# Ground Deformation Associated with the 1975 Magnitude-7.2 Earthquake and Resulting Changes in Activity of Kilauea Volcano, Hawaii

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1276

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*By* PETER W. LIPMAN, JOHN P. LOCKWOOD, REGINALD T. OKAMURA, DONALD A. SWANSON, *and* KENNETH M. YAMASHITA

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*The 1975 earthquake, the largest on Hawaii Island in more than 100 years, was associated with major gravitational slumping of the seaward flank of Kilauea Volcano; maximum displacements were as much as 3.5 m vertically and 8 m horizontally*

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# GROUND DEFORMATION ASSOCIATED WITH THE 1975 MAGNITUDE-7.2 EARTHQUAKE AND RESULTING CHANGES IN ACTIVITY OF KILAUEA VOLCANO 1975–1977, HAWAII

By PETER W. LIPMAN, JOHN P. LOCKWOOD, REGINALD T. OKAMURA, DONALD A. SWANSON, and KENNETH M. YAMASHITA

ABSTRACT

A magnitude-7.2 earthquake on November 29, 1975, the largest in Hawaii in over a century, was associated with large-scale deformation of the entire south flank of Kilauea Volcano. Surface ground breakage occurred along a 25-km-long sector of the Hilina fault system, with vertical displacements of as much as 1.5 m along individual preexisting fault scarps. Reoccupation of extensive horizontal and vertical geodetic networks on Kilauea demonstrated that the entire volcanic edifice and adjacent lower slopes of Mauna Loa were displaced downward and seaward. Maximum horizontal and vertical displacements, about 8 and 3.5 m respectively, occurred along the coastline south of Kilauea's summit area, about 30 km southwest of the earthquake hypocenter.

Large ratios of horizontal to vertical displacements, associated with the 1975 earthquake, strongly support a gravitational slump interpretation, both for the deformation associated with this earthquake and also for the long-term tectonic evolution of the south flank of Kilauea. In addition to the major displacements along the Hilina system of normal faults, more inland ground deformation appears to reflect secondary adjustments to displacements along the Hilina system and to changes in the Kilauea summit area and along the rift zones related to movement of magma. Analysis of the tsunami associated with the 1975 earthquake indicates that a large part of the submarine south flank of Kilauea was uplifted by deformation at the toe of the slump terrain complementary to the subsidence on land. Focal-mechanism determinations for the earthquake and aftershocks indicate seaward displacements along gently dipping fault planes at depths of 6–10 km, near the base of the volcanic edifice where it is inferred to rest on old sea floor. Aftershocks were concentrated largely along the upper part of the south flank of Kilauea, between the rift zones and the Hilina fault system, indicating that faults of the Hilina system mark a major structural boundary on Kilauea, rather than just constituting surficial slump features.

These relations favor an interpretation of the 1975 earthquake as due primarily to gravitational slumping along faults of the Hilina system that penetrate most of the thickness of the south flank of Kilauea Volcano and that flatten at depths of 6–8 km to accommodate seaward displacements. The basic cause of slumping was accumulation of contractional strain throughout the 20th century along the upper part of the south flank, as a result of intrusion of magma as dikes along Kilauea's rift zones. In addition, inflation of Mauna Loa Volcano to the north, culminating in its July 1975 summit eruption, may have contributed to destabilizing Kilauea and triggering the earthquake.

Since the 1975 earthquake, deformation patterns on Kilauea Volcano have changed notably. Previously, rates of horizontal and vertical deformation at the summit were very high (several mm/day) in the 20th century, mainly reflecting inflation-deflation cycles related to eruptive activity as magma accumulated in or was withdrawn from a 2–3 km deep magma reservoir centered near the summit. Since the earthquake, deformation patterns have been complex. The volcano has failed to maintain sustained inflation cycles similar to those of the recent past, and the dominant deformation pattern has been seaward displacement of the south flank, presumably reflecting ongoing adjustments to effects of the 1975 earthquake. In September 1977, Kilauea erupted along its middle east rift zone after the longest period of inactivity in 10 years. No summit inflation preceded this eruption, which, nevertheless, may indicate the beginning of stabilization and return of the volcano to a more typical deformation pattern.

## INTRODUCTION

At 0448 hours on the morning of November 29, 1975, a magnitude-7.2 earthquake—the largest in more than 100 years—struck the island of Hawaii; the epicenter was located on the south flank of Kilauea Volcano (fig. 1). The earthquake was preceded by numerous foreshocks, the largest of which was a magnitude-5.7 jolt 70 minutes earlier. As summarized in a preliminary report (Tilling and others, 1976), the south flank of Kilauea Volcano moved downward and seaward, and ground breakage occurred along a 25-km-long zone, mainly along preexisting faults in the Hilina system. A tsunami, accompanying the earthquake, locally reached heights of 12–15 m above mean sea level. A brief small-volume volcanic eruption, presumably triggered by the earthquake and associated ground movements, occurred within Kilauea's summit caldera about 45 minutes later. The earthquake and tsunami together caused property damage estimated at about \$4.1 million in the southeastern part of the island; the tsunami also caused two deaths. Thousands of aftershocks were recorded during the next year.

Here we report detailed studies of the ground deformation associated with the 1975 earthquake, made possible by the previously established geodetic network of extensive vertical and horizontal controls developed primarily for monitoring Kilauea Volcano. These

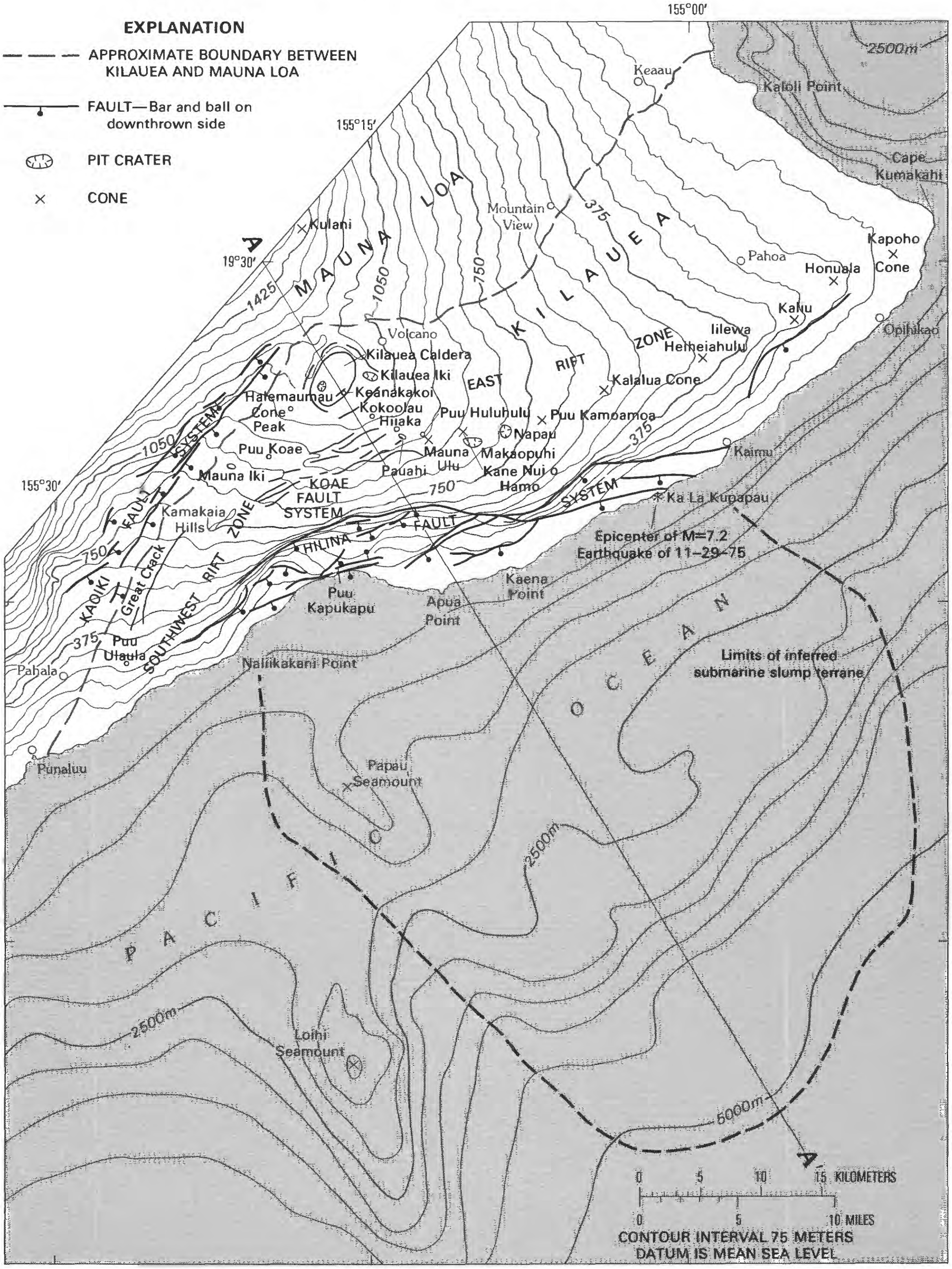



FIGURE 1.—Map of Kilauea and adjacent part of Mauna Loa, showing main structural features and locations of important faults, cones, and pit craters. Modified from Stearns and Macdonald (1946, pl. 1) and Swanson, Duffield, and Fiske (1976a, fig. 2); bathymetry from U.S. Naval Oceanographic Office (1973). Land contour interval, 75 m; bathymetric contour interval, 500 m. Limits of submarine slump terrane from Moore and Peck (1965) and U.S. Geological Survey marine seismic data (W. R. Normark and J. G. Moore, unpub. data, 1976).

studies show that the entire subaerial part of Kilauea was deformed, with maximum downward and seaward displacements of about 3.5 and 8 m, respectively. The general form of the surface deformation was large-scale block slumping involving much of the southeast side of the island of Hawaii. The 1975 deformation was accommodated largely by movement along preexisting structures that show evidence of repeated seaward-directed block slumping in the past.

In addition, ground deformation studies of Kilauea's summit area have indicated a changed pattern of magmatic behavior for several years after the 1975 earthquake (Lipman and others, 1978). Before the earthquake, summit inflation-deflation cycles yielded radial patterns of tilt and horizontal displacement confocal with concentric patterns of vertical displacement. Since the earthquake, vertical changes have been sporadic and relatively subdued, which indicates that the summit region has ceased to undergo sustained inflation; however, horizontal displacements have continued in a uniform seaward direction, similar to the pattern developed in response to the earthquake. At the time of writing this report (fall 1979), it was unclear when the summit area would stabilize from the disruptive effects of the 1975 earthquake, but it has become clear that such earthquakes have after-effects lasting many years.

## ACKNOWLEDGMENTS

Virtually the entire staff of the Hawaiian Volcano Observatory (HVO) of the U. S. Geological Survey assisted at various times in the extensive geodetic measurements on which this report is based. We thank them all, especially Maurice Sako and Jack Harris. Essential helicopter support was provided by the County of Hawaii and their able pilot, Kenneth Ellard. Many of the interpretations presented here evolved and were improved during discussions with our associates, including Lennart A. Anderson, Robert S. Crosson, Daniel Dzurisin, Gordon P. Eaton, Robert Y. Koyanagi, James G. Moore, and Robert I. Tilling.

## RELATIONS BETWEEN STRUCTURAL FEATURES AND ERUPTIVE ACTIVITY

Interpretation of the geodetic changes associated with the 1975 earthquake must be made in the context of the major structural features and patterns of deformation and seismicity associated with volcanic activity on Kilauea. Much has been learned in recent years about these interactions by combined geologic, seismic, geodetic, and other geophysical studies at the Hawaiian Volcano Observatory.

The major eruption-related structures on Kilauea are a collapse caldera in the summit area and the roughly opposed southwest and east rift zones (fig. 1). Between eruptions, magma has recently been generated in the mantle beneath Kilauea at a nearly steady rate of about 0.1 $km^3/yr$ (Swanson, 1972). The magma gradually accumulates in a shallow reservoir 2–5 km below and slightly south of the summit caldera, causing uplift and inflation, as indicated by both seismic and deformation studies (Eaton, 1962: Fiske and Kinoshita, 1969). The rift zones are also typically uplifted between and during eruptive and intrusive events, commonly with the development of a keystone graben along the linear crest of the uplift (Macdonald and Eaton, 1964; Fiske and Koyanagi, 1968; Jackson and others, 1975).

Summit eruptions commonly are accompanied by little or no deflation over the magma reservoir, apparently as overflow of an essentially open magma column. During rift eruptions, in contrast, magma drainage from the summit reservoir causes measureable summit subsidence, at times more than a meter (Kinoshita and others, 1974; Jackson and others, 1975). The rift zones are interpreted as marking the loci of underlying magma conduits, in the shape of shallow blade-like dikes largely confined within the volcanic edifice and fed from the summit region (Fiske and Jackson, 1972). At the surface, each rift zone is marked by a broad topographic crest, along which are alined many open cracks, pit craters, and small cones and shields.

In addition to the rift zones, major structural divisions of Kilauea Volcano include the Koae fault sytem, the south flank, and the north flank. Eruptions seldom, if ever, occur within these areas. The Koae fault system (Duffield, 1975) is an east-northeast-trending zone of open cracks and dominantly north-facing normal faults that connect the east and southwest rift zones and mark the southern margin of summit-related subsidence structures. The south flank is the region south of the rift zones and the Koae fault system. It includes two distinctive subdivisions: (1) a northern part between the Koae and Hilina fault systems that consists of little-faulted lava flows dipping gently seaward, and (2) a southern part that is disrupted by the predominantly south-facing normal faults of the Hilina system. Off-rift seismicity is concentrated largely in the northern part of the south flank, which appears to represent a structurally rigid region capable of accumulating stress. In contrast, seismic activity is more diffuse and lower in intensity along the southern part (Koyanagi and others, 1972). The submarine south flank of Kilauea consists mainly of a block-faulted terrane, similar to the adjacent subaerial part, as indicated by bathymetric data (Moore and Peck, 1964) and by U.S. Geological Survey marine seismic profiles (W. R. Normark and J. G. Moore, unpub. data, 1976). The north flank of Kilauea, bounded by the summit area and the east rift zone, is relatively stable and low in seismicity; it is characterized by northeasterly dipping lava flows that abut and interfinger with flows from Mauna Loa.

Geodetic evidence presented by Swanson, Duffield, and Fiske (1976a) suggests that forceful injection of magma along Kilauea's rift zones has uplifted the south flank and displaced it several meters seaward during the 20th century. In contrast, the north flank has remained relatively stable, presumably because of buttressing effects of the neighboring volcanic edifices, principally Mauna Loa (Fiske and Jackson, 1972). By these interpretations, the Hilina fault system is considered to be a gravity-controlled zone of block slumping, not directly related to the rift zones. Strain that has accumulated from uplift and seaward displacement of the south flank is intermittently relieved by normal faulting along the Hilina system and related submarine faults along the south flank of Kilauea. Swanson, Duffield, and Fiske (1976a) documented a buildup of strain within the Hilina system throughout the 20th century, and anticipated "a subsidence event in the not too distant future." While their report was in press, the November 1975 earthquake and associated ground deformation confirmed their anticipation.

# THE 1975 EARTHQUAKE

Data from HVO seismometers placed the magnitude-7.2 earthquake of November 29, 1975, about 6 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 5–6 km (fig. 2). The earthquake was felt on the island of Oahu, more than 400 km from the epicenter. Damage estimates and an isoseismal earthquake intensity map for the island of Hawaii (Tilling and others, 1976, fig. 4) clearly show that the maximum intensity of the earthquake did not coincide with its epicenter, but lay further to the east, close to the zone of maximum ground deformation documented in this report.

Thousands of aftershocks, which continued in diminishing numbers for several years after the 1975 earthquake, were distributed over a broad zone mainly west of the epicentral region (fig. 2). The main concentration of aftershocks was beneath the unfaulted northern part of the south flank of Kilauea—the region between the two rift zones and the Hilina fault system (fig. 2). Most of these earthquakes occurred at depths of 5–7 km (Ando, 1979, fig. 1; Crosson and Endo, 1981, fig. 8). Many aftershocks also took place beneath the southwest rift zone, but few were recorded along the east rift zone. The virtual lack of aftershocks within the faulted part of the south flank south of Hilina Pali is striking; seismicity was also limited in this part of Kilauea prior to the earthquake (Tilling and others, 1976, p. 9).

# GROUND BREAKAGE

Extensive ground rupture in the summit and south flank areas of Kilauea, along with easily recognized subsidence along the south coast, gave the first indications that substantial deformation accompanied the earthquake.

## FAULTING IN THE HILINA SYSTEM

Ground breakage was nearly continuous along the Hilina fault system (fig. 3). The Hilina system is characterized by south-facing normal fault scarps as high as 500 m (fig. 4). The new breakage 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 displacements are obscured by extensive slumps and landslides that occurred during the earthquake along all of the steep scarps; in many other places, the amount of new offset is difficult to distinguish from older displacements along the same fault scarp.

The new faulting extends about 25 km along the trend of the Hilina fault system, and individual faults have vertical displacements of as much as 1.5 m. In detail, the new faults are discontinuous and are en echelon in pattern; individual breaks extend a few tens to several hundreds of meters. Overall, they define a nearly continuous zone of normal faulting bounding more coherent structural blocks; elsewhere on Kilauea, the most conspicuous ground breakage involves widespread chaotic 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. 4*A*), gradually building them southward toward the sea. The new ground rupture commonly 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 (fig. 4*B*), have not been built seaward by draping of younger flows, but rather they have retreated northward through erosion; hence, ground rupture took place near the base of these scarps (fig. 4*C*).

Much of the new faulting was along the northern part of the Hilina system; several old faults near the coast showed no new ruptures. The most continuous zone of breakage and the largest vertical offsets are along the northeast edge of the system, where vertical displacements were 0.5–1.5 m for a distance of more than 15 km. South and southwest of this zone of maximum faulting, vertical displacements of as much as 0.5–1.0 m are common along other faults. Accordingly, the cumulative observed fault displacement is at least as much as 2.5 m and accounts for about two-thirds of the maximum measured coastal subsidence along Kilauea's south coast.

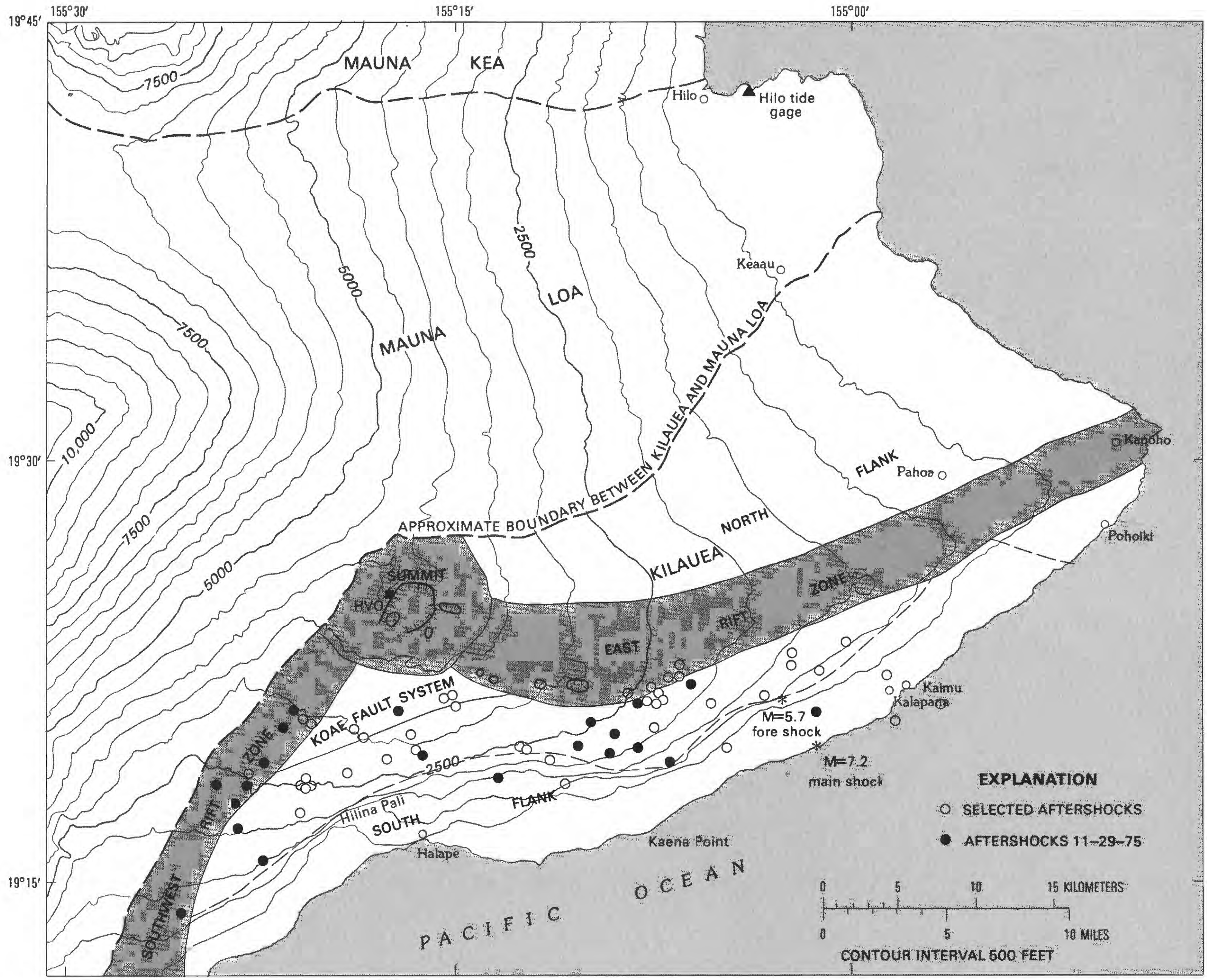



FIGURE 2.—Epicenters of the November 29, 1975, magnitude-7.2 earthquake, its largest foreshock (magnitude 5.7), and selected larger aftershocks (from Tilling and others, 1976). Boundaries of major structural subdivisions of Kilauea are from Swanson, Duffield, and Fiske (1976a, fig. 2). Dashed line within south flank of Kilauea marks approximate location of Hilina Pali (cliff) at northern margin of Hilina fault system. Base from Hawaii Division of Hydrography 1:125,000 map of the Island of Hawaii, 1944; contour interval, 500 feet.

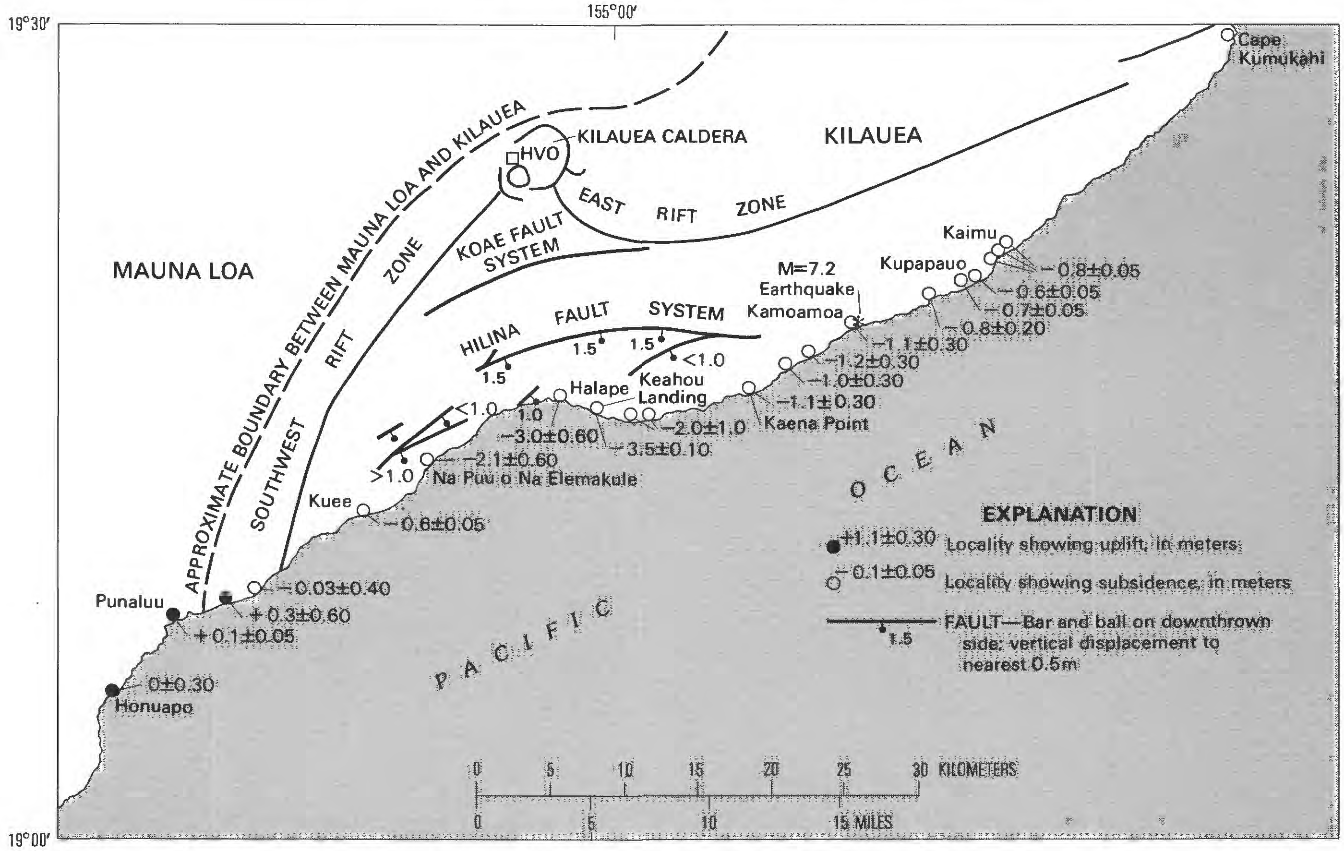



FIGURE 3.—Major zones of new ground breakage in the Hilina fault system, related to the 1975 earthquake, and amounts of associated subsidence along the south coastline. Measured offsets along the Hilina fault system are amounts of new displacement along large preexisting fault scarps, in places draped by prehistoric Kilauea lava flows. Most coastal measurements were made directly from postsubsidence sea level to points of previously known elevation, including bench marks, triangulation stations, topographic control points, and tide gages. All measurements were adjusted to mean sea level, using tide tables to determine the absolute subsidence. Estimated uncertainties in the amounts of subsidence are based on the method of determination and the quality of the observation. (Modified from Tilling and others, 1976, fig. 16.)

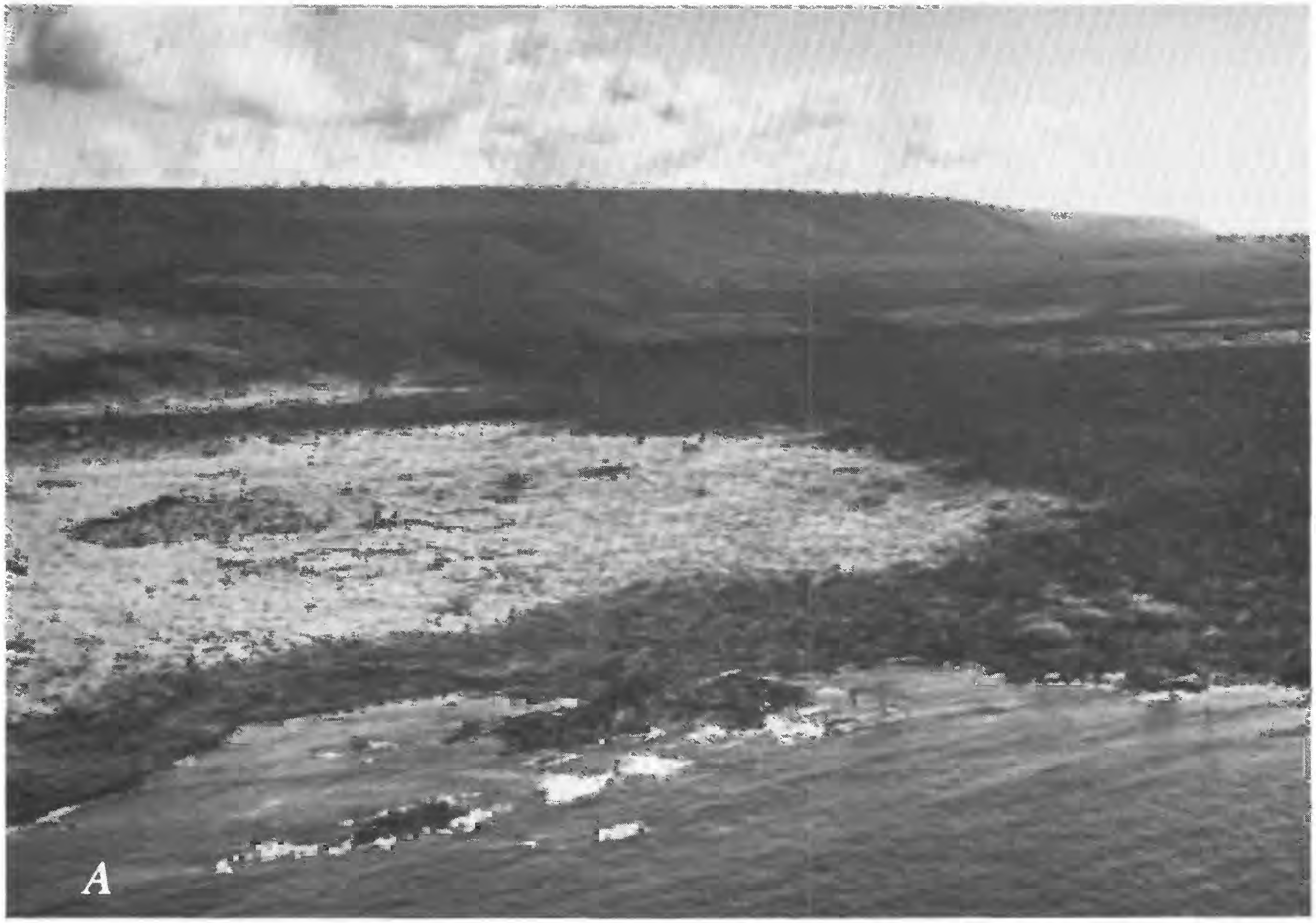
Along the southwestern part of the Hilina fault system, new ground breakage is evident along several northeast-trending zones over an extent of at least 5 km (fig. 3), with vertical displacements locally as much as 1 m. Much of the ground movement in this area, however, seems to have resulted in only slight readjustment along preexisting fractures. Ground breakage was minimal along the eastern part of the Hilina system and was notably lacking near the epicenter or along buried fault scarps inland from there.

In addition to the main faults, widening of many cracks within the Hilina system indicated significant horizontal extension (fig. 4*D*). Most cracks are old, but freshly broken rocks and torn vegetation are evidence of renewed movement during the 1975 events. Small new cracks in alluvium, with openings of as much as a few centimeters, were common near the larger bedrock cracks.

## LANDSLIDES AND GROUND CRACKS

Shaking during the main earthquake caused numerous rockslides and ground cracks, especially on steep slopes such as fault scarps, crater walls, and road cuts. Some of this relatively superficial ground breakage is difficult to distinguish from deeper fault-controlled structures. Rockfalls and landslides along every major cliff in the Hilina fault system and soil cracks within 50–100 m of the edges of cliffs, suggest local lurching of the ground toward cliff faces during the shaking.

Some of the largest ground cracks and rockslides were 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 slumped downward and outward, parts of them crashing into the craters; and gaping



*A.* Post-earthquake aerial view of Kilauea's south flank, looking northeastward along lava-drapped Holei Pali (cliff) of the Hilina fault system. Foreground shows the coast at Keauhou Landing (note palm trees in the water and the dark swath indicating the area washed by the tsunami).

FIGURE 4.—HILINA FAULT SYSTEM

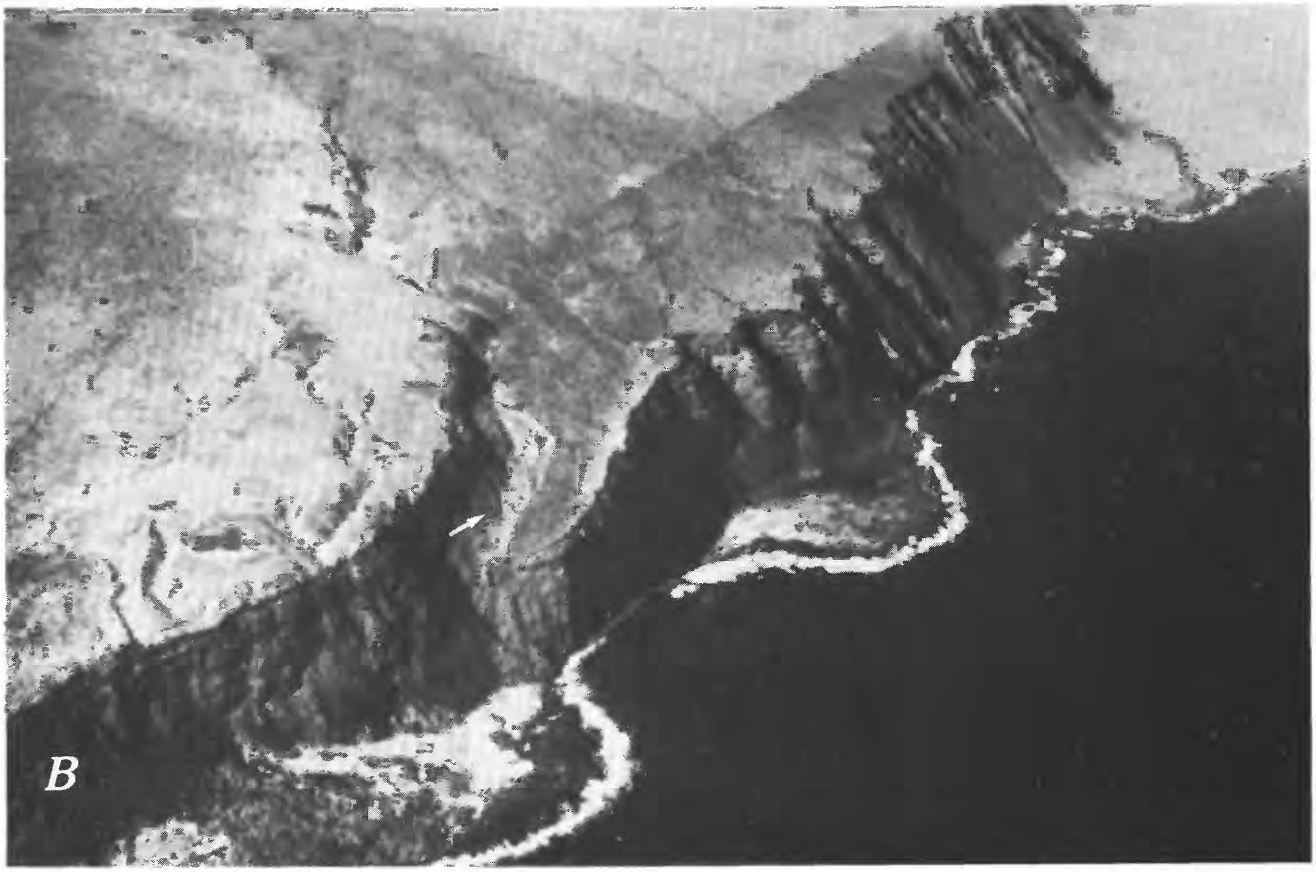
cracks as wide as 25 cm rendered the parts still left too unstable for continued use by park visitors (figs. 5*A*, *B*). Unstable roadcuts collapsed, locally blocking roads in the national park (fig. 5*C*).

Cracks as wide as 1 m on the northeast side of Kilauea Caldera destroyed a 1-km segment of the Crater Rim Road (fig. 6*A*). Most of the ground breakage was extensional, producing new cracks or widening old ones, but 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 north side of Kilauea caldera (fig. 6*B*). In a few places movement along cracks produced lateral components of offset of as much as 10 cm (fig. 6*C*).

Cracking was also conspicuous along the Koae fault system south of Kilauea Caldera. This area is characterized by numerous open fissures (Duffield, 1975); some old cracks opened, others closed, and small new cracks formed in many sand-covered areas (fig. 6*D*). Vertical offsets were not conspicuous, but suitable visible reference points are typically lacking. Geodimeter and leveling data indicate horizontal extensions of as much as 2 m and northward tilting of as much as 0.1 m/km across the Koae fault system.

## VERTICAL DISPLACEMENTS

Major subsidence was evident along the south coast of Kilauea immediately after the earthquake. At the Halape campground, a grove of coconut palms was partly submerged, with an average water depth of 1.2 m and with the new shoreline extending 100–150 m landward of the presubsidence shoreline (fig. 7). A shallow lagoon now covers 2.2 hectares of what formerly was a sand-covered flat above a low sea cliff at Kaaha, 4.5 km west of Halape. At Keauhou Landing, 2.3 km east of Halape, a brackish Hawaiian well was submerged and the narrow beach was destroyed. Near



*B.* Pre-earthquake aerial view of part of the Hilina fault sytem, looking northeast along Puu Kaone (top of cliff at left center) and Puu Kapukapu (top of cliff at upper right). Arrow points to location of figure 4*C*.

FIGURE 4.—HILINA FAULT SYSTEM—Continued

Kalapana, segments of the main highway became subject to regular flooding, and an area that was previously only muddy or even dry during low tides is now continually occupied by a broad shallow lagoon. At the renowned Kaimu black-sand beach, 1 km northeast of Kalapana, waves now enter the fringing coconut grove, and the beach has been extensively eroded.

## COASTAL MEASUREMENTS

Amounts of subsidence could be measured directly at several localities along the coastline from Honuapo to Kaimu (fig. 3). The maximum measured subsidence, about 3.5 m, was in the Halape–Keauhou Landing area, about 25 km west of the epicenter of the main earthquake. Kalue, 3 km west of Halape, may have subsided as much or even more than the measured subsidence, as suggested by visual estimates near a previously established tidal reference point that could not be found after the earthquake. This reference point is thought to have dropped below the post-earthquake shoreline.

Subsidence decreases in both directions from this central area. Toward the southwest, measurements indicate definite subsidence at Na Puu o Na Elemakule and Kuee but not farther southwest (fig. 3). Continuously recorded water-level data for a well at Punaluu indicated about 0.1 m uplift of land—the only detected uplift anywhere in the region, but the Honuapo area showed no detectable change within limits of the measurements.

Subsidence decreases eastward from Keauhou Landing to Kaena Point, then remains at about 1 m to Kupapau. Subsidence was about 75 cm at the Kupapau tide gage. The Kaimu area sank a maximum of about 85 cm; releveling suggests that about 64 cm of this amount resulted from regional subsidence and that about 21 cm from differential dropping or abrupt northward or eastward tilting of the previously known Kalapana graben (fig. 8). As seen in figure 8, the zone of coastal subsidence is asymmetric, terminating more abruptly on the west side than on the east side.

## PRECISE LEVELING

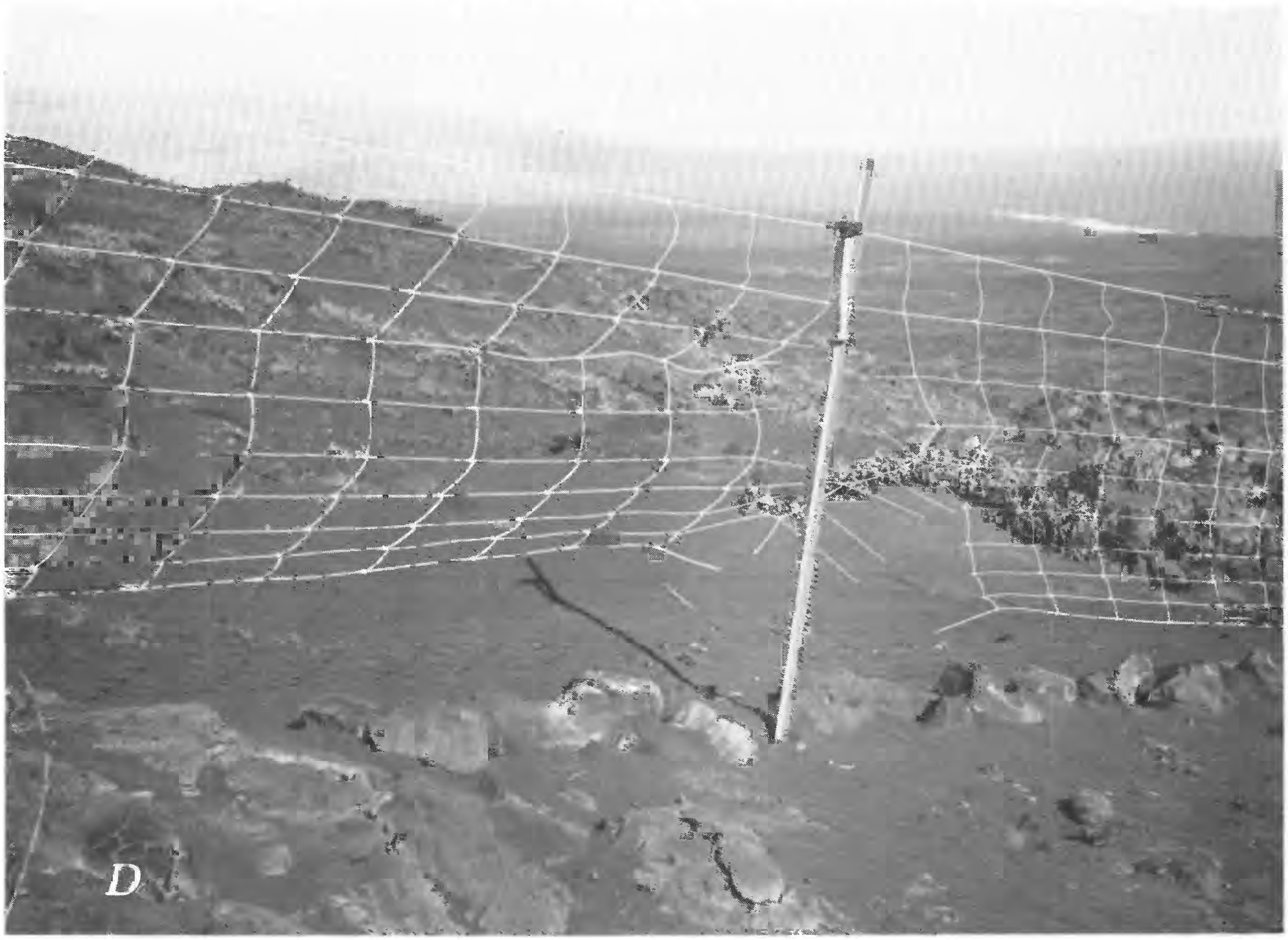
Every major precise leveling line previously established on Kilauea was reoccupied early in 1976; in all


*C*. Vertical offset of about 1.5 m along reactivated fault on south face of Puu Kaone (see fig. 4*B*). The amount of new displacement is indicated by distance between hands and feet of the standing figure.

FIGURE 4.—HILINA FAULT SYSTEM—Continued

about 250 km of line were releveled. The methodology and precision of leveling by the Hawaiian Volcano Observatory have been discussed by Okamura and Swanson (1975); some compromises in quality are made to increase speed of coverage because of the instability of the volcano, but the quality is typically good second order. Results of the releveling are summarized in figure 9; the complete data are on file at HVO. The Hilo tide gage was taken as a zero datum for interpreting elevation changes. Absolute changes of elevation were probably small in the Hilo area, as indicated by the limited relative changes observed within 10 km of Hilo (less than 1 cm), but short-term absolute changes of less than about 5 cm would not be observable directly from the tide-gage data (Moore, 1971, fig. 3).

Interpretation of the leveling data is complicated somewhat by the disparate times at which various lines were previously occupied—the time intervals before the 1976 releveling varied from 3 months to 18 years (fig. 9*A*)—and also is complicated by the high rates of deformation in the Kilauea summit area. All the summit and upper rift lines had been releveled and tied to the tide gage at Hilo within a few months prior to the 1975 earthquake (fig. 9*A*). Data from the less recently occupied lines, especially those on the eastern side of Kilauea last previously leveled in 1958 or 1964, have been adjusted to more recent data. For example, the 1958–76 changes between Keaau and Pahoa were recomputed, using the 1975 elevation at Keaau, the 1973 elevation at Pahoa, and apportioning the necessary internal adjustment linearly with distance. The resulting net changes (fig. 9*B*) are thought to convey a generally valid portrayal of the vertical displacements on Kilauea associated with the 1975 earthquake, especially because these displacements are very large and commonly different in pattern or sense from those observed previously, which were mainly associated with magmatic behavior. For example, the Pahoa-Kaimu line, which documented continued uplift of the east rift zone at rates of 1–5 cm/year between 1958 and 1973 (Swanson and others, 1976a, fig. 13*A*), showed subsidence of 92



*D.* Stretched goat-control fence, indicating horizontal extension across Kukalauula Pali, 3 km northwest of Naliikakani Point. Right margin of photograph shows approximate unstretched geometry of fence.

FIGURE 4.—HILINA FAULT SYSTEM—Continued

cm between 1973 and 1976, a change likely related almost entirely to the 1975 earthquake.

An interpretative contour map, based on the adjusted leveling data (fig. 9*B*) supplemented by coastal sea-level measurements (fig. 3), shows a coherent pattern of subsidence over the entire edifice of Kilauea Volcano (fig. 9*C*). The maximum subsidence of about 3.5 m is along the coast due south of the summit area, and areas of subsidence exceeding 1 m are confined to the region seaward of Hilina Pali and to the summit caldera. The area of summit subsidence extends outward as a well-defined trough along both rift zones. Along the lower east rift zone the trough is asymmetric and displaced to the south of the topographic crest of the rift zone (fig. 9*C*), as is uplift related to intrusive and eruptive activity in this sector of the rift zone (Swanson and others, 1976a, fig. 13*A*).

The amount of subsidence along the south flank of Kilauea decreases relatively abruptly to the west of Halape and more gradually to the east. Adjacent relatively positive and negative areas in the Kalapana-Kaimu area, superimposed on the general subsidence, correlate closely with preexisting horsts and grabens. Ground breakage or other marked effects of faulting were not recognized, however, in the epicentral area of the earthquake, about 6 km southwest of Kalapana.

Between the coastal region of maximum downdropping and the area of secondary subsidence at the summit of Kilauea is an area where subsidence was as little as 0.7 m (fig. 10). This relatively positive area coincides closely with the structurally unfaulted part of the south flank, which had been subjected to significant uplift in the decade prior to the earthquake (Swanson and others, 1976a, p. 19–20), and with the main loci of aftershock activity (fig. 2). The maximum gradient of increasing subsidence is located along the south margin of this block, where ground breakage involving individual offsets of as much as 1.5 m occurred widely along preexisting faults of the Hilina system.

The leveling data locally demonstrate northward tilting of fault blocks in some areas south of the zone of surface ground breakage along the Hilina fault system

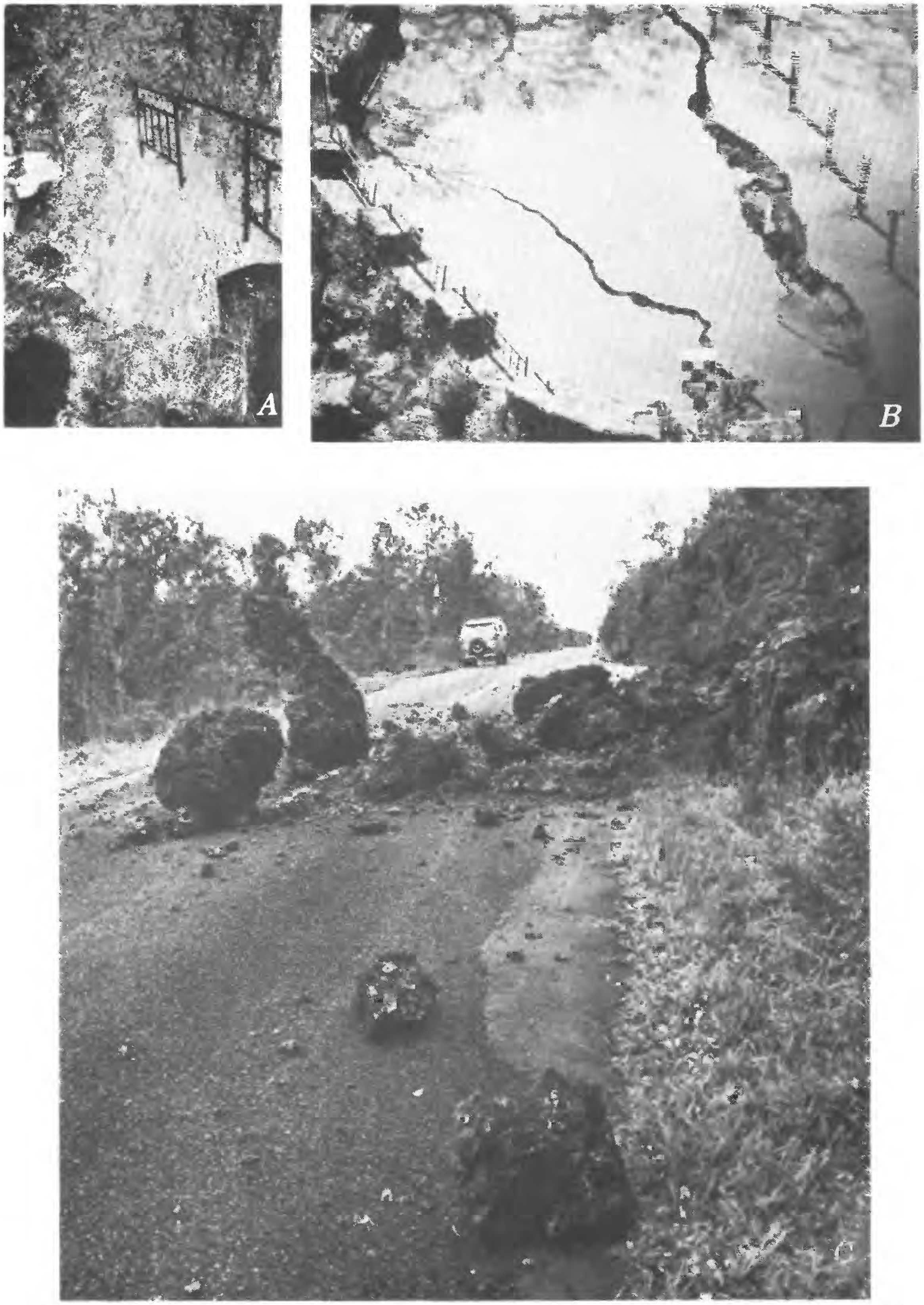


FIGURE 5.—Ground cracking and landslides in Hawaii Volcanoes National Park. *A*, Back part of viewing overlook area at Puhimau Crater slumped completely into the crater, leaving guardrail projecting into space. *B*, Aerial view of large cracks in viewing overlook area of Pauahi Crater (photograph by Hugh Clark, Honolulu Advertiser). *C*, Small landslide from spatter and cinder cone partially blocking Chain of Craters Road (photograph by Boone Morrison).


A
B
C


FIGURE 6 (above and facing page).—Road damage and en echelon cracks in Hawaii Volcanoes National Park. *A*, Large crack in Crater Rim Road resulted from slumping toward the caldera rim, the edge of which is a few meters to left of view. *B*, Small compressional chevron fold across road on southeast side of Kilauea Military camp along north side of the caldera. *C*, Collapse offsetting center line of Chain of Craters Road, just south of Pauahi Crater. *D*, En echelon cracks in weakly consolidated volcanic ash along the Koae fault zone. Compass is alined with the main trend of Koae faults (N. 75° E.; Duffield, 1975), and the en echelon pattern indicates a left-lateral component of offset.

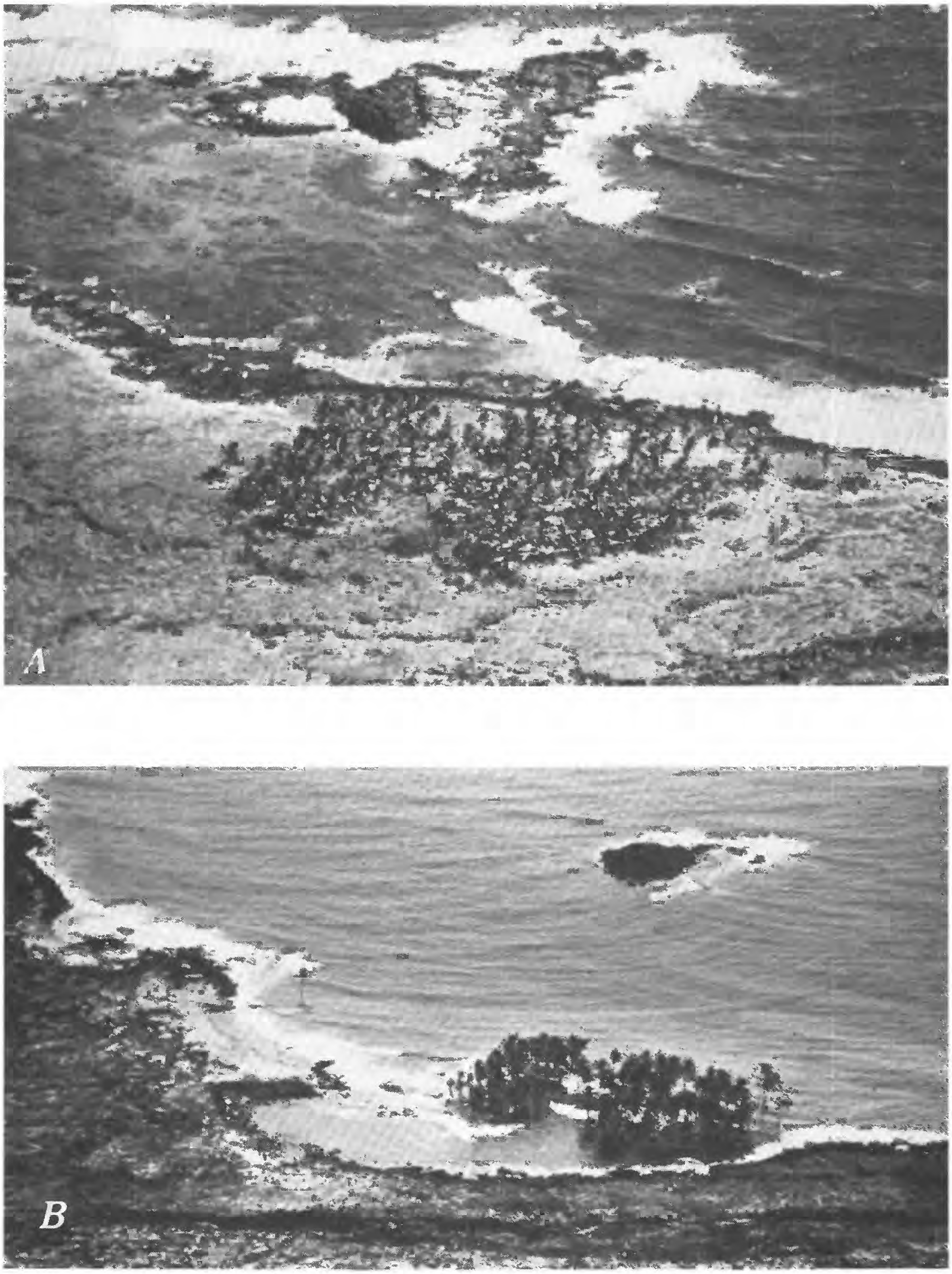



FIGURE 7 (above and facing page).—Pre- and post-earthquake views of south coast, illustrating subsidence near Halape. *A*, Pre-earthquake view of Halape area from Puu Kapukapu (photograph by Don Reeser, National Park Service). *B*, Post-earthquake view of Halape from Puu Kapukapu, showing the palm grove standing in the sea and an offshore island nearly submerged as a result of 3.5 m of subsidence. During the earthquake, campers were swept by the tsunami into the crack (arrows) behind the palm grove, and two persons died. *C*, After subsidence, surf surges through the palm grove at Halape (photograph by Boone Morrison).

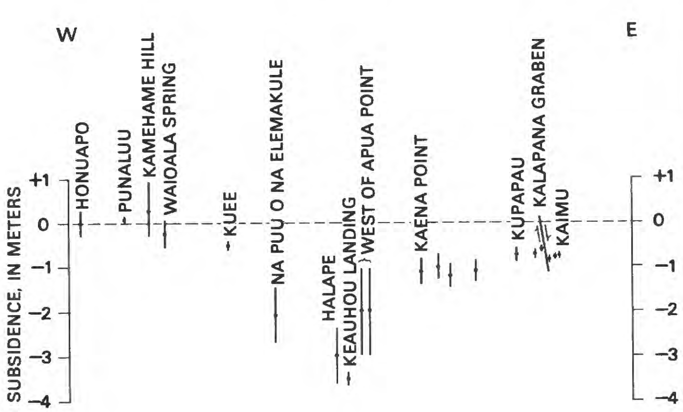




FIGURE 8.—Amount of subsidence at points along the coastline from Honuapo to Kaimu. Bars indicate estimated measurement uncertainties (from fig. 3); dashed horizontal line, zero change. Note disruption of profile along west edge of Kalapana graben, indicating dropping or abrupt tilting along graben fault.

and within the general area of maximum subsidence. Surveys near Kaena Point and Kaimu (fig. 9) indicate landward rotational tilting of about 1 cm/100 m and 1.5 mm/100 m, respectively. A similar prehistoric pattern of back rotation is also indicated by anomalously flat and locally north-sloping topography at the bases of several other major faults of the Hilina system. (See Makaopuki Crater 7½′ topographic quadrangle; also Swanson and others, 1976a, fig. 22.)

Subsidence greater than 5 cm occurred north and west of Kilauea's rift zones and extends at least 10 km up the southeast slope of Mauna Loa adjacent to the summit region of Kilauea. Gradients of subsidence contours north and northwest of the summit region of Kilauea are approximately on trend with those across the unfaulted block south of the summit area (fig. 10), which indicates that subaerial Kilauea and adjacent portions of Mauna Loa were subjected to a relatively unified pattern of subsidence, although Mauna Loa was affected less than Kilauea as distance from the epicenter increased. Clearly, the deformation pattern was dominated by Kilauea's mobile subsiding seaward block, but the regional scale of the deformation suggests that other factors influenced the deformation patterns as well. In addition to detachment of the south flank of Kilauea along the Hilina fault system, the rift zones clearly opened, and much of the adjacent southeast side of Hawaii Island appears to have subsided sympathetically.

## HORIZONTAL DISPLACEMENTS

The magnitude of horizontal displacements during the 1975 earthquake was not fully evident from the visible structures. Many cracks in the summit area and along the Hilina fault system opened, but others closed (fig. 6*B*). Only as the large Kilauea flank trilateration net (fig. 11) was reoccupied did it become apparent that the horizontal movements were generally greater than the more obvious vertical movements. Individual lines lengthened as much as a meter per kilometer, and the cumulative effect was displacement of the coastal areas as much as 8 m seaward.

The Kilauea trilateration network can be conveniently considered in two parts: (1) a summit net of 59 lines (fig. 12) that can be reoccupied in about 3 days by a crew of 5 and has accordingly been measured several times each year on the basis of fluctuations in behavior of the volcano, and (2) the flank net of about 150 lines (fig. 11) that takes 4 weeks or more to reoccupy and requires helicopter support for access to remote stations. The flank net was established in essentially its present configuration in 1970 and has been reoccupied twice—in the fall of 1974 and, after the earthquake, in the spring of 1976. The horizontal distance measurements on Kilauea are routinely made with an AGA Model 8 Geodimeter[1], an electronic laser-beam instrument with a precision as used at HVO of about 2–3 parts per million, or 2–3 mm/km of line length. Methods of operation and data reduction are summarized by Kinoshita, Swanson, and Jackson (1974) and Swanson and Okamura (1975). Changes in line length for the periods bracketing the 1975 earthquake are summarized in figures 11 and 12; complete data for the trilateration measurements are on file at HVO.

Horizontal displacements were determined for the 1974–76 interval, using graphic methods (Kinoshita and others, 1974) that were especially useful in evaluating some special problems. One major difficulty was that a key trilateration station, Puu Koae (figs. 11, 12), was destroyed by slumping during the earthquake. An attempt was made to determine the position of this bench mark with respect to surviving reference marks, but all displacement solutions are nevertheless somewhat anomalous. Accordingly, Puu Koae was bypassed as completely as possible in the overall solution for the flank net, even though this unavoidably reduced the precision of solutions for adjacent stations.

Another problem concerned the stability of the "base stations" (Swanson and others, 1976a, p. 36–37). One standard base station for the summit net (Keakapulu; fig. 11) had been displaced during an intrusive event along the southwest rift zone in 1974, as discussed later (p. 24). Additionally, Mauna Loa Volcano, on whose southeast flank all but one of these base stations are located, was inflating during 1974–76 (Lockwood and others, 1976), so that geodetic changes of uncertain magnitude related to Mauna Loa are superimposed on the Kilauea "baseline" measurements. Given these factors—and the scale of deformation associated with the 1975 earthquake, including a measured contraction of 12 cm along the 9 km line between two other primary base stations (Kulani and Strip, fig. 11)—we tried to make the displacement solution as independent as possible of assumptions concerning base-line stability. Trial solutions using alternative assumptions indicated only small effects for the large indicated displacements on the south flank of Kilauea, although the much smaller interpreted movements of the stations on Mauna Loa could vary significantly. Accordingly, only the marginal stations of the flank net (Kaiwiki New and Kaaha 2,

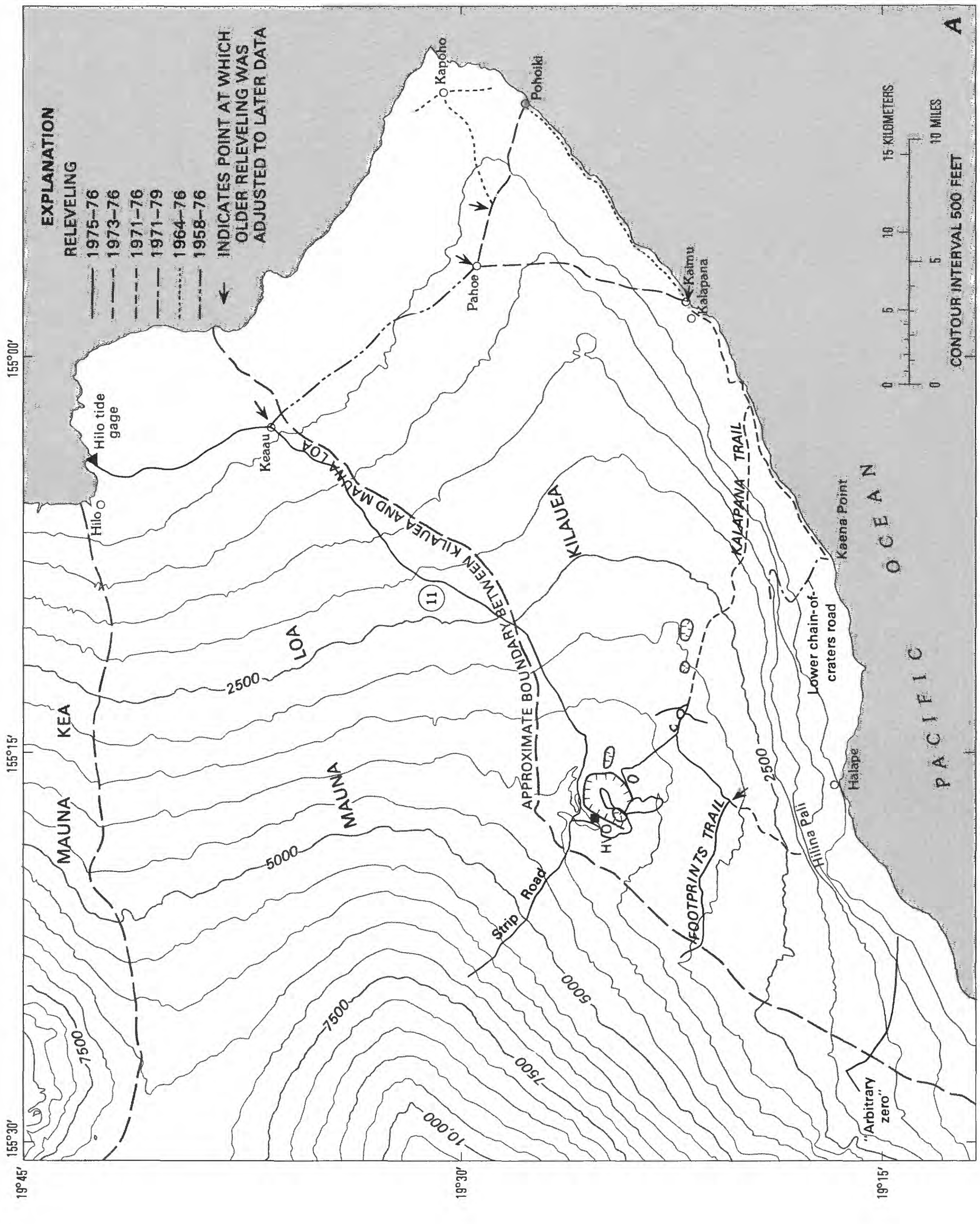
[1]Use of trade names in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

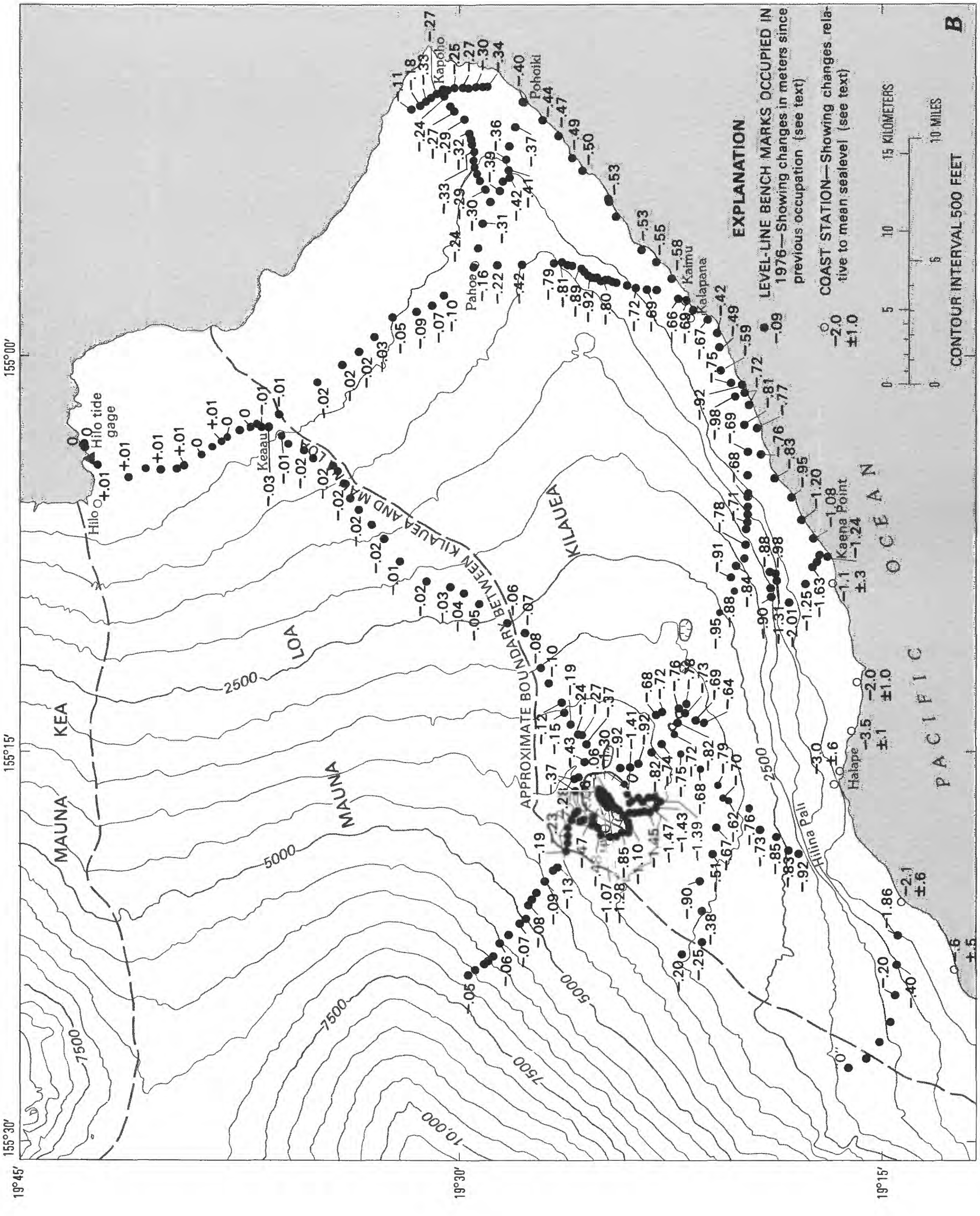
FIGURE 9 (following 3 pages).—Vertical displacements on Kilauea Volcano. Dashed lines separate major volcanic edifices; contour interval, 500 feet.

*A*, Major level lines on Kilauea occupied in 1976, showing times of last previous leveling and adjustment assumptions. Contour interval, 500 feet.

*B*, Locations of benchmarks along level lines and selected vertical changes between 1976 and last previous occupation, adjusted as indicated in figure 9*A*. Changes in elevation are relative to the Hilo tide gage; zeros have been deleted before the decimal point to save space. Quoted zero ("0") is arbitrary zero point. Contour interval, 500 feet.

*C*, Interpreted contours of elevation changes associated with the 1975 earthquake, based on data summarized in figures 3 and 9*B*. Rift zones indicated by shaded pattern; locations of profiles shown in figure 10 are also plotted. Contour interval 0.1 m; supplemental 0.01 amd 0.05 m contours; alternate contours omitted for values larger than −1.0 m. Hachures show direction of relative movement.


EXPLANATION
RELEVELING
1975–76
1973–76
1971–76
1971–79
1964–76
1958–76
INDICATES POINT AT WHICH OLDER RELEVELING WAS ADJUSTED TO LATER DATA
A
15 KILOMETERS
10 MILES
CONTOUR INTERVAL 500 FEET
155°00′
155°15′
155°30′
19°45′
19°30′
19°15′
Hilo tide gage
Hilo
Keaau
Pahoe
Kapoho
Pohoiki
Kaimu
Kalapana
Kaena Point
Halape
Lower chain-of-craters road
Hilina Pali
"Arbitrary zero"
MAUNA KEA
MAUNA LOA
KILAUEA
APPROXIMATE BOUNDARY BETWEEN KILAUEA AND MAUNA LOA
KALAPANA TRAIL
FOOTPRINTS TRAIL
Strip Road
HVO
11
PACIFIC OCEAN
2500
5000
7500
10,000



EXPLANATION
LEVEL-LINE BENCH MARKS OCCUPIED IN 1976—Showing changes in meters since previous occupation (see text)
COAST STATION—Showing changes relative to mean sealevel (see text)
CONTOUR INTERVAL 500 FEET
15 KILOMETERS
10 MILES
B
MAUNA KEA
MAUNA LOA
KILAUEA
APPROXIMATE BOUNDARY BETWEEN KILAUEA AND MAUNA LOA
PACIFIC OCEAN
Hilo
Hilo tide gage
Keaau
Pahoa
Kapoho
Pohoiki
Kaimu
Kalapana
Kaena Point
Halape
Hilina Pali
155°30′
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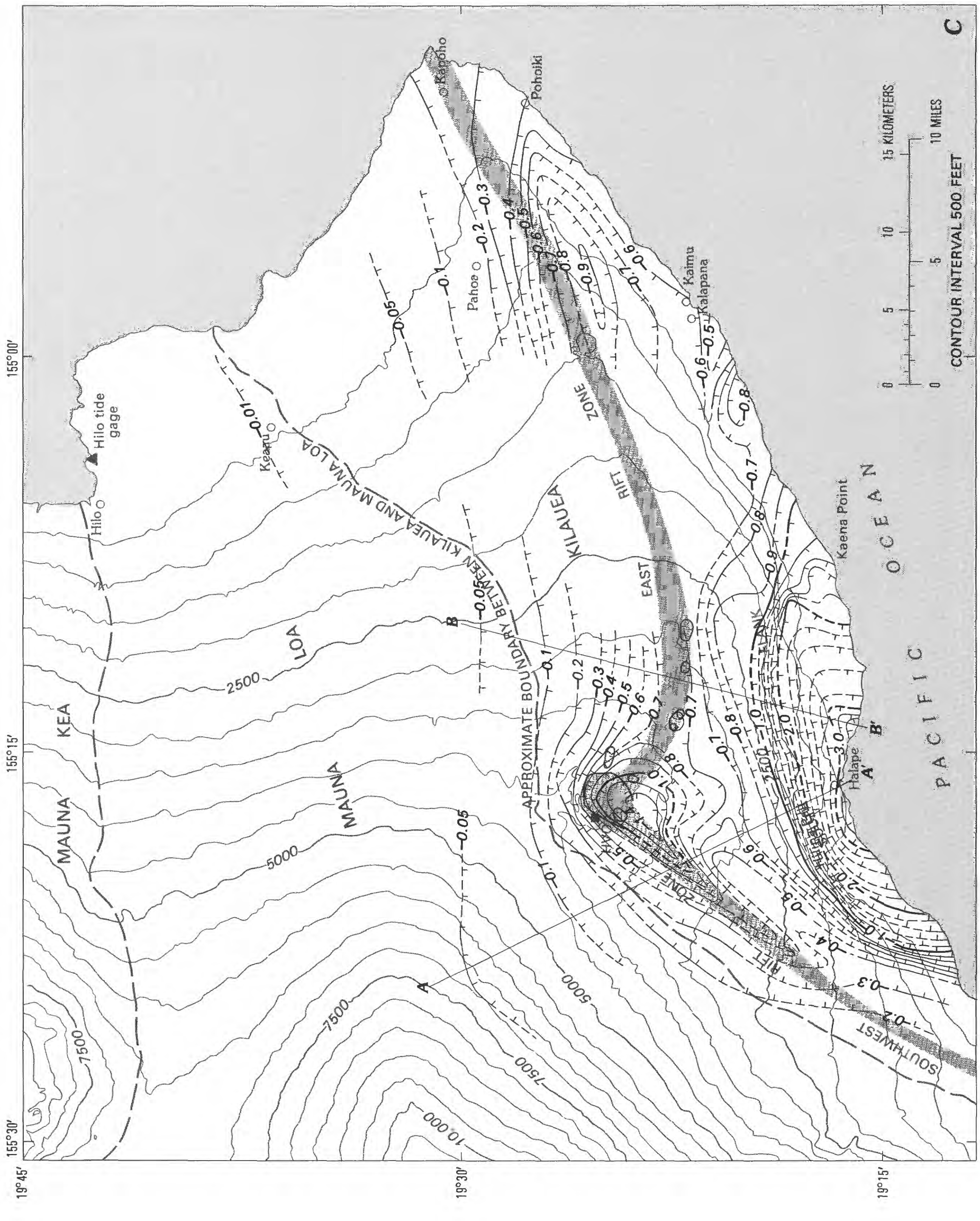
155°00′
19°45′
19°30′
19°15′


155°30′
155°15′
155°00′
19°45′
19°30′
19°15′
MAUNA KEA
MAUNA LOA
KILAUEA
EAST RIFT ZONE
SOUTHWEST RIFT ZONE
APPROXIMATE BOUNDARY BETWEEN KILAUEA AND MAUNA LOA
PACIFIC OCEAN
Hilo
Hilo tide gage
Keaau
Pahoa
Kapoho
Pohoiki
Kaimu
Kalapana
Kaena Point
Halape
A
A′
B
B′
2500
5000
7500
10,000
0 5 10 15 KILOMETERS
0 5 10 MILES
CONTOUR INTERVAL 500 FEET
C

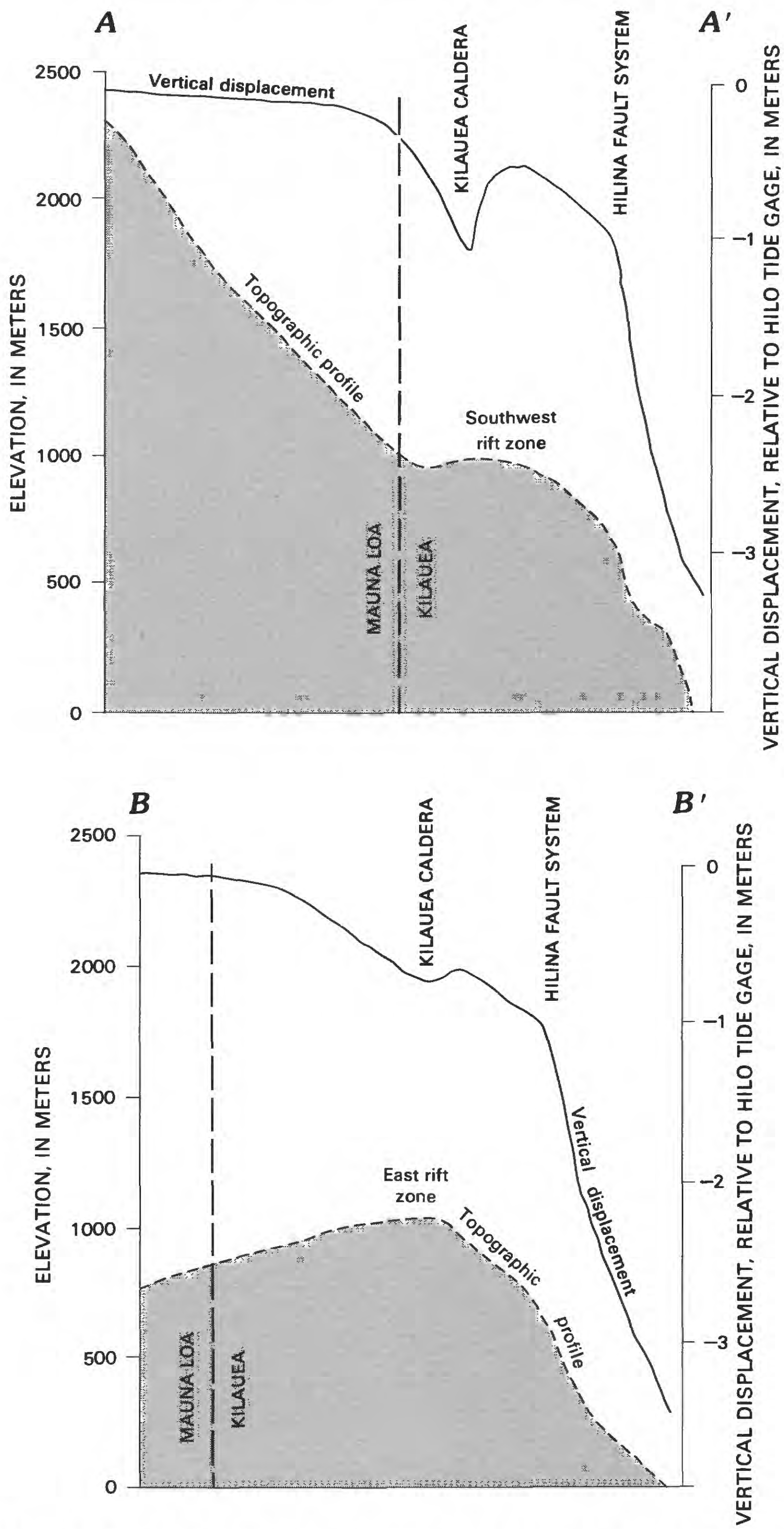



FIGURE 10.—Profiles of vertical displacement across Kilauea Volcano. See figure 9C for locations of profiles.

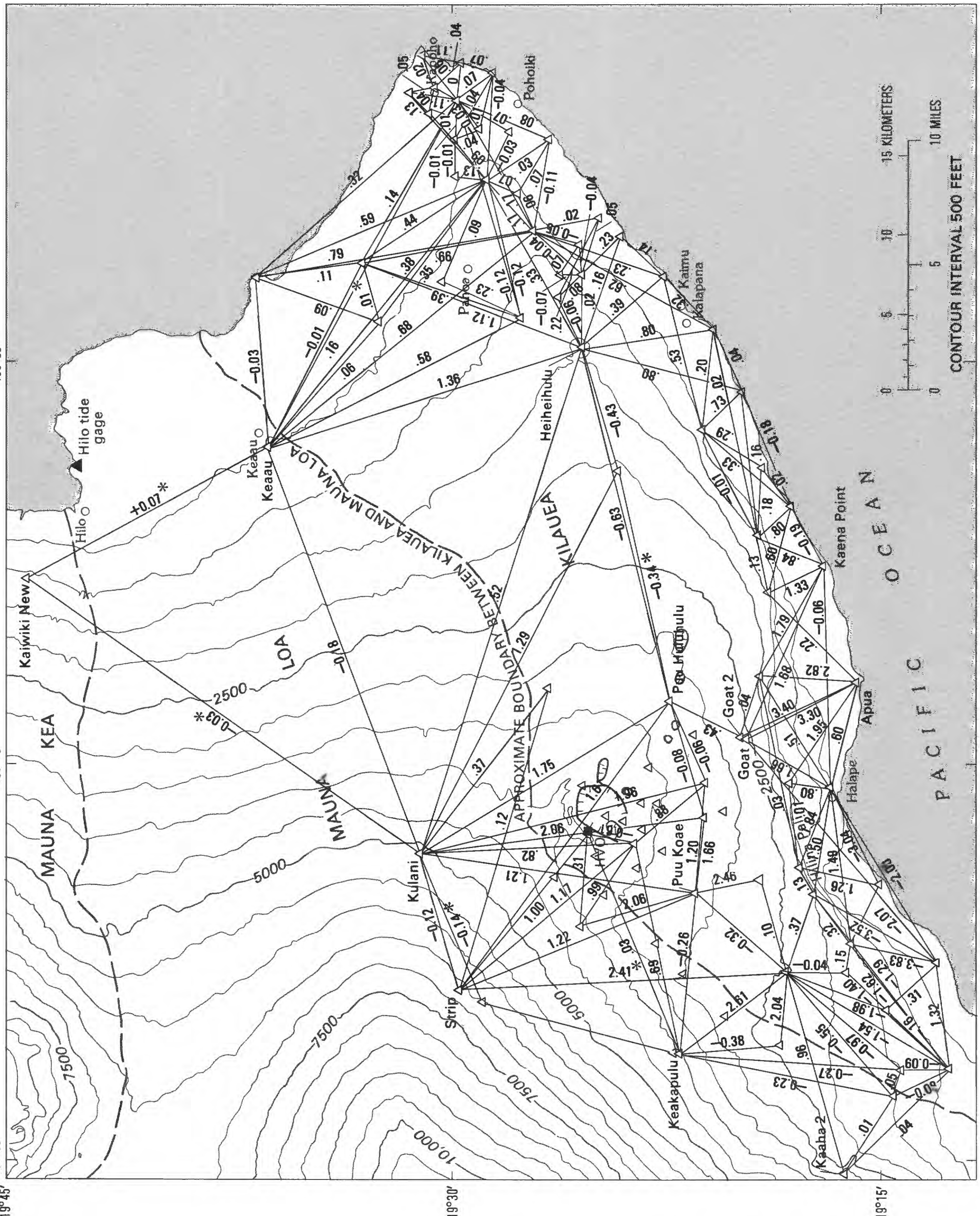



FIGURE 11.—Kilauea flank trilateration net, showing changes in distance (meters) between fall 1974 and spring 1976. Positive values are amounts individual lines lengthened; negative values are amounts lines shortened. *, starred values indicate changes between 1970 and 1976. (Contour interval, 500 feet; hachures indicate craters.)

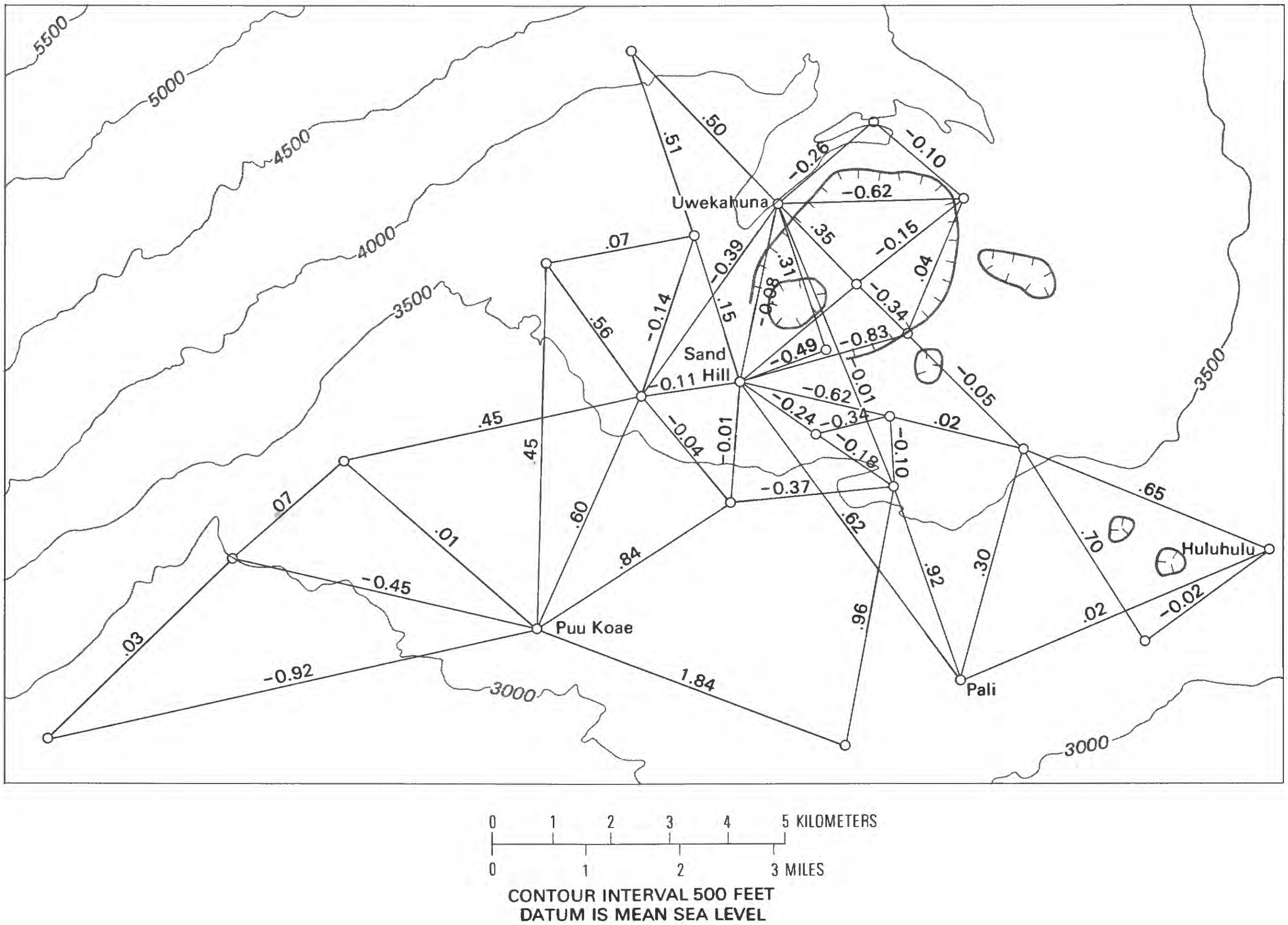



FIGURE 12.—Kilauea summit trilateration net, showing changes (in meters) in line lengths, September 1975 to January 1976. (Contour interval 500 feet; hachures indicate craters.)

fig. 11) were assumed fixed; changes in line length between these and the nearest adjacent stations were only slightly greater than measurement uncertainties, which indicates relative stability in comparison with the large changes in other parts of the trilateration net on Kilauea. One other assumption was necessary. The 18-cm contraction between Kulani and Keaau was arbitrarily evenly divided between these two stations; then the remainder of the net could be solved including several other standard base stations (Strip, Keakapulu), without using the suspect values for Puu Koae.

The resulting preferred solution for 1974–76 horizontal deformation (fig. 13) yields a geologically coherent pattern of displacements that generally increase seaward and converge slightly toward the area of maximum subsidence on the south coast of Kilauea (fig. 13). All the inland stations not fixed (Keakapulu, Strip, Kulani, Keaau, fig. 11) show small but significant displacements (10–35 cm), also in a generally seaward direction. These stations may have moved either during the earthquake, during the inflation and the July 1975 summit eruption of Mauna Loa, or at both times. Solutions for the stations on Mauna Loa, involving alternative assumptions, yield geologically less reasonable displacements. For example, if Keakapulu is held fixed along with Kaaha 2 (fig. 13), then displacements on the lower southwest side of Kilauea are rotated implausibly into northeasterly directions. Similarly, if Kulani is fixed along with Kaiwiki New, the displacements on the northeast side of Kilauea are rotated into more westerly directions than those shown in figure 13. None of these alternatives significantly modifies the coastal

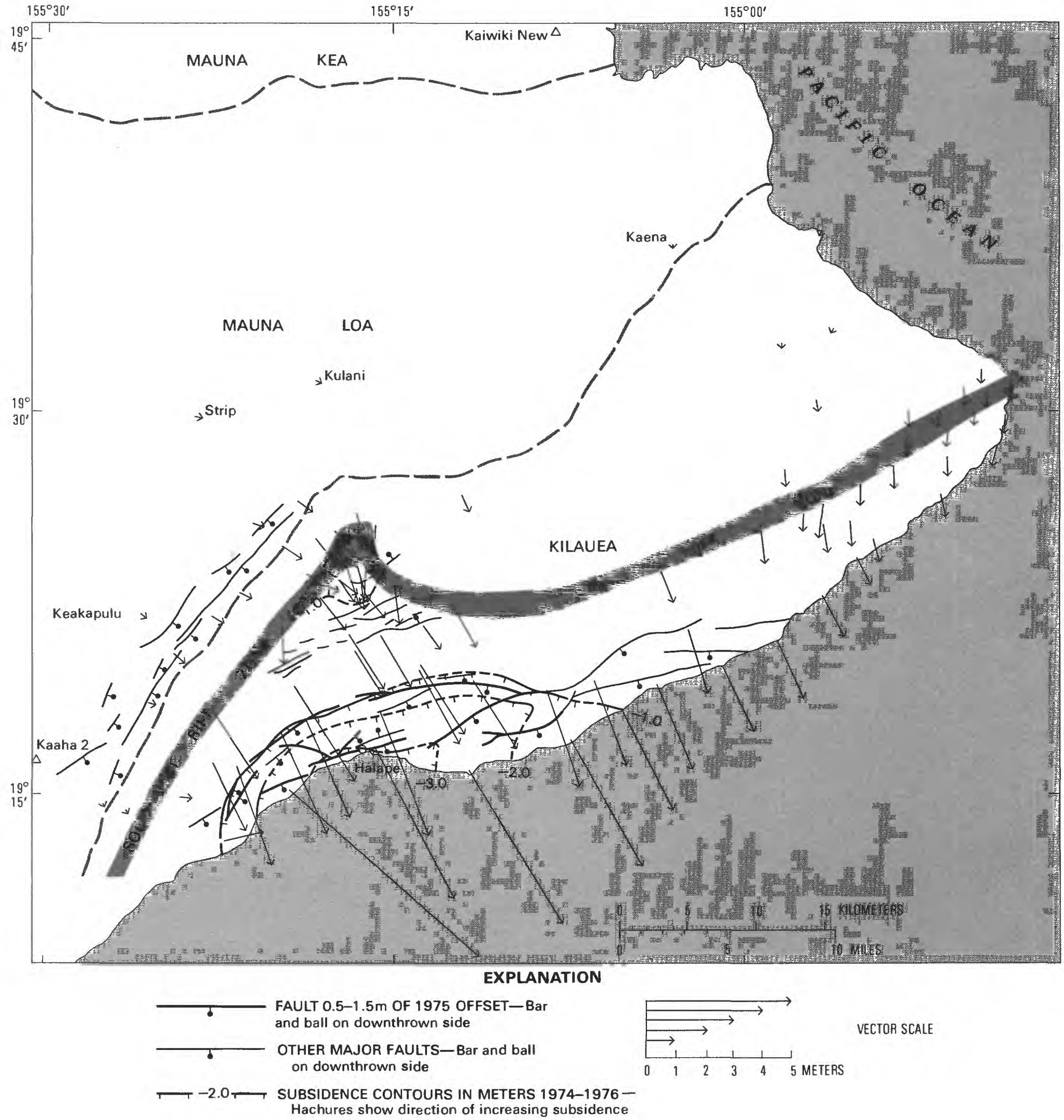



FIGURE 13.—Preferred displacement solution for fall 1974 to spring 1976 trilateration of Kilauea flank network. See text for a discussion of assumptions. Arrow tails are at geodetic stations shown in figure 11; lengths of arrows indicate amounts of displacement. The summit caldera area and rift zones are patterned.

pattern of large seaward displacements with southeasterly azimuths.

The cumulative displacements across Kilauea for the interval 1974–76 show a generally simple pattern of southeasterly movements increasing seaward, but the details of this pattern are complicated in the summit area and along the upper southwest rift zone of Kilauea where magmatic events took place between the two surveys. Just as with the leveling data, we have attempted to separate effects of these events from those of the earthquake-related deformation.

The eruption-related summit deformation of Kilauea between the fall 1974 survey and the November 1975 earthquake can be considered in two phases: the December 1974 eruption, and subsequent re-inflation in 1975. The summit area deflated and contracted during the upper southwest rift eruption on December 31, 1974 (Lockwood and others, 1978), and a pattern of horizontal ground displacement away from the middle southwest rift zone developed adjacent to an area marked by a major earthquake swarm, presumably caused by intrusion of magma (fig. 14). Displacements along the middle southwest rift zone, as much as 1.3 m, were among the largest ever previously observed for a single event on Kilauea. Another notable feature of this event was that several stations on Mauna Loa showed displacements away from the area of intrusion, including the Keakapulu "base station." Following this magmatic event, Kilauea resumed a typical pattern of steady summit inflation that continued through 1975 until terminated by the November earthquake and associated deformation.

An interpretive displacement map, showing the horizontal displacements interpreted to be due mainly to effects of the November 1975 earthquake, was constructed by determining displacements for three subareas in different time frames (fig. 15).

For roughly the eastern half of the Kilauea flank net, the displacements are for fall 1974–spring 1976, the same as in figure 13, because no significant eruption-related deformation has been documented in this area for the interval prior to the earthquake. Changes were also small in this area for the period 1970–74. For Kilauea's southwest rift zone, displacements are for the interval spring 1975–spring 1976 for all stations for which data are available, so to avoid interfering effects of the eruption-intrusion event of Dec. 31, 1974. For the Kilauea summit area, the solutions are for the shortest possible interval, September 1975–January 1976, to minimize the effects of the December 1974 eruption and the summit inflation during most of 1975.

The resultant interpretation for the 1975 earthquake (fig. 15) differs from the geometrically more rigorous 1974–76 solution (fig. 13) in several significant respects. In the Kilauea summit area, the amount of seaward displacement is reduced slightly and azimuths of the displacement vectors are more nearly parallel for the limited time interval related most directly to the earthquake. Seaward displacements on the southwest side of Kilauea are somewhat smaller, because of elimination of the December 1974 effects. The seaward displacement of the south flank decreases west of the Halape–Puu Kapukapu area, just where effects of the 1974 event begin to be significant. A possible implication is that some regional stress had been relieved during the 1974 deformation along the southwest rift zone, so that strains in this area resulting from the 1975 earthquake were smaller than they otherwise would have been. In addition, the accumulation of contractional strain around margins of the 1974 intrusion area may have been significant in localizing the area of maximum horizontal displacement and the westerly increase in deformation from the epicentral area of the 1975 earthquake. The steep gradient of the coastal subsidence in the same area (fig. 9) may reflect a similar response to a preexisting strain pattern.

Another effect related to the 1974 events along the southwest rift zone may be the small but systematic deviation of the 1975 displacement vectors within the central region of maximum deformation, about S. 60°–65° E. (fig. 15), from the direction of dilation along the east rift zone and the Koae fault system—about S. 75° E. (Duffield, 1975; Swanson and others, 1976a). Movement of the south flank is largely normal to trends of the dilation of the Koae system and the east rift zone, but the effect of opening along the southwest rift zone, because of its divergent trend, would be to introduce an oblique easterly component to south flank displacements. Such an effect is especially evident near margins of the region deformed during the December 1974 intrusion: small easterly displacements, nearly parallel to the trend of the east rift zone and the Koae system occurred on the upper south flank (figs. 14, 17*A*), requiring a component of left-lateral motion on these dominantly dilatant structures. Such strike-slip displacements are also shown by cracks that formed in alluvium and along paved roads during the 1975 deformation (fig. 6).

In a pattern consistent with the leveling data, terrain inland of Kilaeua's summit area and rift zones moved southeastward, the displacements increasing seaward. The maximum horizontal displacements are in the same

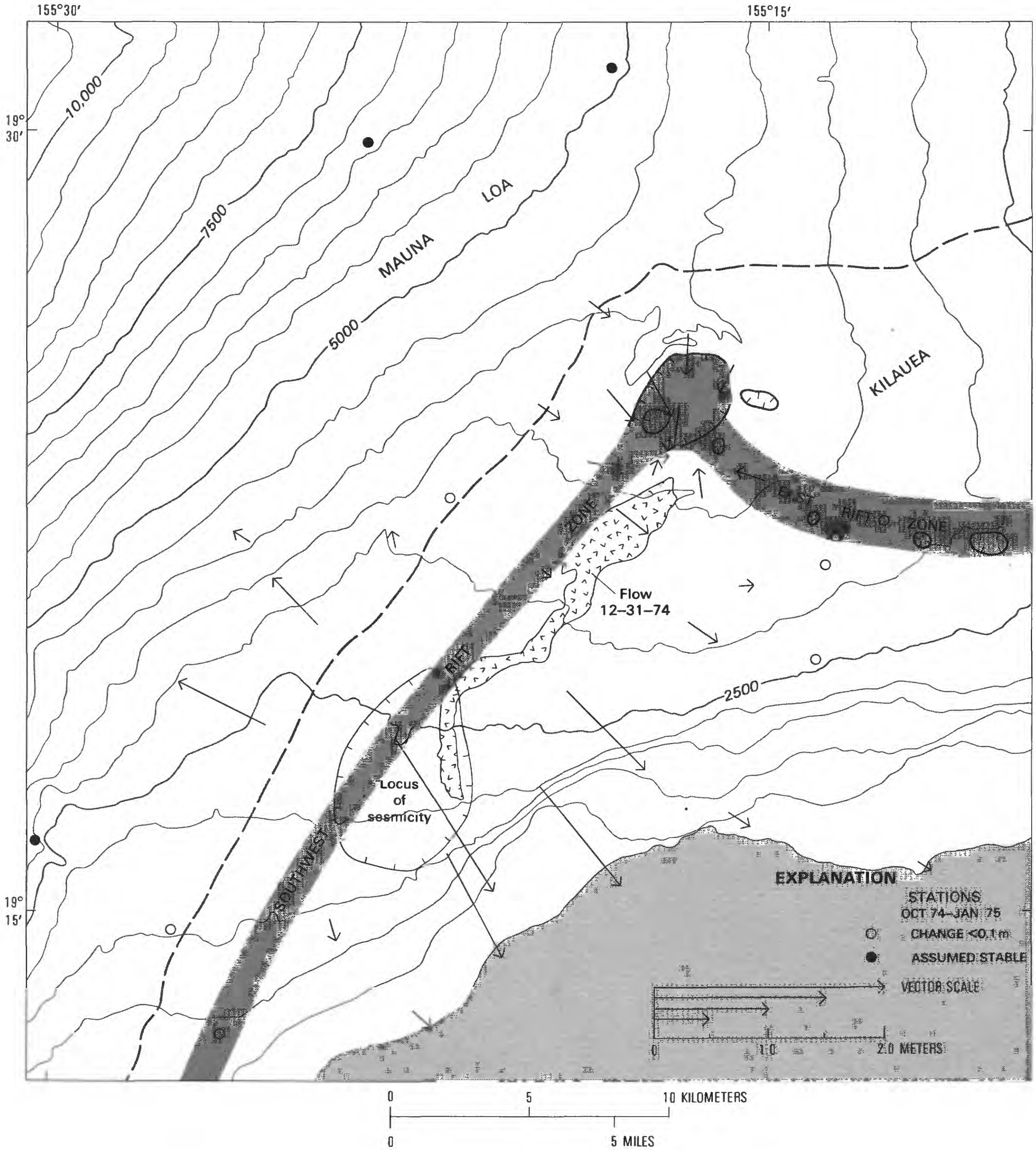



FIGURE 14.—Displacement solution for deformation on southwest flank of Kilauea Volcano, associated with eruption and intrusion events on December 31, 1974. Location of seismic swarm is from Koyanagi, Stevenson, Endo, and Okamura (1978, figs. 7–8). Arrow tails are at geodetic stations shown in figure 11; lengths of arrows indicate amounts of displacement. The summit caldera area and rift zones are patterned. Hachures indicate craters. (Contour interval, 500 feet.)

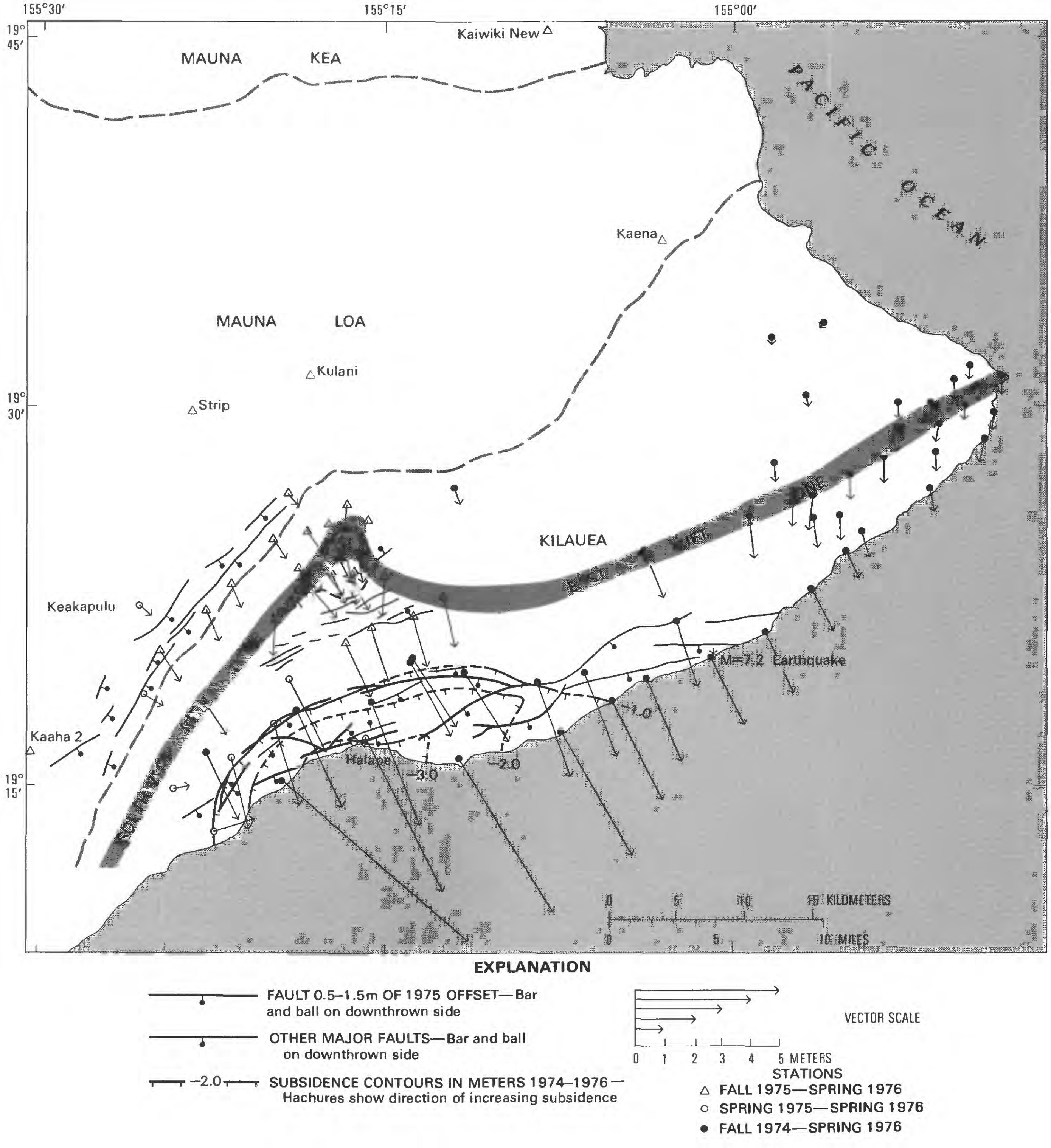



FIGURE 15.—Interpretation of displacements associated with November 1975 Kilauea earthquake. See text for discussion of assumptions involved. Arrow tails are at geodetic stations shown in figure 11; lengths of arrows indicate amounts of displacement. The summit caldera area and rift zones are patterned.

area of the south flank as the maximum subsidence, far west of the earthquake epicentral area. Vectors at both margins of the region of maximum ground deformation tend to converge toward the central area, more notably on the southwest side, where the gradient in subsidence is also steep. Unlike the leveling data (fig. 9*C*), however, the pattern of horizontal deformation is not conspicuously influenced by the rift zones, the caldera, or the unfaulted upper northern part of the south flank. Amounts of displacement increase seaward relatively uniformly across every sector of Kilauea, without obvious discontinuities across any of these structural zones.

## SUMMIT DEFORMATION 1974–77

The summit deformation of Kilauea, which has been determined by trilateration and releveling several times a year before and after the earthquake, is of interest for several reasons. First, the style of deformation related to the earthquake may have been influenced by previous deformation, such as that associated with the December 1974 eruption. Also, to the extent that the 1975 earthquake is related to stressing of the south flank of the volcano by inflation of the summit area and dike injection along the rift zones (Swanson and others, 1976a), antecedent deformation of the summit area may offer some premonitory clues. Finally, the post-earthquake deformation of the summit area is significantly different from any previously observed pattern on Kilauea, and it offers insight into the manner in which the volcano has responded to disruptive effects of the earthquake. Accordingly, we briefly review the record of summit deformation from late 1974 through September 1977, the time of the first post-earthquake eruptive activity on Kilauea.

Interpretation of many geodetic measurements at Kilauea, including both leveling and trilateration, is complicated by the relative infrequency of reoccupation and by high rates of episodic deformation. Accordingly, continuously recorded deformation data are especially valuable. At present, the only such data are from tiltmeters; these tilt measurements, supplemented by seismic observations, are utilized both to monitor short-term fluctuations in behavior of the volcano and to select times for reoccupation of the more extensive geodetic networks.

Tilt data from the Uwekahuna station, on the northwest side of the summit caldera (fig. 12), have proved especially informative and illustrate the general behavior of the volcano in the 1974–77 period (fig. 16). After a major deflation associated with the December 1974 eruption and intrusive event along the southwest rift zone, the summit area entered a period of steady inflation through much of 1975 that was terminated by the November 29 earthquake and associated major deflation. This deflation "bottomed out" early in 1976, but throughout 1976 and 1977 the volcano failed to maintain any sustained summit inflation. Periods of slow inflation during this interval were interrupted by significant summit deflations in June 1976, July 1976, August-September 1976, and February 1977. Each of these events, except the prolonged August-September deflation, was accompanied by earthquake swarms along the east rift zone, and each has been interpreted as marking intrusive activity along the east rift zone (Dzurisin and others, 1980). Similar rift intrusions have also occurred repeatedly in the past (Duffield and others, 1976; Swanson and others, 1976a, table 1). Finally, in September 1977, a major east rift eruption—the first eruption since the 1975 earthquake—was accompanied by a similar but larger summit deflation.

The summit deformation of Kilauea can be documented in more detail by combining information from leveling and trilateration measurements with the tilt data for key periods. Figure 17 shows horizontal displacement vectors determined by graphical solution of the Kilauea summit trilateration net and contours of equal vertical displacements interpreted from releveling in the summit area (fig. 9*A*) and partly constrained by tilt vectors.

The period of September 1974 to January 1975 (fig. 17*A*) is dominated by effects of the December 31, 1974 eruption along the southwest rift zone and associated intrusive events. Summit deflation of more than 0.6 m occurred during and immediately after the eruption, amounting to a total of about 120 microradians of east-west tilt as recorded on the Uwekahuna tiltmeter[2] (fig. 16). Subsidence occurred at peak rates of more than 10 microradians/hour on December 31, and continued at decreasing rates until January 5. This eruption was also accompanied by significant horizontal changes. Convergence of horizontal vectors toward the deflation center defined by the contours of vertical change (fig. 17*A*) is a typical pattern for summit deflation events associated with Kilauea rift eruptions, as has been documented repeatedly for eruptions in the late 1960's (Fiske and Kinoshita, 1969; Jackson and others, 1975). The inflation-deflation is typically eccentric to Kilauea's summit area, centered along or just outside the southeast topographic margin of the caldera. In addition to

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

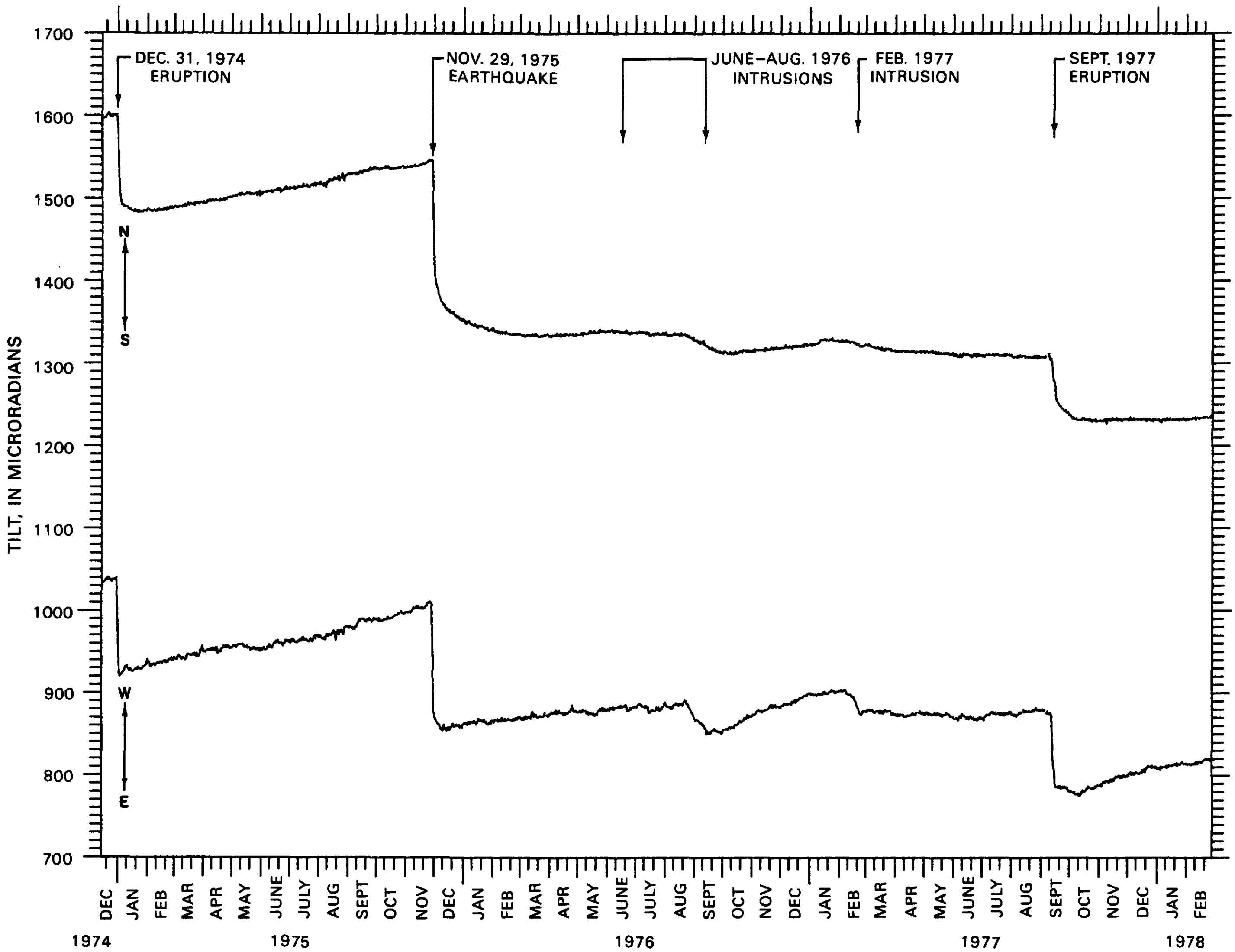
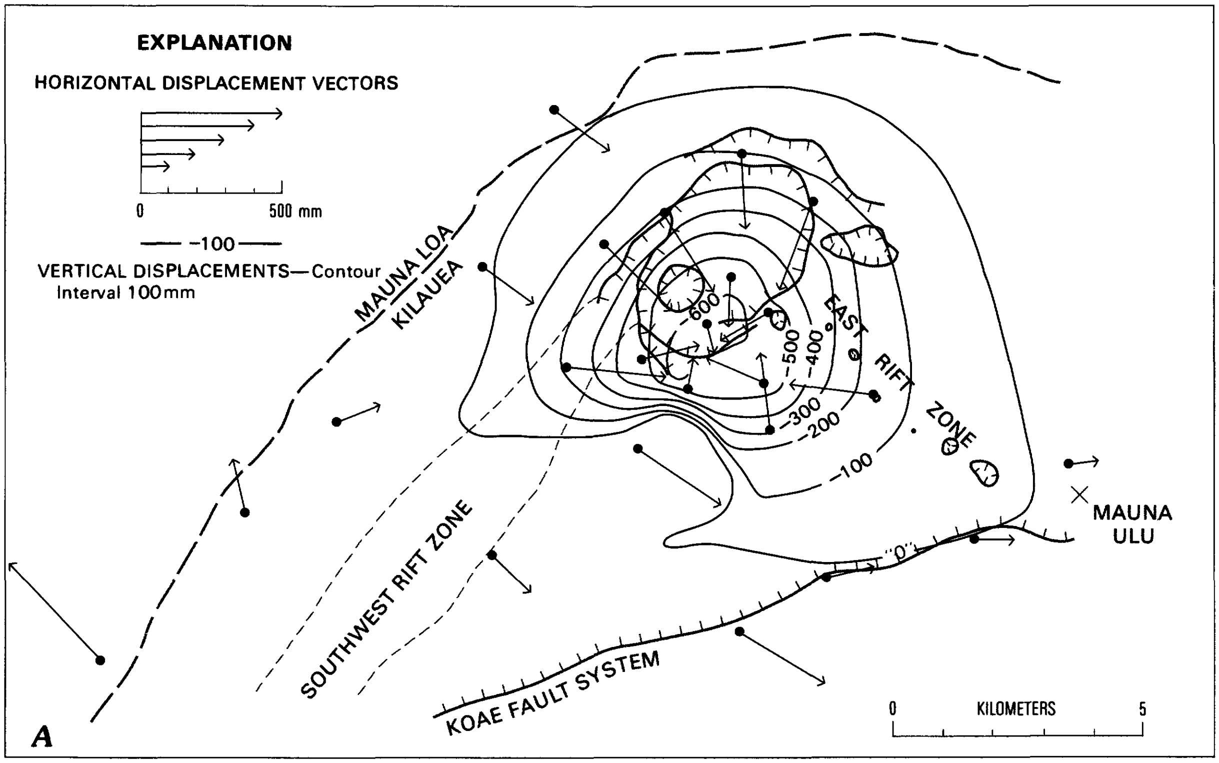



FIGURE 16.—East-west and north-south components of tilt, water-tube tiltmeter at the Uwekahuna vault on west rim of Kilauea caldera.

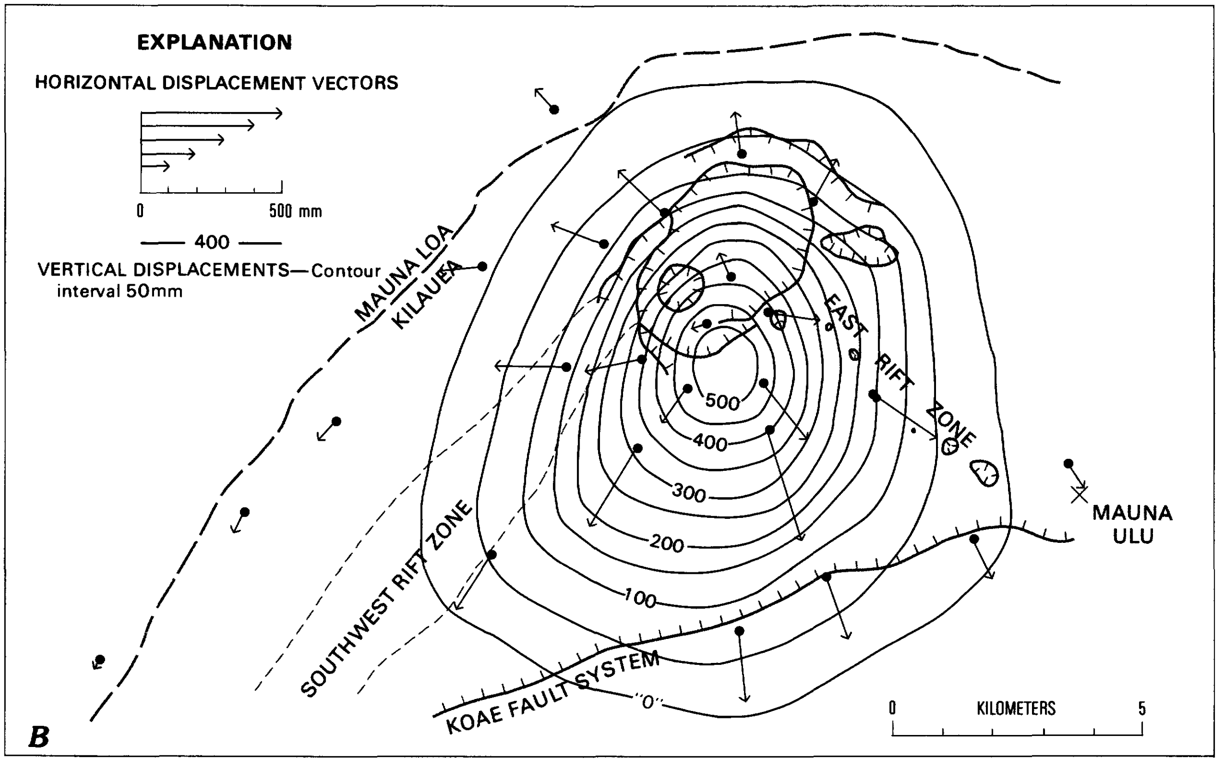
summit deformation, an intrusive event along the middle southwest rift zone was indicated by seismicity and by large horizontal ground movements, as already discussed (fig. 13). The easterly displacements near Mauna Ulu and the upper east rift zone (fig. 17*A*) are thought to reflect dilation of the southwest rift zone in a more easterly direction than that of the dominant southward opening along the east rift zone. This difference in displacement probably introduces a small component of left-lateral displacement along the Koae fault system and between the south flank and the more stable area north of the east rift zone.

During the first 9 months of 1975, both the Uwekahuna tiltmeter (fig. 16) and the leveling and trilateration data (fig. 17*B*) show a typical pattern of

FIGURE 17 (following 4 pages).—Horizontal and vertical deformation of the summit area of Kilauea from 1974 to 1977, as interpreted from leveling, tilt, and trilateration measurements for successive time intervals. Note the variable contour intervals for vertical displacements; also the change in scale for horizontal displacement vectors in diagram encompassing period of the 1975 earthquake (17*C*). Vertical displacement contours are relative to assumed stable benchmark in town of Volcano; therefore, the zero contour has quotation marks. Horizontal displacement vectors are relative to standard "base stations" (Keakapulu, Strip, and Kulani, see fig. 11), which are assumed to be stable except for period encompassing the earthquake (17*C*). Solutions for this period are based on control from the Kilauea flank trilateration net (fig. 11). Hachures indicate craters and faults.

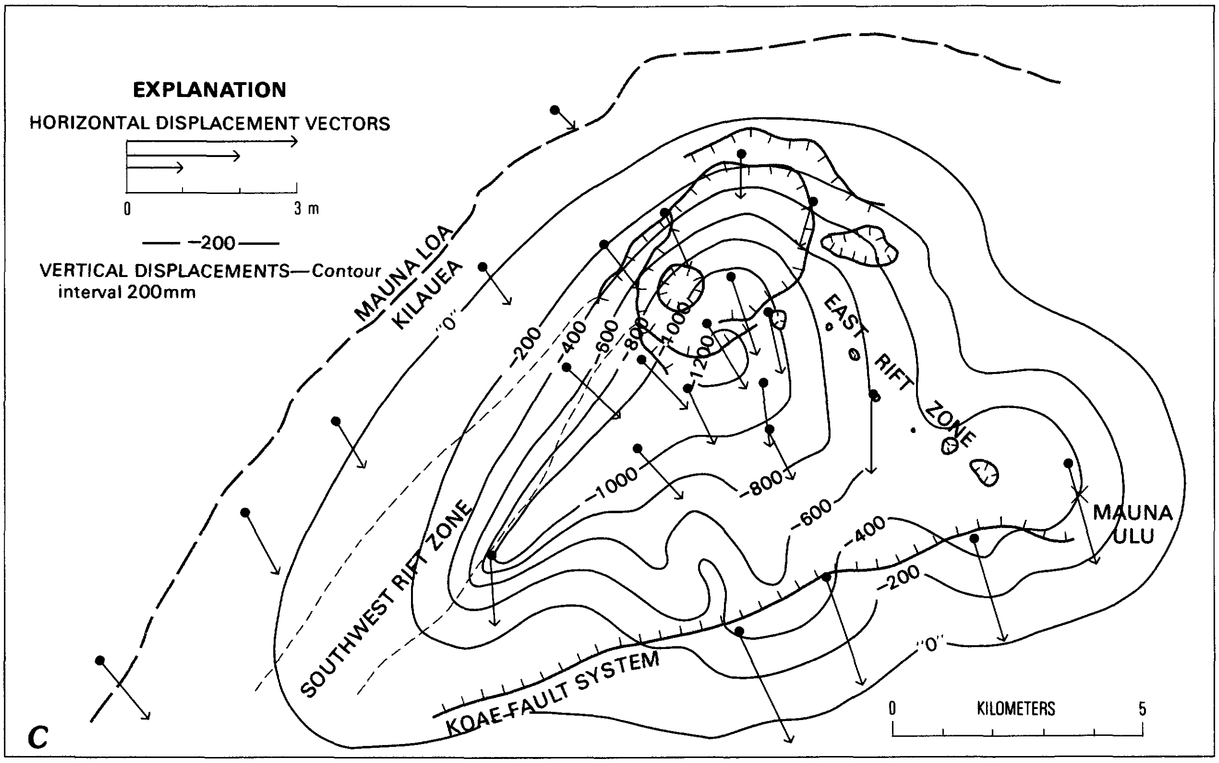



*A.* September 1974 to January 1975. Includes December 31, 1974, eruption and intrusion along the southwest rift zone.

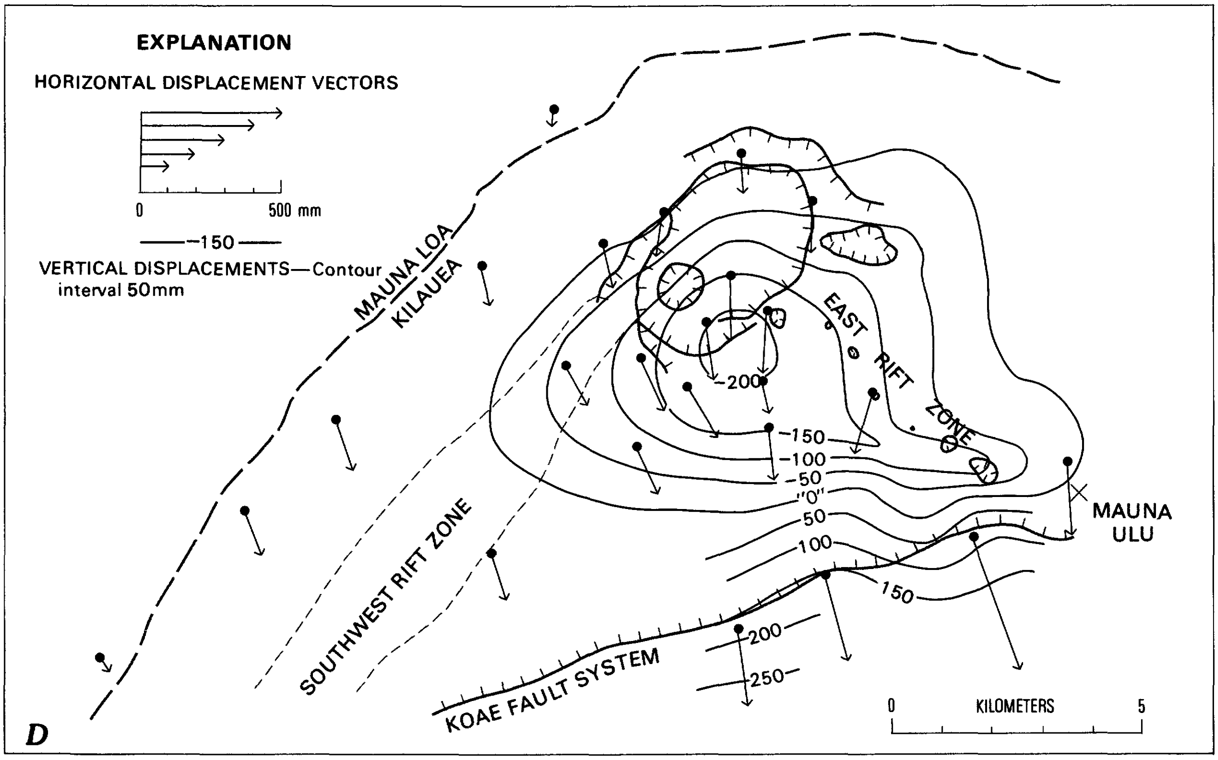



*B.* January to September 1975. A period of sustained summit inflation.

FIGURE 17.—HORIZONTAL AND VERTICAL DEFORMATION OF THE SUMMIT AREA OF KILAUEA

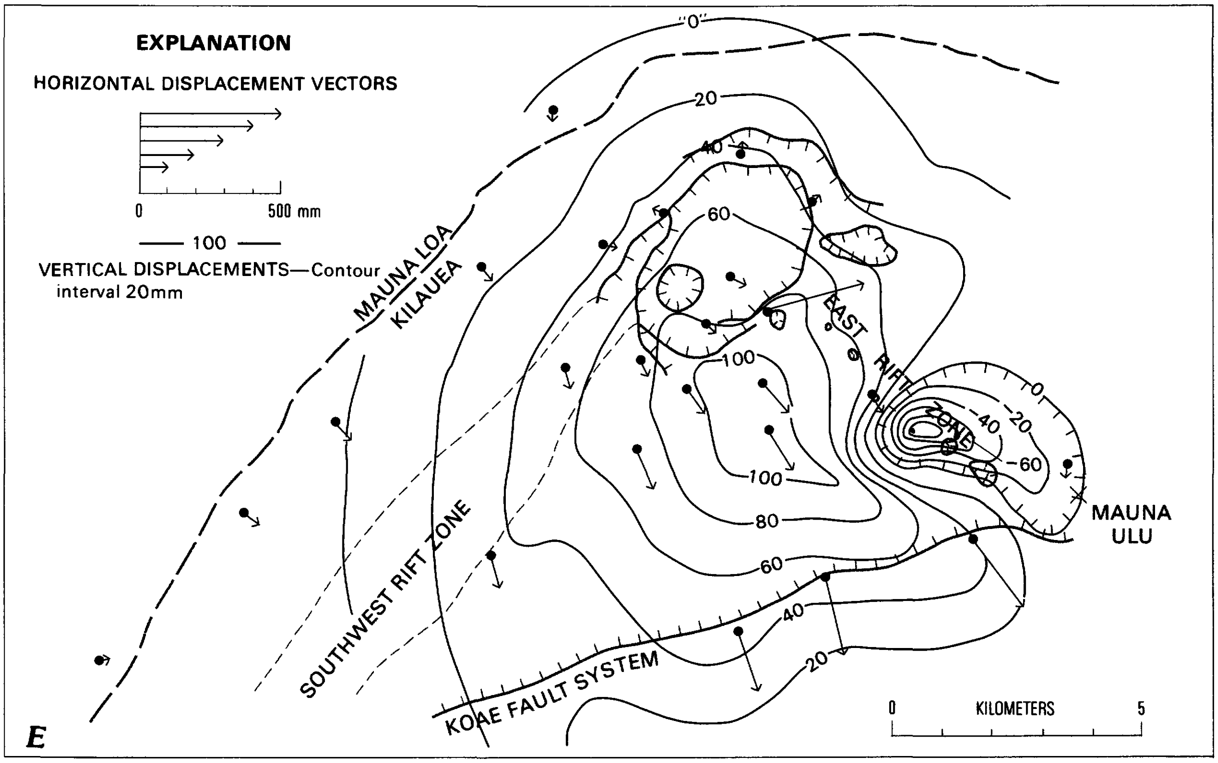



*C.* September 1975 to January 1976. Includes November 29, 1975, magnitude-7.2 earthquake.

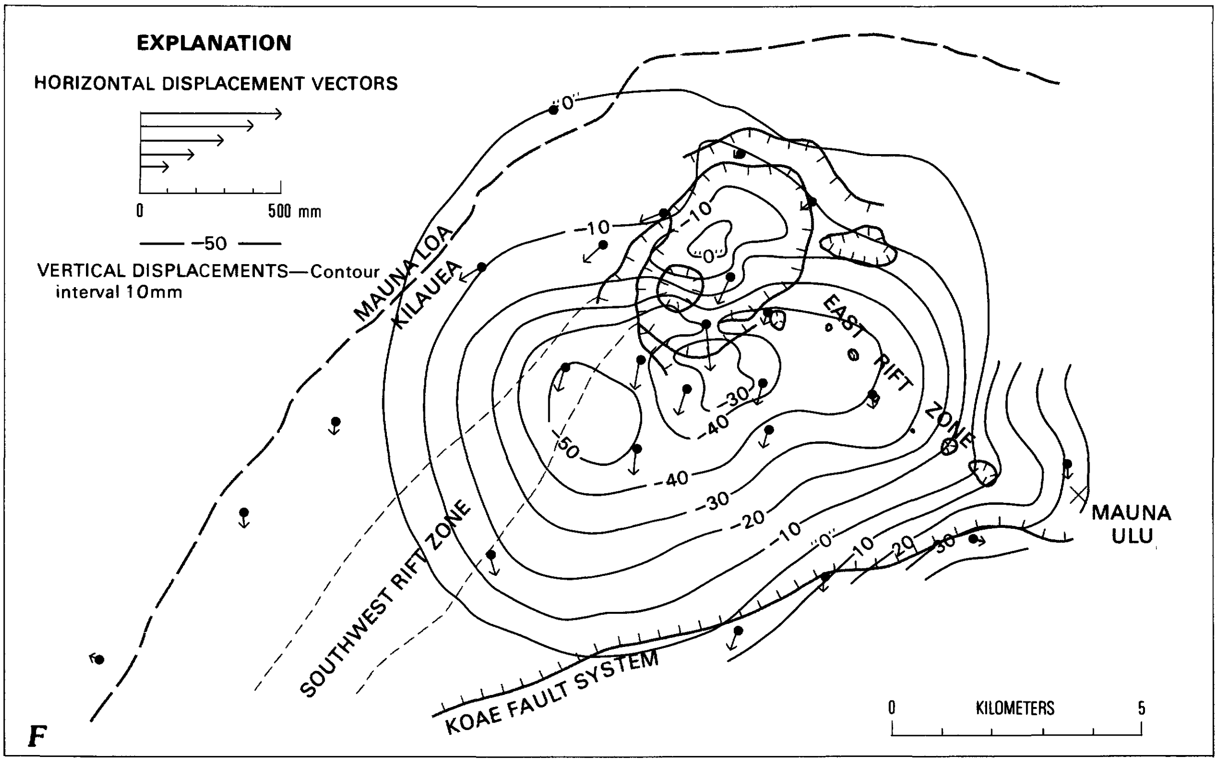



*D.* January to September-October 1976. Includes several intrusive events along the east rift zone.

FIGURE 17.—HORIZONTAL AND VERTICAL DEFORMATION OF THE SUMMIT AREA OF KILAUEA—Continued

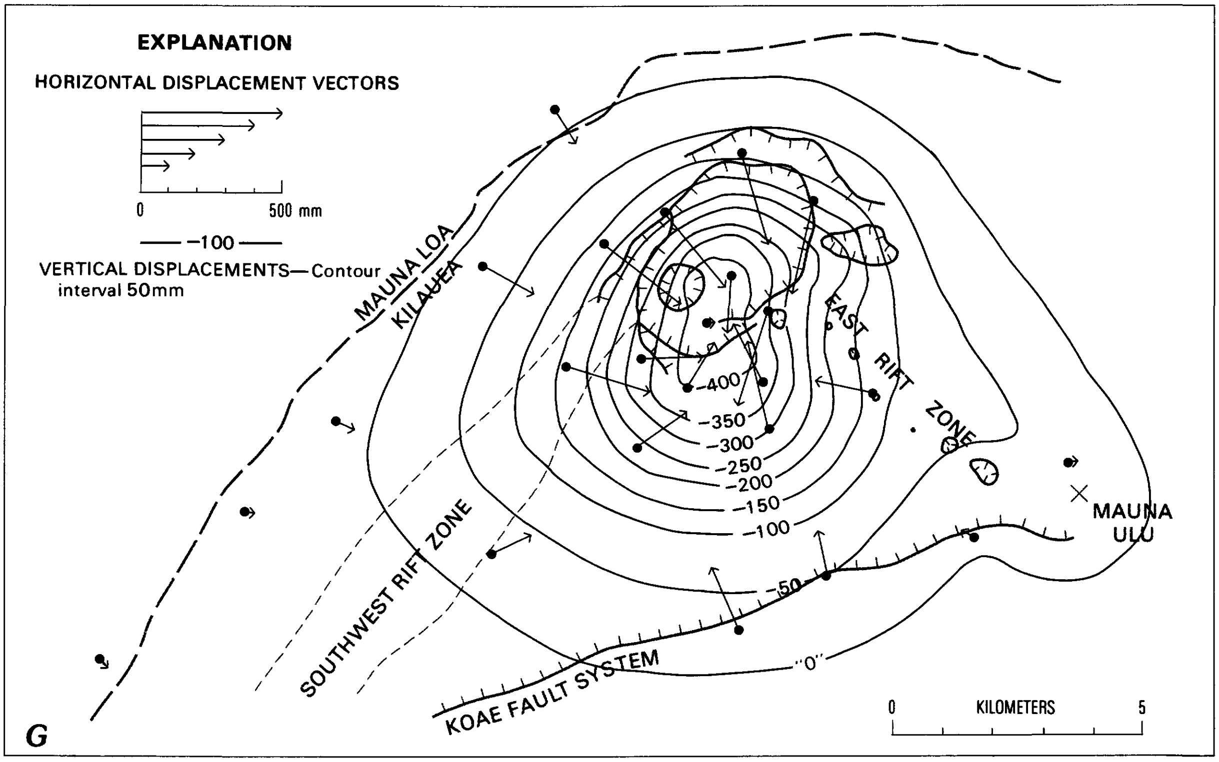



*E.* September-October 1976 to March 1977. Includes one intrusive event along the east rift zone.




*F.* March to August 1977. A period of general structural and seismic quiescence.

FIGURE 17.—HORIZONTAL AND VERTICAL DEFORMATION OF THE SUMMIT AREA OF KILAUEA—Continued




*G.* August 25 to September 23, 1977. Includes early phase of eruption along the middle east rift zone.

FIGURE 17.—HORIZONTAL AND VERTICAL DEFORMATION OF THE SUMMIT AREA OF KILAUEA—Continued

sustained summit inflation. The inflation contours determined by leveling and tilt measurements focus near the south margin of the caldera, and the horizontal displacement vectors radiate outward from a nearly confocal center. Nothing seems anomalous about this deformation pattern, in comparison with other well studied recent periods of inflation between eruptive events at Kilauea (Kinoshita and others, 1969; Swanson and others, 1976b, figs. 4, 5), and in the fall of 1975, HVO scientists anticipated renewed eruptive activity at Kilauea in the near future.

Instead, the magnitude-7.2 earthquake struck on November 29, 1975, triggering the largest overall ground deformation thus far recorded at Kilauea Volcano. The summit area subsided more than 1.2 m (fig. 17*C*), as also indicated by the approximately 145 microradians of eastward tilt at Uwekahuna (fig. 16). Unlike the confocal deformation patterns of previous inflation-deflation cycles, the horizontal and vertical components of movement were spectacularly decoupled in the summit region, with horizontal displacements trending uniformly south-southeasterly toward the coastline and increasing in amount seaward, independently of patterns of subsidence in the summit region and upper rift zones. This pattern of summit deformation thus provides a more detailed documentation for the similar geometry of deformation already described for the entire subaerial edifice of Kilauea. (Compare fig. 9*C* and fig. 15.)

Post-earthquake deformation patterns for the Kilauea summit area during three successive time intervals of 6–9 months each (figs. 17*D*–*F*) are relatively similar. All show a component of continued seaward horizontal displacement, independent of vertical changes, that contrasts notably with the inflation-deflation sequences (figs. 17*A*, *B*), normal for Kilauea prior to the 1975 earthquake.

The period January 1976 to September-October 1976 (fig. 17*D*) includes two small inferred intrusive events along the east rift zone, as indicated by seismic swarms associated with abrupt deflation at the summit in June and July (fig. 16). A more prolonged episode of aseismic deflation also occurred between mid-August and mid-September; no locus of accumulation has been identified for the magma that drained from the summit region during this episode. This general time interval is characterized by deformation patterns roughly similar to those associated with the 1975 earthquake (fig. 17*C*), but at greatly reduced magnitudes. Horizontal displacement vectors show a coherent pattern of continued seaward movement in a south-southeasterly direction, independent of continued deflation centered along the south margin of the summit caldera. A significant change, however, is the uplift along the Koae fault system and the unfaulted upper part of the south flank. Uplift of this general area was a significant feature of the regional deformation of Kilauea prior to the 1975 earthquake (Swanson and others, 1976a, p. 17–23), and the uplift along the Koae fault system early in 1976 may have indicated the beginning of renewed stabilization of the south flank (fig. 17*D*). The absence of continued uplift centered in this area for later post-earthquake time intervals (figs. 17*E–F*) suggests, however, that the episode of uplift alternatively may have reflected some more ephemeral post-earthquake isostatic readjustment.

The period of September-October 1976 to March 1977 shows a more complex pattern of relatively small-scale deformation. This period includes another intrusive event along the east rift zone, in February, as indicated by a concentrated seismic swarm accompanying abrupt summit deflation (fig. 16). Loci of such seismic swarms commonly have coincided with areas of intrusion and uplift along Kilauea rift zones (Duffield and others, 1976), but, in this case,the location of the seismic swarm coincided with an area of net subsidence just uprift of Maunu Ulu (fig. 17*E*). Horizontal extensions of as much as 25 cm in individual Geodimeter lines across the area of the seismic swarm provide additional evidence of an intrusive event; some of the subsidence may be due to formation of an apical graben over the intrusion, analogous to the troughs of subsidence along both of Kilauea's rift zones (fig. 9*C*). However, lack of local uplift adjacent to the area of February 1977 subsidence, as well as detailed analysis of continuously recorded tilt data, suggest that magma migrated downrift from this area during later stages of the intrusion event (Dzurisin and others, 1980). Some magma probably accumulated 15–20 km farther east along the rift zone, in an area where steaming cracks had developed, where tilt measurements indicated sizeable inflation early in 1977, and where the September 1977 eruption subsequently broke out. In contrast to the subsidence along the upper east rift zone, the overall change in the summit area from September 1976 to March 1977 was weak inflation centered near the south margin of the caldera. The pattern of horizontal displacements was still dominated by seaward motion increasing to the southeast, but deviations from this pattern occurred locally near the deflation locus along the upper east rift zone and in the north part of the caldera. Thus, on its northern flank the weak inflation at the main deformation center appears to have reduced and partially reversed the still prevalent regional pattern of seaward displacement. Elsewhere, this regional pattern continued to dominate the orientation of horizontal movements, although at reduced rates.

From March 1977 until August 1977—just before the September eruption, the same general style of deformation prevailed, but the changes were smaller and slower than previously. This 6-month period was geodetically one of the most stable periods thus far observed at Kilauea's summit. Virtually no net tilt occurred at Uwekahuna (fig. 16), and there was essentially no net change of elevation on the caldera floor (fig. 17*F*). Modest deflation was centered along the south side of the caldera, which cancelled out much of the weak inflation of the previous observation period (fig. 17*E*). A weak pattern of seaward displacement still characterized the horizontal deformation, but the changes were so small that the vector solutions are uncertain for many stations.

The general pattern of summit deformation for nearly 2 years after the November 1975 earthquake can thus be characterized by two significant features: a lack of sustained inflation and the seaward displacement of the south side of Kilauea at gradually decreasing rates. This pattern appears to have represented continued deformation like that triggered by the earthquake, gradually evolving into greater structural stability. At no time did the loci of horizontal and vertical deformation share a common focus, as had been characteristic prior to the earthquake (fig. 17*B*). If magma is generated and accumulates at a steady rate of about 0.1 $km^3$/yr beneath Kilauea, as inferred by Swanson (1972), all of it could not have been stored in the summit reservior after the 1975 earthquake. Some magma may have filled voids generated by the earthquake in the summit region, but calculations based on microgravity measurements (Jachens and Eaton, 1980; Dzurisin and others, 1980) suggest that any such voids would have been largely filled within 6–8 months after the earthquake. Subsequently, most of the newly generated magma appears to have moved into the east rift zone, instead of accumulating at a summit magma reservoir. Attempts to evaluate volumetric relations between rift expansion and rates of magma supply at Kilauea are not very satisfactory, because of limited geodetic information along the heavily forested east rift zone, but on the basis of seemingly plausible assumptions, the magma supply of Kilauea for about 1 year may have emptied into voids opened along the east rift zone by the 1975 earthquake. This rift zone was the site of repeated intrusive events, and magma accumulated along the middle part of the rift zone, where sizeable inflation was documented by tilt and Geodimeter measurements in the spring and summer of 1977.

A major eruption broke out along the middle east rift zone of Kilauea on September 12, 1977 (Moore and others, 1980), after a several-week period of gradually increasing seismicity. A lack of any premonitory summit inflation makes this eruption different from any other Kilauea eruption since detailed ground-deformation studies began. Major subsidence in the summit region (fig. 17*G*) associated with this eruption was rather similar to subsidence associated with earlier Kilauea rift eruptions such as in December 1974. (Compare fig. 17*A* with fig. 17*G*.) However, detailed examination of the horizontal deformation patterns for this period, August to October 1977, suggests that a component of seaward horizontal displacement was still present but largely obscured by the contraction accompanying subsidence. In particular, the southeasterly displacements on the north and west sides of the caldera were larger than complementary inward displacements on the south and east sides (fig. 17*G*), which suggests that some of the movement on the south and east sides was counterbalanced by opposing seaward movement.

The summit area of Kilauea began to reinflate by mid-October 1977, a pattern that continued until November 1979, when a brief east-rift eruption occurred. Trilateration measurements of the summit net indicate continued seaward mobility of the south flank as recently as fall 1980, largely independent of the vertical changes, in a pattern similar to that documented above for the entire period between the 1975 earthquake and the 1977 eruption. Clearly, the period of post-earthquake stabilization has been prolonged.

# DISCUSSION

Analysis of ground deformation data related to the 1975 earthquake has yielded several significant results: (1) the large size of ground movements, (2) supporting documentation for a gravitational slump or glide hypothesis for the main structural features of Kilauea's south flank, (3) insights into the cause of the earthquake and associated surface deformation, (4) evidence of the profound effect of the earthquake on the nature of subsequent deformation in the Kilauea summit area, and (5) implications for future seismic and volcanic hazards on the Island of Hawaii.

## SCALE OF MOVEMENTS

The scale of the extensional ground deformation related to the 1975 earthquake and associated normal faults was as much as 3.5 m vertically and 8 m horizontally on land, with a strong probability that even larger downdip displacements occurred below sea level. These are among the largest movements recorded in the United States that can be related to a single seismic event. By way of comparison with other major North American earthquakes, the 1906 San Francisco earthquake of magnitude 8.3 was associated with lateral movement of as much as 6.5 m along the San Andreas fault (Richter, 1958, p. 476–486). As much as 4.5 m of dominantly vertical movement occurred during the 7.1-magnitude Hebgen Lake earthquake in Montana in 1959 (Myers and Hamilton, 1964). Among 20th century American earthquakes, only the 1964 Alaska earthquake of magnitude-8.4+ caused greater earth movements than those observed in Hawaii in 1975, as much as 14 m vertically and 19.5 m horizontally (Plafker, 1969).

An important aspect of the deformation pattern related to the 1975 Kilauea earthquake is the distinct spatial separation between the epicenter, which marks initiation of the earthquake, and the region of maximum ground deformation, centered nearly 30 km farther west along the south coast. Strong-motion seismograms of the earthquake document at least 5 maxima of energy release over an interval of 65 seconds (Rojahn and Morrill, 1977, fig. 3A), and together with asymmetry of the deformation maxima, strongly indicate that the initial earthquake triggered a sequence of dislocations that migrated westward along the Hilina fault system.

## GRAVITATIONAL SLUMP HYPOTHESIS

The generally large ratios of horizontal to vertical displacement associated with the 1975 Kilauea earthquake strongly support a gravitational slump or block-glide interpretation, both for the deformation associated with this earthquake and also for the long-term tectonic evolution of the south flank of Kilauea. The hypothesis that the block-faulted terrain on the south flank may be due to "landsliding on a huge scale" goes back many years (Stearns and Macdonald, 1946, p. 130) and has more recently been argued persuasively (Moore and Krivoy, 1964; Fiske and Jackson, 1972). A recent comprehensive model for structural evolution of the south flank (Swanson and others, 1976a), based on 20th century seismic and ground-deformation studies, relates seaward displacement of the unbuttressed south flank of Kilauea to the result of forceful injection of magma into the rift zones. By this interpretation, gravitational instability of the south flank, which results from uplift and seaward displacement along the rift zones, is expected to be relieved intermittently by normal faulting and slumping along the Hilina fault system. Contractional strains were shown to have been accumulating within the south flank during the 20th century, destabilizing the Hilina fault system, and a possible subsidence event was anticipated "in the not too distant future" by Swanson, Duffield, and Fiske (1976a, p. 35). The 1975 earthquake occurred while their report was in press.

The patterns of ground breakage along the central Hilina fault system (fig. 3) and the leveling contours, showing maximum gradients of subsidence in the same area (figs. 9*C*, 15), offer convincing evidence that much of the earthquake-related deformation involved seaward gravitational slumping or block gliding. In detail, however, the geometry of displacement is more complex. The entire subaerial surface of Kilauea moved seaward, and the patterns of vertical deformation (fig.

9*C*) were significantly different from those of the horizontal deformation (fig. 15).

While the horizontal displacements show a relatively uniform seaward increase, with little or no reflection of the summit caldera, inflation center, or rift zones, the patterns of vertical movements reflect these primarily volcanic structures and apparently were much more influenced by movement of magma. The subsidence at the summit and along both rift zones is most readily accounted for by movement of magma into voids that opened during the earthquake. The volume of summit deflation, computed from the leveling data, was at least $68 \times 10^6$ m$^3$, about 270 times the volume of the lava erupted during the brief earthquake-induced caldera-floor eruption on November 29, 1975 (estimated at about $25 \times 10^4$ m$^3$; Tilling and others, 1976, p. 26).

The contrast in behavior between horizontal and vertical components of the deformation is well illustrated by contours of the ratios of horizontal to vertical components (fig. 18). Because the seaward increase in horizontal displacement is quite uniform, the contours of the ratios largely mimic the changes in vertical displacement (fig. 9*C*). Clearly evident are effects related to the summit subsidence, the axial troughs along both rift zones, and the positive upper part of the south flank. The ratio of horizontal to vertical changes is greatest at inland parts of the deformed area, where deformation was relatively slight, and the ratio generally decreases as the intensity of deformation increases.

Both the dominance of the horizontal component of movement over the vertical component, and the semi-independent behavior of the two components, suggest that the earthquake-induced deformation is related primarily to seaward movement along gently dipping master slip structures, with the vertical changes—on land at least—reflecting magmatic movements and jostling of the horizontally displaced mass along preexisting steeply dipping faults. If the primarily magma-related subsidences at the summit and along the rift zones are disregarded, three-dimensional displacement vectors, determined by combining the horizontal and vertical data, plunge gradually more steeply seaward, from horizontal on Mauna Loa to approximately 30° at the coastline. This pattern differs from simple models of block slumps, in which vectors would be steepest near the breakaway zone and would decrease gradually downslope to the toe of the slump. If, however, the main detachment zone for the 1975 deformation was along the Hilina fault system, as suggested by the areas of observed ground breakage, most of the primary slump structures may be underwater, with major deformation perhaps extending all the way to the base of the volcanic edifice at water depths of about 5000 m (fig. 1). The bulk of the subaerial deformation would, accordingly, reflect adjustments upslope of the primary slump feature. The large area affected and the relatively smooth gradients of horizontal deformation (and also vertical changes, if features related to movement of magma are neglected: see fig. 10) are a qualitative measure of the lack of rigidity and delicate balance of most of the volcanic edifice.

Both the main 1975 earthquake and most aftershocks were at depths of 5–10 km beneath the south flank, close to the basal contact of the volcano on the Pacific sea floor. This geometry suggests that the block slumping involved nearly the entire thickness of the volcanic edifice, with much of the lateral movement possibly accommodated within originally poorly consolidated submarine rubble, formed low on Kilauea's south flank during early stages of its growth. Fragmental submarine volcanic deposits have been interpreted as significant to the structural evolution of Hawaiian volcanoes by Moore and Fiske (1969), Swanson, Duffield, and Fiske (1976a), and Nakamura (1980).

Step topography, similar in geometry to the Hilina fault system, is present on submarine slopes of the south flank (fig. 1), and a prominent bulge low on the submarine slope may be a reflection of the toe of the slump structure (fig. 19). The sparcity of post-earthquake seismicity on lower parts of Kilauea's south flank (fig. 2) suggests that this area—especially the submarine flank—is structurally incompetent, and that major stress accumulations occur mainly close to the rift zones.

## RELATION BETWEEN THE EARTHQUAKE AND SURFACE DEFORMATION

An incompletely resolved problem is the relation between the cause of the earthquake and the deformation patterns observed at the surface. Was the earthquake a direct reflection of catastrophic failure along the Hilina system, along which large displacements are observed, or is the deformation observed at the surface a relatively superficial second-order reflection of gravitational slumping, fundamentally different from deformation processes associated with the observed seismicity deeper within the volcano?

Teleseismic focal-mechanism studies and analysis of other seismic parameters indicate that initial failure during the 1975 earthquake occurred along a fault plane striking approximately N. 70° E. and dipping gently. Solutions for dip angle, vary from about 20° southeast (Ando, 1979), to 4° northwest (Furumoto and Kovach, 1979), but regardless of the exact dip, motion of the upper block is seaward (to the southeast). Determinations of focal mechanisms from the detailed local seismic network on the Island of Hawaii also favor a low-angle

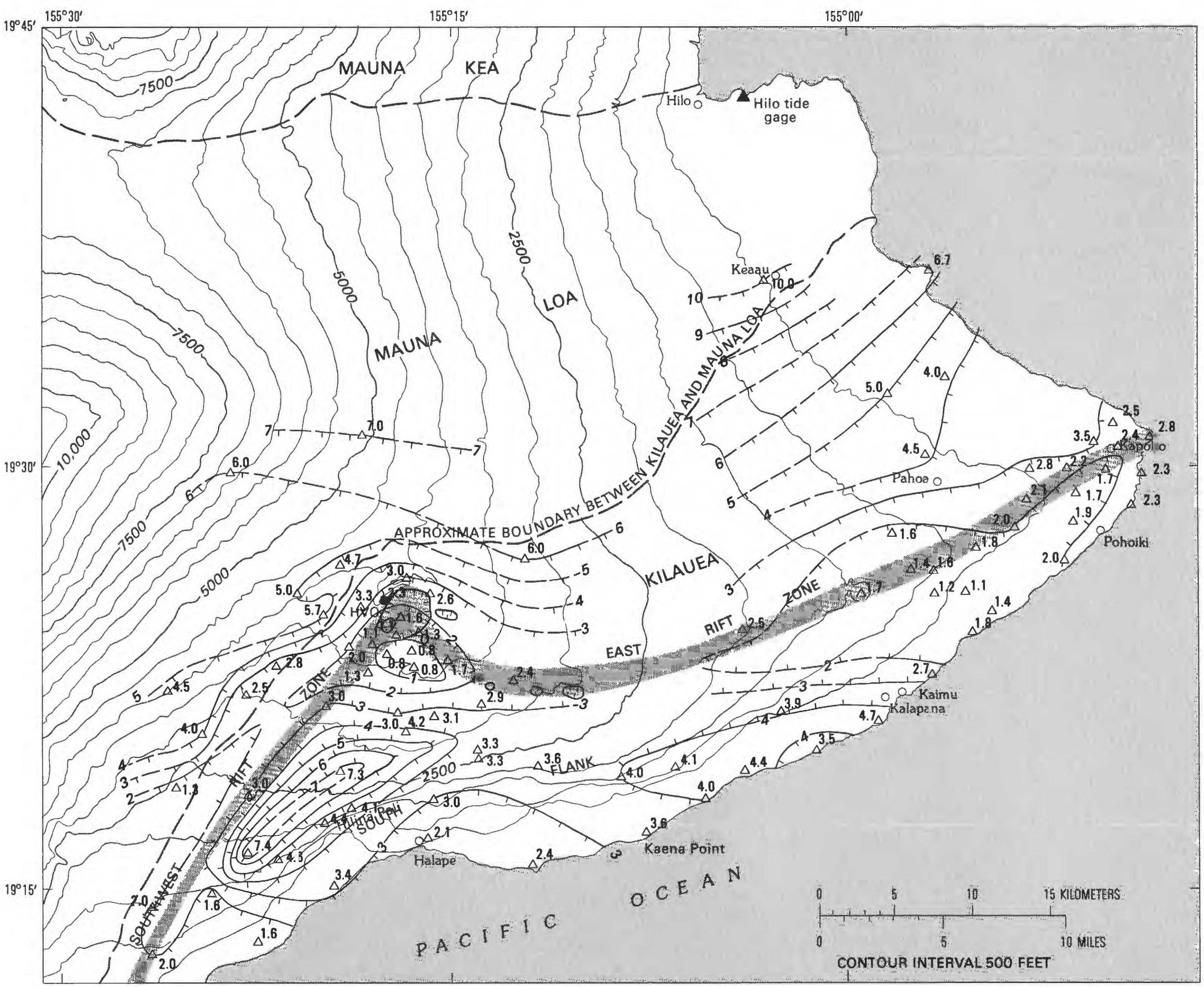



FIGURE 18.—Contours of the ratio of horizontal to vertical displacement between 1974 and 1976. Data from interpretative maps of figures 9C and 13. The summit caldera area and rift zones are patterned. Gaps in contours are areas for which displacement data are lacking, mainly because of heavy vegetation. Hachured contours indicate direction of decrease in ratios of displacement data.

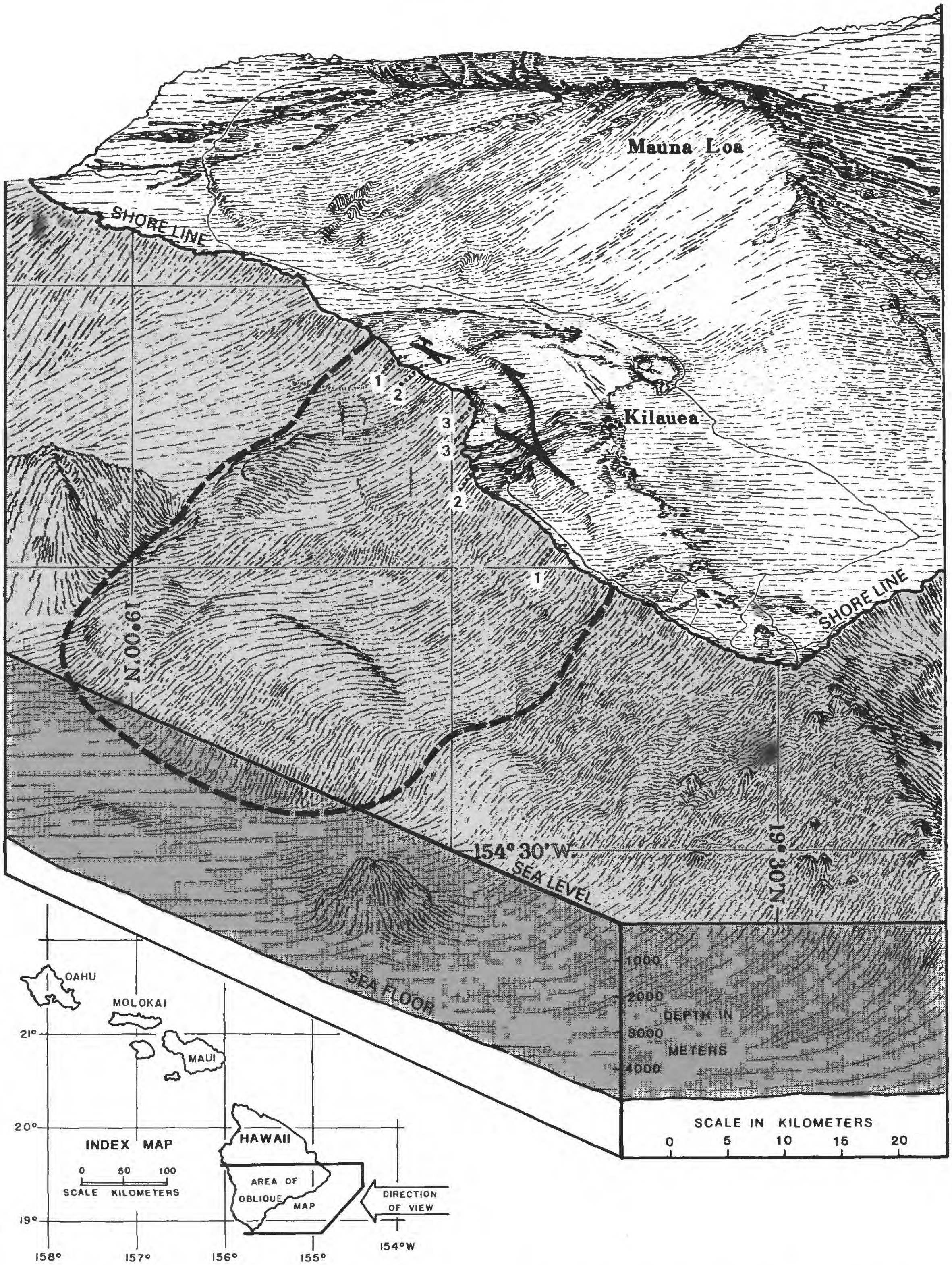



FIGURE 19.—Oblique map of the south half of the island of Hawaii, as viewed from the east, showing marine topography. Physiographic drawing by Tau Rho Alpha (1977). Heavy solid lines define new faulting related to the 1975 earthquake, dashed line indicates possible boundary of the submarine slump terrane, and numbers along coastline give amount of measured subsidence on transects marked by dotted lines.

normal fault solution, dipping gently seaward (Crosson and Endo, 1981; Wyss and others, 1981), although the interpretation is strongly model dependent.

These relations have led to a deformation model, accepted with only minor variations in all these seismic studies, in which the major dislocation is along a gently dipping master fault at a depth of 8–10 km, near the base of Kilauea Volcano, that permits the south flank to move seaward and release compressional strain acummulated during injection of dikes along the rift zones. Deformation along the Hilina system is interpreted as secondary gravitational slump features, bottoming at 2–3 km depth and triggered by movements along the deeper low-angle fault (Ando, 1979; Wyss and others, 1981), or disregarded entirely (Furumoto and Kovach, 1979).

Various structural, geodetic, and seismic features suggest to us, however, that the Hilina fault system and its associated gravitational slump structures penetrate a large part, perhaps the entire thickness, of the south flank of Kilauea Volcano and flatten at a depth of 6–8 km to accommodate seaward displacement of the lower south flank (fig. 20). The best evidence that faults of the Hilina system penetrate deeply comes from the concentration of earthquakes along the upper part of the south flank (fig. 2; also Koyanagi and others, 1972; Wyss and others, 1981, fig. 10). Earthquakes as deep as 7–8 km are strikingly concentrated in a 10-km-deep volume bounded by the rift zones and the Hilina system; this pattern has been quite consistent since a seismic net sufficiently detailed for accurate epicentral locations was established in the middle 1960's. The region seaward of the bounding Hilina faults has been characterized by much lower levels of seismic activity, probably reflecting lower strengths of rocks within the block-faulted area. Even after the 1975 earthquake, aftershocks were sparse in the region seaward of the main Hilina faults where the ground deformation was most intense. Whatever the cause for the contrast in seismicity across the Hilina fault system, these structures seemingly constitute a major structural control on seismicity, extending through much of the edifice of Kilauea volcano.

The Hilina system and the area to the south clearly accomodated major deformation in 1975, as indicated by the horizontal and vertical displacements documented in this report (figs. 9, 13) and by the geometry of the associated tsunami, which required uplift of a large portion of the submarine south flank of Kilauea (Hatori, 1976). The location and area interpreted by Hatori (1976, fig. 2) for the source of the tsunami coincide closely with the submarine slump terrain on the south flank of Kilauea (figs. 1, 19), and his estimate of the required deformation (1 m of uplift for an area of 2,200 $km^2$ of sea floor) is approximated by the subaerial volume changes on Kilauea. We estimate these changes as an average of 1 m of subsidence over an area of about 1,000 $km^2$ (figs. 9*C*, 19)—$1\times10^9$ $m^3$, plus an average of 3 m seaward displacement along 40 km of coastline (fig. 13) to a depth of 8 km (the base of the volcano)—$0.96\times10^9$ $m^3$, or a total of about $2\times10^9$ $m^3$.

A relatively deep sole to the gravitational slump blocks of the Hilina system is also indicated by the listric geometry of the faults, which are wedge-shaped and curved in plan view but all dip steeply (70°–90°) at the surface. Large displacements along curved normal faults of listric geometry tend to preserve a relation in which bedding remains approximately perpendicular to the fault plane (Anderson, 1971; Proffett, 1977). Relatively old basalt flows of the Kahuku Volcanics (>20,000 years before present: Kelley and others, 1979), which normally dip 3°–5° away from the summit of Kilauea (Stearns and Macdonald, 1946, pl. 1), mostly dip subhorizontally to a few degrees seaward where exposed in scarps of Hilina faults, which indicates only limited back rotation. Ponding of lava flows and closed depressions near bases of some fault scarps indicate local back tilting (Swanson and others, 1976a, fig. 22), but the generally limited tilting requires that any curvature present along Hilina faults must penetrate deeply. The limited tilting along the Hilina fault blocks also demonstrate a style of deformation somewhat transitional between block slumping (rotation significant) and block gliding (rotation limited or absent).

The main fault along the lava-draped Hilina Pali has a displacement of at least 500 m, the height of the present topographic scarp; this amount of offset along a curved fault plane flattening at depth of only 3 km, as assumed by Wyss, Klein, and Johnston (1981), would produce 9.5° rotation of bedding. These considerations strongly suggest that upper parts of Hilina faults have steep average dips, probably in the range of 60°–80°, similar to many measurements on actual fault surfaces and open cracks along the Hilina system (Easton, 1978); dips as low as 35° on some small Hilina faults and cracks are adjacent to steep scarps and are likely related to surficial sliding. The broadly arcuate planimetric traces of the individual fault scarps, extending as much as 20 km along strike and with radii of curvature of 10–15 km, also qualitatively suggest relatively deep penetration to a master sole fault.

In light of these considerations, the initial rupture of the 1975 earthquake could have occurred along a fault of the Hilina system that flattened from near vertical at the surface to about 20° at a depth of about $6\pm1$ km, the depth and dip indicated by focal-mechanism determinations. The hypocenter is about 2

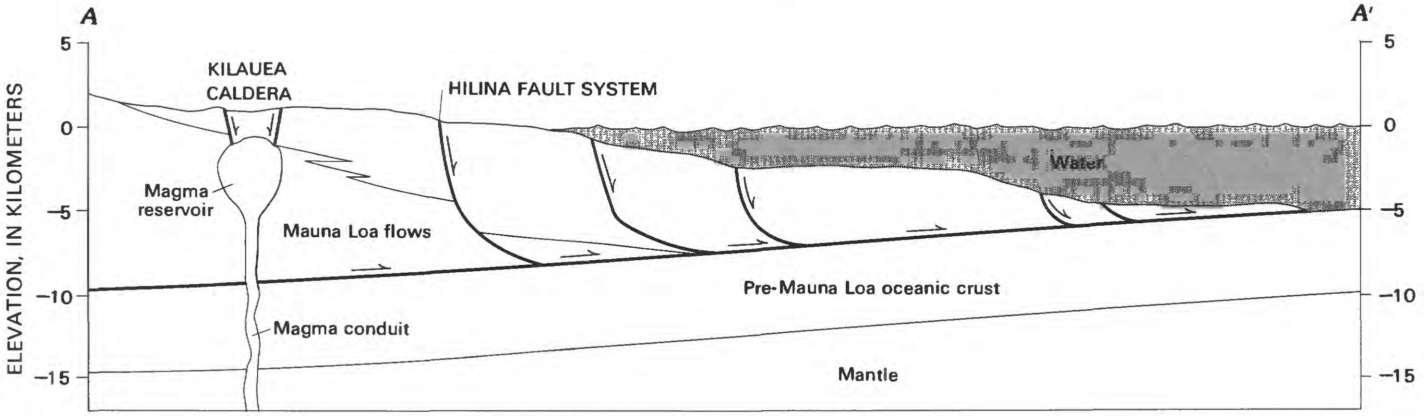



FIGURE 20.—Diagrammatic cross section, with no vertical exaggeration, through the summit region and south flank of Kilauea. Location of section shown in figure 1. Thickness and dip of pre-Mauna Loa oceanic crust are from Hill (1969) and Zucca and Hill (1979).

km south of the main Hilina fault along this sector of the south flank and would lie along the downward projection of this fault if the average dip is about 70°. If the epicentral depth is correct, the main shock may have occurred deep within the edifice of Kilauea Volcano, rather than along its basal contact with old sea floor, at a depth of approximately $9 \pm 1$ km at this site as indicated by seismic refraction data (Hill, 1969; Zucca and Hill, 1979).

Whether the initial rupture of the 1975 earthquake occurred along some such gently dipping deep part of a Hilina fault, or within the margin of the adjacent more structurally coherent upper part of the south flank, the rupture clearly propagated rapidly westward, causing major failure along the Hilina system. This failure and the associated subsidence occurred largely within a minute or so of the beginning of the earthquake, as indicated by observations of initially slowly rising water by beach campers, prior to arrival of the first tsunami wave (Tilling and others, 1976, p. 2). The coastal subsidence could not have been primarily a secondary adjustment over a period of weeks following the earthquake, as suggested by Furumoto and Kovach (1979, p. 207). The horizontal and vertical displacements, increasing seaward, define a coherent pattern that clearly continued below sea level, with the sense of vertical displacement reversing, as indicated by analysis of the tsunami (Hatori, 1976).

By our interpretation (fig. 21), the seaward and downward movements of the adjacent parts of Kilauea, inland of the Hilina fault system, reflect adjustment to decreased support from the seaward flank, plus magma-related movements in the summit region and along the rift zones. The displacement of the lower south flank was sufficiently large to stabilize this part of the Kilauea edifice. From late 1975 to 1977, the upper south flank, now less supported from the south, continued to deform slowly seaward in a pattern much like that during the earthquake, as indicated by displacements within the summit trilateration net (figs. 17*C*–*F*) and by continued seismicity on the upper south flank at rates higher than typical for Hawaiian aftershock sequences (Tilling and others, 1976, fig. 5). In contrast to relations at many major earthquakes, aftershocks of the 1975 event thus do not define the fault plane responsible for the associated ground deformation, which is at a maximum seaward of the bounding faults of the Hilina system.

We are uncertain what features account for the contrasting structural behavior of the relatively immobile but seismically active upper part of the south flank versus the mobile but seismically inactive lower part. Large-scale gravitational slump structures occur widely on Hawaiian volcanoes, largely on the submarine slopes (Moore, 1964; Normark and others, 1979). Could the boundary between gravitationally stable and unstable regions on these volcanoes be related to thermal gradients away from the summit areas and rift zones, which results in contrasts between a thermally dehydrated central region and flanking areas of cooler lavas that have reduced frictional coefficients because of saturation by seawater? Whatever the fundamental cause, the boundary between the upper and lower parts of the south flank is a major structural feature of Kilauea Volcano.

An equally speculative question involves the possible role of Mauna Loa in destabilizing Kilauea and triggering the 1975 earthquake. The earthquake occurred essentially concurrently with the first significant seismic and volcanic activity on Mauna Loa in 25 years, culminating in the July 1975 summit eruption (Lockwood and others, 1976), and magma-related deformation of a large region of Mauna Loa was seemingly indicated by the instability of the baseline stations for the Kilauea summit trilateration net during 1974–76. Could inflation of Mauna Loa have exerted a destabilizing in-

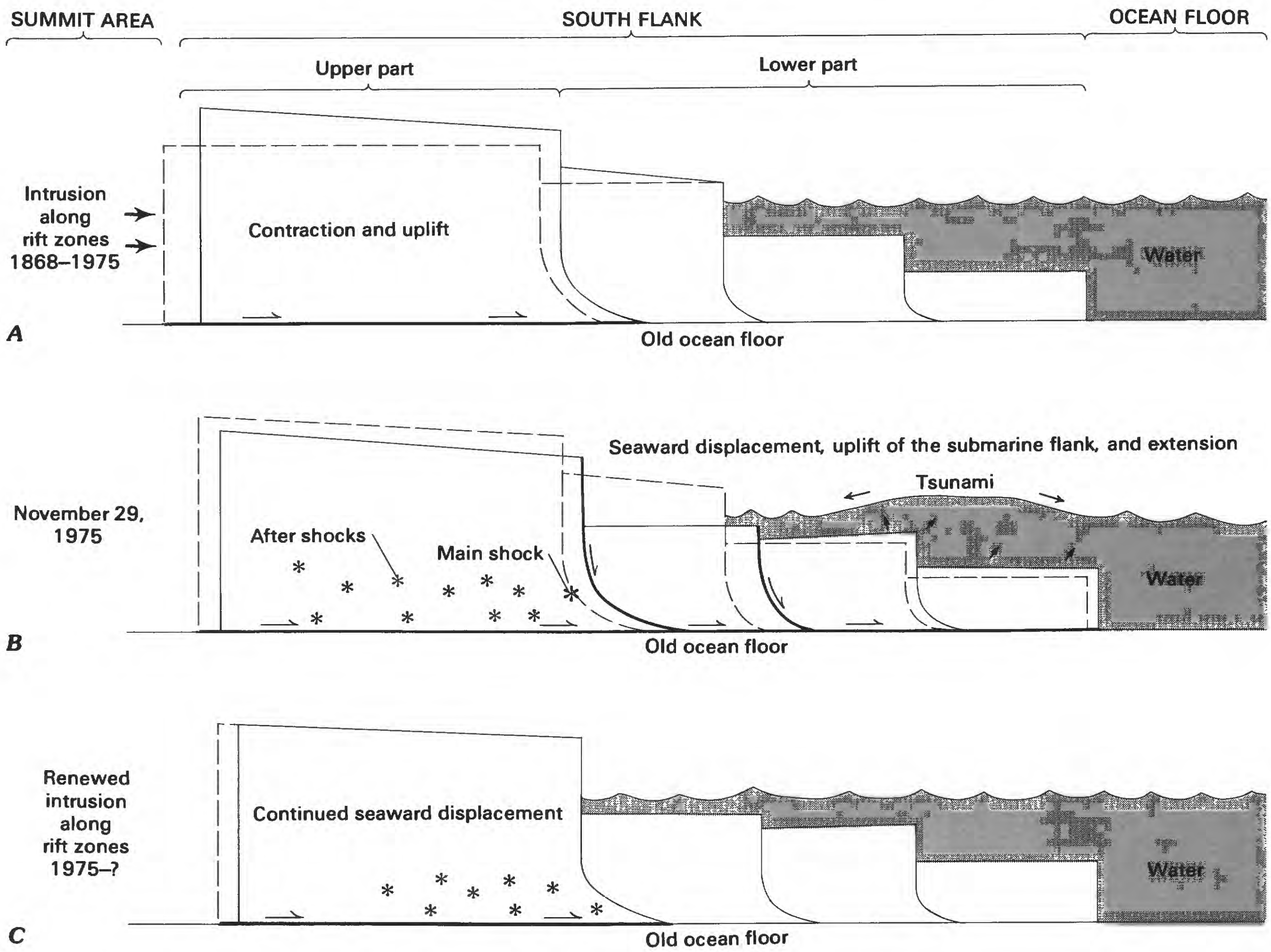



FIGURE 21.—Interpretation of relations between seismicity and deformation within the south flank of Kilauea, associated with the 1975 earthquake. Dashed lines are former positions of moved blocks. No scale.

*A*. Twentieth-century intrusion in the summit region and emplacement of dikes along the rift zones wedge the upper part of the south flank seaward and upward. Contractional strain accumulates within this block, and seismicity is concentrated at depths of 5–10 km within its lower parts.

*B*. In November 1975, accumulated strain within the upper part of the south flank causes failure and seaward displacement along its southern margin, perhaps along the gently dipping lower part of a Hilina fault that marks the boundary between upper and lower parts of the south flank. Displacements increase seaward, and the maximum displacements occur along faults of the Hilina system, which extend through the south flank of Kilauea to merge with the zone of adjustment at the base of the volcano. Uplift of the submarine flank along the toes of the Hilina faults causes a major tsunami. The smaller displacements in upper parts of the south flank and farther landward on Kilauea largely represent second-order adjustments to failure along the Hilina system.

*C*. Since 1975, regeneration of magmatic pressures in the summit area continues to displace the upper part of the south flank, which is less buttressed on its seaward side as a result of the earthquake-related movements. As a result, the upper south flank continues to deform in a seaward direction at gradually diminishing rates for several years after the 1975 earthquake, accompanied by high levels of aftershock activity.

fluence on an already delicately balanced Kilauea edifice? The plausibility of this possibility is enhanced by comparisons with events in 1868, the time of the last similarly large historic earthquake on the Island of Hawaii. The 1868 earthquake, of magnitude about 7.5–8.0, occurred one week after a Mauna Loa summit eruption and during a time of marked change in eruptive behavior of this volcano (Lipman, 1980). The earthquake was associated with major deformation on the south side of Mauna Loa (Wood, 1914, p. 196–199), including several meters of offset along the Waiohinu fault, near the south coast. It also caused as much as 2.1 m of subsidence and a devastating tsunami along the south flank of Kilauea.

In addition to recording the response of an oceanic basaltic volcano to stressing of its flanks by dike intrusion and loading of its slopes by lava accumulation, the deformation associated with the 1975 Kilauea earthquake has significance for other tectonic environments. The geometry of the deformed south flank of Kilauea (fig. 20) is strikingly similiar to that currently inferred for large-scale thrust and fold belts on the cratonic sides of Cordilleran tectonic regimes. For example, just as on the south flank of Kilauea, the Cordilleran foreland in the southern Canadian Rocky Mountains has been interpreted as an allochthonous wedge that has been thrust up along gently dipping regional basal detachment faults, as a consequence of lateral gravitational spreading under its own weight down a regional surface slope with more than 20 km of structural relief (Price and Montjoy, 1970; Price, 1981). Although gravitational spreading in the Canadian Rockies is thought to have been caused by buoyant upwelling of a hot metamorphic core and associated magmatic rocks, in contrast to the stressing of the Kilauea rift zones by dike intrusion, geometric relations are similar in the two regions. Thus, active deformation of the Kilauea south flank may provide an intermediate-scale model for interpretation of large thrust faults in Cordilleran tectonic belts.

## EFFECT ON THE SUMMIT MAGMA SYSTEM

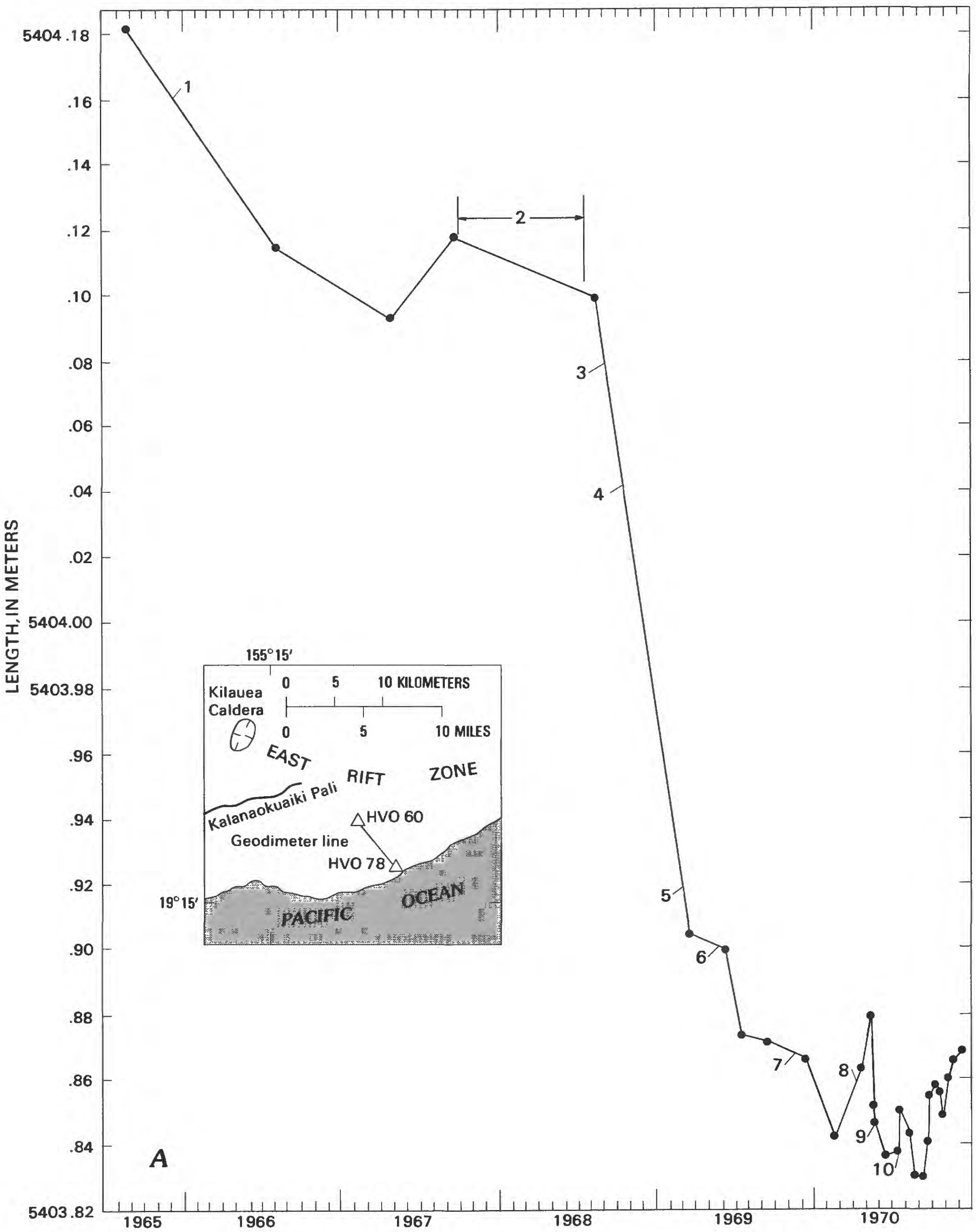
The summit deformation pattern at Kilauea subsequent to the earthquake (figs. 17*D–G*) clearly demonstrates that the 1975 earthquake and associated ground displacements caused long-term disruptions in the magmatic conduit system of the volcano. Prior to 1975, summit ground deformation was dominated by inflation-deflation events related to a magma reservoir centered near the south margin of the caldera. Inflation was reflected by uplift and a pattern of outward-radiating vectors of horizontal displacement; whereas, deflation and subsidence were associated with a pattern of inward-converging vectors, all confocal at nearly the same center. Since 1975, one major effect has been a decoupling of horizontal and vertical components of displacement. Vertical changes have continued to reflect magmatic movements in the summit region, and they show relatively small changes, both positive and negative, in a pattern generally confocal with pre-earthquake changes. In contrast, horizontal displacements have documented continued southward displacement of the summit area, with amounts of displacement increasing seaward. This pattern essentially represents a continuation, at a reduced rate, of the same style of deformation as occurred during the earthquake period. The net effect appears to have been to keep the upper east rift zone open for intrusion of magma and, simultaneously, to have impeded magmatic inflation of the summit area.

## IMPLICATIONS FOR THE FUTURE

The 1975 earthquake and accompanying activity represent the latest events in a recurring pattern of behavior for Kilauea. A large earthquake of about the same magnitude, with associated coastal subsidence, tsunami, and eruption, occurred at Mauna Loa and Kilauea in 1868, and a less powerful earthquake and similar related events are believed to have occurred in 1823. The deformation associated with the 1975 earthquake had a geometry appropriate for formation of the large scarps and palis of the Hilina fault system, and this event is almost certainly the latest in a series of many similar episodes that have formed the present palis. The subaerial Hilina system has about a kilometer of structural relief, which suggests that approximately 1000 events of the magnitude of the 1975 earthquake may have occurred, perhaps at a tempo suggested by the earthquakes and associated subsidence events of 1823(?), 1868, and 1975. As long as Kilauea remains active, gravitational and magma-induced stresses will inexorably accumulate, and the mobile south flank will shift seaward and downward episodically and abruptly, providing stress relief. Then the cycle will begin anew.

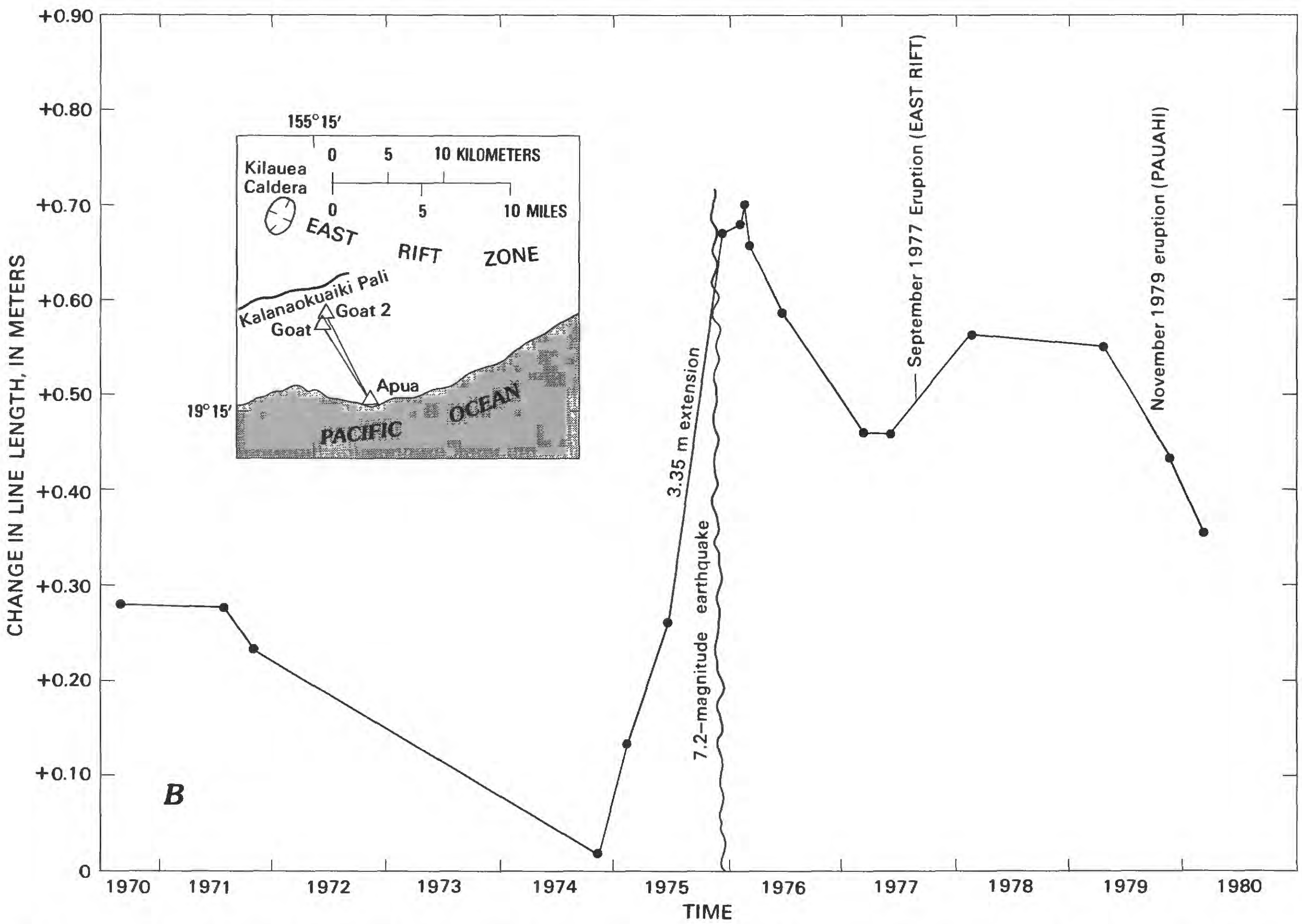
How may we tell when to anticipate another such event? One approach would be to search for seismic precursors, as has been attemped by Johnston (1978) in connection with the 1975 earthquake. Johnston recognized compressional-velocity decreases at the nearest seismometer station to the epicentral area, beginning about 3.5 years prior to the earthquake. In addition, much information may come from ground-deformation studies. The 1975 events were preceded by accumulation of contractional strain on Kilauea's south flank throughout the 20th century (Swanson and others, 1976a, fig. 5), and many years of such strain accumulation is probably a necessary prerequisite for a major subsidence event. Advance warning of a subsidence event may be, accordingly, decipherable from changes in strain rates. For example, Swanson, Duffield, and Fiske (1976a, p. 16) noted that strain along a frequently measured 5.4-km-long line normal to the south flank of Kilauea, which consistently contracted during the late 1960's, experienced alternate periods of extension and contraction in the early 1970's related to east rift magmatism and to nearby earthquakes (fig. 22*A*; Swanson and others, 1976a, p. 16). Unfortunately, the bench mark at one end of this line was covered by new lava flows early in 1971, ending the measurements.

Another line to the south coast, although occupied relatively infrequently, showed contraction until about a year before the 1975 earthquake (fig. 22*B*). Extension during this last period may have been signaling that the south flank was strained to a point that further contraction was not possible—and a subsidence event




*A*. Contraction of 5.4-km-long Geodimeter line (upper right inset) on south flank of Kilauea between August 1965 and early December 1970. Major magmatic and structural events are (1) December 1965 eruption and ground cracking, (2) November 1967–July 1968 summit eruption, (3) August 1968 eruption, (4) October 1968 eruption, (5) February 1969 eruption, (6) beginning of May 1969–October 1971 Mauna Ulu eruption, (7) new fissure north of Alae Crater, December 1969, (8) new fissure and cracks in and west of Aloi Crater, April 1970, (9) intrusion and cracking in southern part of Kilauea Caldera, May 1970, (10) new fissure east of Mauna Ulu, July 1970 (from Swanson and others, 1976a, fig. 10).

FIGURE 22.—CHANGES IN LENGTH OF TWO GEODIMETER LINES ACROSS THE SOUTH FLANK OF KILAUEA, 1970–77




*B.* Changes in length of line between Apua Point and Goat or Goat 2 stations. Observations until 1974 are to Goat station; subsequent measurements are to Goat 2.

FIGURE 22.—CHANGES IN LENGTH OF TWO GEODIMETER LINES ACROSS THE SOUTH FLANK OF KILAUEA, 1970–77—Continued

was imminent. Since the 1975 earthquake, this line has shown steady contraction, interupted only by the period encompassing the September 1977 eruption, which indicates that strain is again accumulating along the south flank.

A similar change in strain pattern is indicated by fragmentary data for the upper south flank. A 5.1-km-long Geodimeter line between Puu Huluhulu and Goat 2 (fig. 11), first established in 1974, has shown extension for every subsequent occupation, including the pre-earthquake interval October 1974 to January 1975, indicating continued seaward movement of Goat 2 relative to Puu Huluhulu. In contrast, displacement solutions of the Kilauea flank net suggest that this line contracted about 25 cm between October 1970 and October 1974. Thus, this area, like the two Geodimeter lines shown in figure 20, also changed from a contractional to extensional strain regime prior to the 1975 earthquake.

Much might be learned about the stability of the south flank by establishing a chain of short frequently measured lines or triangles normal to the south coast, which would permit locating and monitoring the boundary between domains of extensional and contractional strain. Since the earthquake, this boundary appears to be relatively low on the south flank, as indicated in the summit area by the increasing size of displacements toward the coastline (figs. 17*D–E*). In the future this boundary can be expected to migrate northward, as the south flank and southern part of the summit area stabilize further, and as a typical pre-1975 pattern of confocal horizontal and vertical deformation becomes reestablished in the summit area. When the accumulated compressive strain on the south flank exceeds some presently unknown level, however, destablization similar to that during 1970–75 (fig. 22*B*) should be reflected by a reversal in strain pattern and seaward migration of the compensation boundary. A major gravitational slump event could then be expected in the near future.

A concluding caution, however: only a small portion of the diverse eruptive behavior of Kilauea Volcano indicated by the geologic record has actually been observed during the relatively short period of recorded history, beginning only with observations by the missionaries in the early 19th century. Unknown to us are the premonitory patterns of magmatic behavior—with associated ground deformation and seismicicity—leading up to such major events as (1) caldera collapse, which appears to have occurred at Kilauea several times in the past thousand years or so (Holcomb, 1979), (2) large-scale phreatomagmatic activity, such as apparently occurred in 1790 (Christiansen, 1979) and at least twice more in the preceding 2,000 years (Kelley and others, 1979, p. 318–319), or (3) the long-continued summit overflow and rift eruptions of tube-fed pahoehoe that appear to have covered nearly the entire surface of Kilauea in late prehistoric time, probably largely in the 17th and 18th centuries (Holcomb, 1979). Future studies may be expected to document patterns of ground deformation and other geophysical changes at Kilauea related to events such as these, that we can only dimly anticipate from present experience.

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