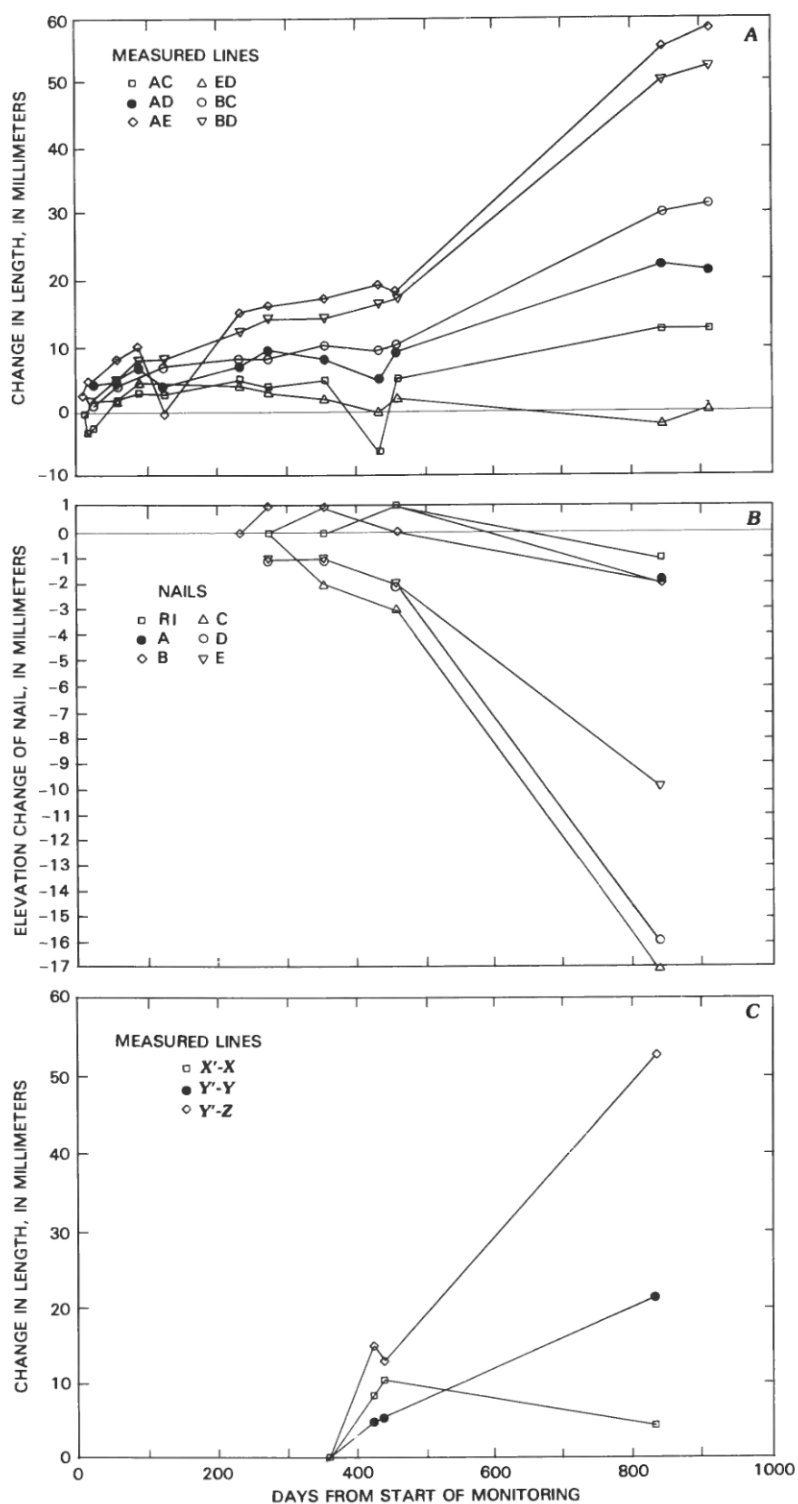


FIGURE 44.27.—Results from monitors established across incipient landslide on Waldron Ledge. **A**, Changes in line lengths recorded by monitor 1, the quadrilateral. **B**, Vertical changes recorded by monitor 1 between nails of quadrilateral and rebar 1 (R1). **C**, Changes in line length recorded by monitor 2, lines measured with steel tape.



FIGURE 44.28.—Arcuate road crack along Kaumana Drive (fig. 44.15, area A) formed in November 1983 earthquake. Ground slopes downward to right. Houses were structurally damaged and water main was broken in area just out of photograph to left.

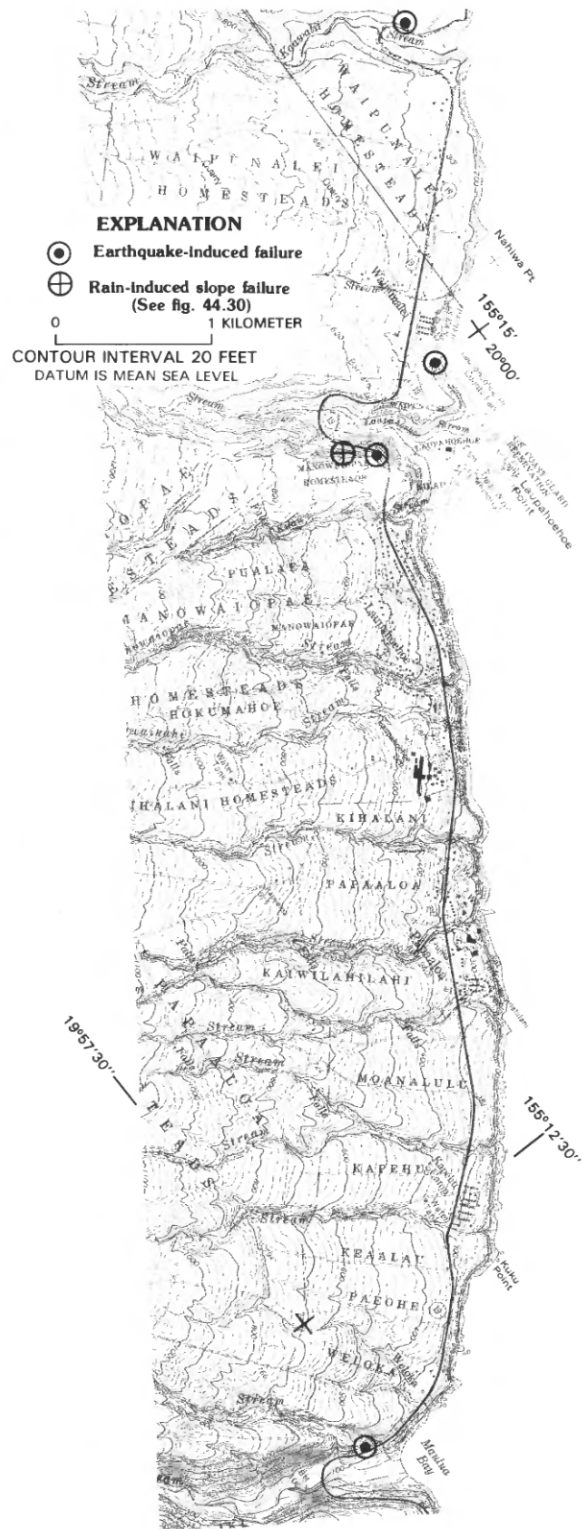


FIGURE 44.29.—Locations of earthquake-induced and subsequent rain-induced slope failures that occurred in North Hilo District between Maulua Bay and Kaawali Gulch as a result of November 16, 1983, earthquake. Topography from U.S. Geological Survey Keanakolu, Kukaiau, and Papaaloa 7.5-minute quadrangles, 1981, scale 1:24,000.



FIGURE 44.30.—Rain-induced slope failure in Laupahoehoe Gulch a few months after November 1983 earthquake. Heavy rains caused earthquake-loosened material to slide. Material below road was pushed over by bulldozer. Light-colored grassy area above road to right of new slide lacks vegetation and indicates that area has been site of landslides in past. At time of earthquake, a smaller rock slide occurred from the nearly vertical cliff just below the power poles (left), and blocked highway for a few hours. Photograph by N.G. Banks.

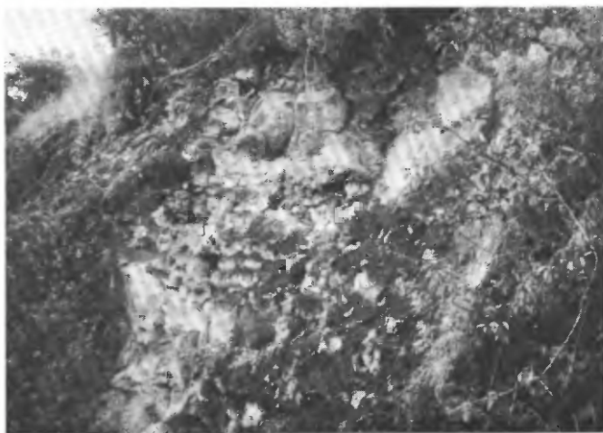


FIGURE 44.31.—Headwall scarp of earthquake-induced rock slide that briefly blocked secondary road to Laupahoehoe Point. It was not possible to picture entire slide in one photograph because of steep cliff bounding road and fact that slide occurred between two curves in road. Lower part of rock slide cannot be seen here; slide was about 1 m deep, 9 m high, and 4 m across (volume about 36 m^3). In-place formation of spheroidal boulders of weathering in Mauna Kea lava flows attests to severity of disintegration of these rocks.



FIGURE 44.32.—Narrow chutes (outlined) formed at time of November 1983 earthquake by landslides from steep slopes surrounding Kealakekua Bay, west coast, Island of Hawaii. Rock falls (rf) occurred on lower, steeper slopes. View northwestward.

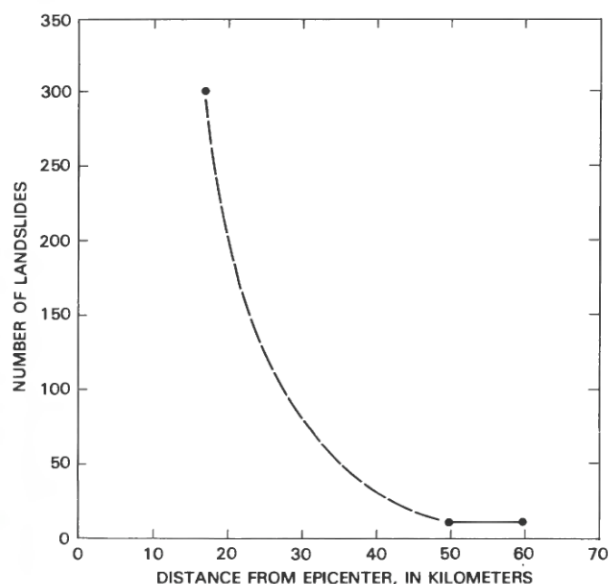


FIGURE 44.33.—Number of landslides caused by November 1983 earthquake in relation to distance from epicenter. Dashed line is estimated interpolation.

TABLE 44.1.—*Selected parameters of damaging earthquakes in Hawaii, 1962–1983*

[Modified from Koyanagi and others, 1984, table 1]

Date	Location	Magnitude	Energy release (10^{12} J)	Maximum intensity (modified Mercalli)	intensity (location)	Damage (millions)	Depth (km)	Focal mechanism
June 27, 1962	Kaoiki	6.1	40	VI	Volcano	\$1.0(?)	8	Strike slip
April 26, 1973	Honomu	6.2	60	VII	Hilo, Hamakua	5.6	48	Strike slip
November 30, 1974	Kaoiki	5.5	4	V	Kapapala, Volcano, Hilo	<1	6	Strike slip
November 29, 1975	Kalapana	7.1	2170	VIII	Hilo, Puna, Volcano	4.1	8	Low-angle thrust?
November 16, 1983	Kaoiki	6.6	260	VIII-IX	Volcano, Kapapala, Hilo	7.0(?)	12	Strike slip

TABLE 44.2.—Intensity and description of damage at various localities on the Island of Hawaii, November 16, 1983, Kooiki earthquake (magnitude 6.6)

City, town, village	Intensity (modified Mercalli)	Description of damage
South Hilo District		
Hilo	V-VIII	Extensive damage in downtown area. Minor cracks in roads and water pipes, concrete walls and floors, and plaster. Connecting pipes to an underground gasoline storage tank were ruptured. Most public buildings sustained damage to architectural plaster and acoustic-tile ceilings, and had spalling concrete. The public library also had plate glass windows broken. Hilo Hospital suffered structural damage, roofing, and architectural-plaster damage estimated at \$250,000. Apartments and business buildings suffered structural and equipment damage. Numerous plate glass windows broke. Shelved items in markets fell or tumbled over. Homeowners reported losses because of houses and garages shifting from foundations; cracked windows, retaining walls, driveways, and concrete house pads; broken windows; water pipes, and water heater fittings; collapse of rock walls and fences; steps torn away from houses; plumbing damage and septic tank cave-ins; doorways, window frames and cupboard doors distorted; chimneys separated from walls; lightweight furniture and table lamps fell over; loose and hanging objects fell and broke. Several people experienced difficulty standing. A driver described his car trying to wander as if it had a flat tire. Another observer described undulating ground waves with crests and troughs approximately 0.3 m high and 0.5 m across.
Papaikou	VI	Septic tank caved in; shelves fell from framing; objects fell from high shelves; books and mirrors fell; dishes broke; minor cracks to interior walls. One householder reported damage to interior walls, as well as structural damage to house and cracking of concrete slab in carport.
Pepeekeo	VI	Water splashed out of sink.
Honoum	VI	Loose objects fell off shelves and broke; dishes and bottles broke; stone walls opened up.
Puna District		
Hawaiian Paradise Park	V-VII	A few knickknacks tipped or fell; 5 percent of the water in a 75,500-L (20,000-gal) pool was lost through sloshing. There was one report of a destroyed water tank.
Orchidland	IV	Many objects on shelves fell. Nothing broke.
Ainaloa		Cupboard doors opened and dishes toppled out; book shelves fell; two support beams for a deck moved 10 cm off blocks.
Keaau	VI	House rocked; objects on shelves and in cupboards fell over but few broke. Water sloshed out of catchment tank.
Kurtistown	VI	Television, lamp, and statue fell off shelves. Dishes broke and pictures fell off wall.
Mountain View	VI-VIII	One house shifted 2 cm on its foundation piers, pulling away from back wall. A resident reported water pipe to toilet broke and fittings to water heater were damaged and leaking; water sloshed in water tank; cupboard doors opened and contents fell out; dishes and lamps broke; bookcases overturned and books were scattered; furniture was moved; loose objects tumbled off shelves. Hand-stacked rock wall collapsed in some places. A driver traveling at about 50 mph uphill on Highway 11 between Mountain View and Glenwood found it impossible to maintain control of the car. It felt as though the car had several flat tires, and he was forced to stop. He observed two other cars coming downhill whose drivers also stopped and got out to examine their cars.
Glenwood	VII-VIII	Loose objects fell off shelves; items fell from cupboards and freezer; contents of closets spilled; television overturned and books were dumped off bookshelves; large appliances moved, drywall was cracked in some places; stacked lumber was unstacked; full doughboy water tank moved about 5 cm.

Volcano	VI-VIII	Houses and garages were moved off foundations as much as 1 m. Masonry was broken and house frames cracked. Carports were leaning and a few collapsed. Many water tanks were damaged and some collapsed; others were moved as much as 0.5 m and pipes were broken. Three fireplace chimneys at residential homes collapsed. Ground cracks opened about 2 cm; pavement cracks occurred and small soil slips were observed on steep road cuts. Doors of cabinets and refrigerators opened and contents spilled out; dishes broke; objects fell off shelves; cabinets overturned. Chest drawers opened. Books fell from shelves, and furniture moved. A driver travelling northeast on Wright Road felt as if car had flat tire, then it turned at right angle to the road. He saw the ground undulating.
Kau District		
Hawaii Volcanoes National Park	VIII	Substantial ground cracking and ground failures resulted in extensive road damage. On Crater Rim Drive damage was severe at Waldron Ledge, Kilauea Military Camp, the Southwest Rift Zone, Keanakakoi Overlook, and Puu Puai. The main highway was damaged at the entrance to Kilauea Military Camp. Ground cracking also occurred on the Chain of Craters, Ainaho, Hilina Pali, and Mauna Loa Roads. Many hiking trails were damaged by slope failures that removed parts of trails and buried other trails. Some instruments at the Hawaiian Volcano Observatory were temporarily out of order and others were damaged; books were tossed from shelves and bookcases fell over; file cabinets shifted. There was some cracking and minor offsetting of concrete foundation slabs. Dishes and loose objects on shelves fell and broke.
Volcano Golf and Country Club Subdiv.	IX	Many houses and garages were moved off their foundations towards the southwest. Hairline cracks occurred in concrete slabs. People reported difficulty in standing or walking. Water tanks moved across their gravel beds as much as 5 cm, and some of their roofs were knocked off or damaged; water sloshed out of many tanks; water heaters were moved and the PVC lines to the water tanks were snapped. Refrigerator and cupboard contents were dumped on floors; cabinet drawers opened; books and tools were thrown off shelves; televisions were overturned, and bookcases toppled. Lamps and canned goods fell to the floor. Heavier furniture moved.
Old Golf Course Road	VIII	Dishes broke and scattered; books fell off shelves; bookcases overturned; file cases moved; objects thrown out of closet and medicine chest with velocity. An 18,500-L (5,000-gal) water tank that was two-thirds full moved 2.5 cm.
Kapapala Ranch	VII-VIII	Main house moved nearly 17 cm off its foundation toward the southeast. Hot water tank torn from pipes and thrown over; partially collapsed rock walls.
Wood Valley	VII-VIII	A few wood-frame houses moved off their foundations; PVC pipes broken and minor cracks in stucco facing; nearly every headstone in the cemetery overturned.
Pahala	VI	In Kau Hospital, bookshelves fell over, ceiling panels dislodged, patients' beds moved as much as 1.5 m, wall clocks dangled by wires and contents of cabinets were displaced. Dishes fell from cupboards and loose objects fell from shelves; pictures and mirrors fell from walls; bookcases, books and shelving fell; tables and floor lamps were broken as well as dishes and an aquarium. Cabinet, refrigerator and freezer doors opened and contents fell out. Appliances and furniture moved as much as 10 cm from original locations and small appliances fell from stands. A few water heaters were knocked over and one was moved about 0.3 m, breaking and connecting pipes. At a store, 75 percent of the merchandise fell from the shelves and was damaged.
Naaiehu	V	Table lamps, bookshelves, and knickknacks tipped over and dishes broke; television and microwave oven were moved; water splashed out of fish tank; slight leak in water pipe.

TABLE 44.2.—*Intensity and description of damage at various localities on the Island of Hawaii, November 16, 1983, Kahoiki earthquake (magnitude 6.6)*—Continued

City, town, village	Intensity (modified Mercalli)	Description of damage
Kau District (continued)		
Ka Lae	V	Part of cliff fell into ocean; a large sand hill subsided; rock walls in north-south direction were damaged. One house was moved about 1.5 m off its foundation. North of the highway, a few water pipes were broken; refrigerator doors opened and contents fell out; loose objects on shelves fell; damage to bookshelves, table lamps, and glassware; stone walls were severely damaged.
Ocean View Estates	IV	Cabinets and drawers opened; objects on shelves fell to floor; rocks fell into driveway.
South Kona District		
Honaunau	V	Rocks tumbled from stone walls; houses shook vigorously; loose objects tumbled from shelves and cupboards, and some broke; bookshelves fell over; filing cabinets moved; a few water pipes were broken. Wave action was observed in a pond and a concrete water tank. Water spilled out of toilet tank.
Kealahou Bay	IV	Landslides from cliff into bay discolored water and caused substantial dust cloud over bay. Rock falls also occurred off slopes into some driveways. Loose objects tumbled from shelves but there was little breakage.
Captain Cook	IV	Lamp, vases, bottles and books fell from shelves.
South and North Kohala		
Hawi, Kapaau, Kamuela	V	Buildings shook, rattling dishes; pictures fell; loose objects fell from shelves; hanging plants swayed.
Hamakua		
Kukuihaele	V	Houses shook and dishes rattled; a few dishes and loose objects fell from shelves; a stone wall cracked. There was one report of house siding splitting and clocks being damaged.
Honokaa	V	Wood-frame buildings shook severely. A few objects fell from shelves; rocks fell from roadcuts.
Paauhau	V	Minor damage to objects on shelves.
Paauilo	V-VI	Some objects fell off shelves, houses shook. Driver on main highway did not feel quake while driving his truck, but noted rock debris on highway.
North Hilo		
Laupahoehoe	VI	Landslides from slopes along the circum-island highway and on the road down to the coastal village blocked roads. Buildings swayed, cupboard doors opened and items fell out; loose objects fell from shelves and broke; items inside cabinets fell over. At the school library, ceiling tiles fell, books fell off shelves and scattered, bookcases were loosened from walls.
Ninole	VI	Report spoke of wierd rumbling noise accompanied by vigorous rolling and shaking; bottles and pictures fell.

TABLE 44.3.—Data from strong-motion accelerographs for November 16, 1983, Kahoiki earthquake

[Distance is distance of station from epicenter. Components are: L, longitudinal with instrument; V, vertical; T, transverse to instrument; figures by horizontal components are azimuth directions. Slightly modified from Arnold V. Acosta and Richard P. Maley, USGS, Branch of Engineering Seismology and Geology, unpublished table, 1984]

Station	Latitude, Longitude	Distance (km)	Component	Peak acceleration of gravity	Comments
Volcano Observatory, Hawaii Volcanoes National Park	19.423°N. 155.291°W.	17	360°L up V 270°T	¹ 0.67 .21 .39	Greater than 0.1 acceleration of gravity for 8.5 seconds.
Wahaula Maintenance Center, Hawaii Volcanoes National Park	19.329° 155.031°	45	145°L up V 055°T	.12 .07	Long period record. 18 Hz superimposed near beginning.
Fire Station, Pahoa	19.498° 154.951°	53	087°L up V 357°T	.18 .07 .11	
Sewage Plant, Hilo	19.734° 155.050°	54	333°L up V 243°T	.10 .02 .07	
University of Hawaii, Hilo	19.707° 155.083°	49	085°L up V 355°T	.07 .04 .11	Dominant sinusoidal response, about 2.8 Hz horizontal.
U.S. Fish and Wildlife Office, Hilo	19.731° 155.100°	49	360°L up V 270°T	.40 .15 .50	
Fire Station, Honokaa	20.080° 155.465°	72	021°L up V 291°T	.25 .10 .37	Dominant sinusoidal response, about 8 Hz horizontal.
Kahala Police Station, Kapaau	20.230° 155.801°	95	102°L up V 012°T	.07 .05 .09	
Fire Station, Kamuela	20.03° 155.66°	70	155°L up V 065°T	.13 .07 .08	Dominant sinusoidal response, about 7 Hz horizontal.
Mauna Kea State Park, Saddle Road	19.752° 155.530°	36	050°L up V 320°T	.17 .21 .26	
Mauna Loa Observatory, 3,350-m (11,000-ft) elevation, Mauna Loa	19.539° 155.580°	18	030°L up V 300°T	.34 .46 .58	V and T peaks were single simultaneous spikes.
Fire Station, Kailua-Kona	19.649° 155.996°	62	312°L up V 222°T	.04 .01 .03	
Kona Hospital, Kealahakua	19.523° 155.879°	46	346°L up V 256°T	.10 .07 .10	
Kau Baseyard, Waiohinu	19.070° 155.615°	43	065°L up V 335°T	.19 .09 .17	
Kau Hospital, Pahala	19.20° 155.47°	26	188°L up V 098°T	.59 .16 .31	

¹A high-frequency peak (raw scaling 0.87 acceleration of gravity) was superimposed on the main pulse. This is believed to be other than ground motion.

TABLE 44.4.—Length and elevation changes recorded by monitoring programs at head of incipient Waldron Ledge landslide, April 1980 to October 1982

[Positive length changes represent extension, negative ones, shortening; positive elevation changes represent uplift, negative ones subsidence; ---, not measured]

Measured item	Original measurement (m)	Measured change (mm)														
		1980							1981					1982		
		¹ Apr. 14	¹ Apr. 21	³ Apr. 28	³ Jun. 2	² Jul. 3	² Aug. 8	² Nov. 25	² Jan. 5	² Mar. 26	Jun. 13	³ Jun. 27	² Jul. 9	³ Jul. 23	² Jul. 26	² Oct. 1
Length changes in lines of monitor 1 originally measured April 7, 1980																
Line AB	14.905	0	0	0	0	4	3	3	2	3	² ₁₄	--	0	--	6	-2
Line AC	15.712	0	-3	-2	2	3	3	5	4	5	² ₋₆	--	5	--	12	12
Line AD	15.444	3	0	2	5	7	4	7	9	8	² ₅	--	9	--	22	21
Line AE	3.726	3	5	5	8	10	0	15	16	17	² ₁₉	--	18	--	55	58
Line EC	14.102	3	-2	2	3	5	3	5	-9	2	² ₋₂	--	3	--	-3	-5
Line ED	13.558	3	0	2	2	5	4	4	3	2	² ₀	--	2	--	-2	0
Line EB	13.885	2	-2	2	5	8	3	3	3	2	² ₋₁	--	3	--	2	2
Line BC	2.525	2	1	1	4	5	7	8	8	10	² ₉	--	10	--	30	31
Line BD	3.651	2	2	4	5	8	8	12	14	14	² ₁₆	--	17	--	50	52
Elevation changes, relative to rebar 1, at monitor 1 originally measured November 25, 1980																
Base	0.234	--	--	--	--	--	--	--	0	0	--	--	1	--	-1	--
Nail A	1.854	--	--	--	--	--	--	--	0	1	--	--	1	--	-2	--
Nail B	2.461	--	--	--	--	--	--	--	1	1	--	--	0	--	-2	--
Nail C	2.487	--	--	--	--	--	--	--	0	-2	--	--	-3	--	-17	--
Nail D	2.477	--	--	--	--	--	--	--	-1	-1	--	--	-2	--	-16	--
Nail E	1.949	--	--	--	--	--	--	--	-1	-1	--	--	-2	--	-10	--
Length changes in lines of monitor 2 originally measured April 10, 1981																
Line X'-X																
Hard pull	23.764	--	--	--	--	--	--	--	--	--	³ ₆	10	--	6	--	--
Soft pull	23.771	--	--	--	--	--	--	--	--	--	³ ₁₁	11	--	3	--	--
Line Y'-Y																
Hard pull	7.620	--	--	--	--	--	--	--	--	--	³ ₅	0	--	11	--	--
Soft pull	7.623	--	--	--	--	--	--	--	--	--	³ ₅	11	--	32	--	--
Line Y'-Z																
Hard pull	24.098	--	--	--	--	--	--	--	--	--	³ ₁₄	12	--	52	--	--
Soft pull	24.101	--	--	--	--	--	--	--	--	--	³ ₁₆	14	--	54	--	--

¹Measurement by J.M. Buchanan-Banks and R.B. Moore.²Measurement by K.M. Yamashita and M.K. Sako.³Measurement by J.M. Buchanan-Banks and N.G. Banks.