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CHANGED MAGMA BUDGET SINCE 1975 AT KILAUEA VOLCANO, HAWAII

By

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ABSTRACT

The pattern of subsurface magma movements within Kilauea volcano was dramatically altered by a M = 7.2 earthquake in November 1975. Since the earthquake, Kilauea's summit magma reservoir has repeatedly fed intrusions into the volcano's east rift zone, while dilation has increased the rift zone's magma storage capacity and reduced the frequency of eruptions. The interval October 1977-August 1980 was characterized by a continuing pattern of east rift intrusions punctuated by one small-volume eruption in November 1979.

A newly-developed technique for calculating magma supply to the summit and rift zone magma reservoirs is based solely on summit tilt changes recorded at Uwekahuna Vault. Results indicate that summit magma storage increased by roughly 35 X 10^6 m^3 during October 1977-August 1980, while east rift storage increased by at least 140 X 10^6 m^3. This suggests a minimum rate of magma supply to Kilauea during this interval of 5.0 X 10^6 m^3/month. A specific comparison of total supply rate to Kilauea for two periods of oscillatory summit tilting yields 10.9 X 10^6 m^3/month during 24 May-31 December 1969, and 5.0 X 10^6 m^3/month during 1 March-31 August 1980. A similar comparison of longer and admittedly more complex intervals yields minimum estimates of 7.9 X 10^6 m^3/month during July 1956-December 1975, and 4.9 X 10^6 m^3/month during January 1976-August 1980. Combined with several independent calculations by other authors of 6-12 X 10^6 m^3/month supply during 1952-75, our results indicate that the apparent magma supply rate to Kilauea has diminished by roughly 40% since 1975.

However, the seismic energy content of sporadic harmonic tremor originating from Kilauea's inferred magma source region in the upper mantle shows no corresponding decrease, but rather suggests that the rate of magma generation at depth has been essentially constant since 1962. We therefore interpret the apparent decrease in near-surface supply as a change in the partitioning of newly-delivered magma between various subsurface storage reservoirs. One explanation for the apparent decrease in magma supply is that the November 1975 earthquake caused new leaks to develop in Kilauea's near-surface plumbing system, so that proportionally more magma now escapes geodetic detection. Alternatively, the earthquake may have temporarily disrupted feeding conduits from depth, or altered the volcano's geodetic response to near-surface magma accumulation. The latter possibility is suggested by increased rates of horizontal ground deformation relative to vertical deformation since the earthquake. Another intriguing possibility is that part of Kilauea's former supply may now be tapped by neighboring Mauna Loa volcano, which ended 25 years of quiescence with a small eruption in July 1975 followed by continuing summit inflation.

Lack of a unique interpretation for the apparent decrease in magma supply since 1975 makes it impossible to uniquely specify the most likely course of events at Kilauea during the next few years. Increased magma storage capacity along the east rift zone simultaneously decreases the likelihood of frequent small near-summit eruptions and increases the likelihood of infrequent large flank eruptions. Subject to this qualification, a conservative extrapolation of events during 1975-80 favors relative quiescence with frequent intrusions seldom culminating in eruptions. However, should a vent develop along Kilauea's middle or lower east rift zone, the potential exists for a sustained, high-volume eruption comparable in magnitude to the largest events in Kilauea's recorded history.

INTRODUCTION

Purpose and Scope

Our intent here is two-fold. First, in order to document activity at Kilauea volcano during October 1977-August 1980, we present results from a battery of geophysical monitoring techniques applied routinely at the Hawaiian Volcano Observatory. We have chosen to focus on the interval beginning immediately after the September 1977 eruption at Kilauea and ending with an intrusion into the volcano's east rift zone on 27 August 1980. This period included only one small-volume eruption in November 1979, but was characterized by repeated intrusions into Kilauea's east rift zone. Intrusions which do not culminate in eruptions have become increasingly common at Kilauea since a M = 7.2 earthquake struck the volcano's southeastern flank on 29 November 1975.

After documenting the continuing sequence of intrusions into Kilauea's east rift zone, we present a quantitative assessment of the volcano's magma budget since 1956. The term "magma budget" was used by Dzurisin and others (1980) to describe the quantitative balance between magma sources and sinks which must exist if an active volcano forms a closed system for magma production and transport. An ideal magma budget should specify the rate of magma production at depth (i.e., source) and the rates of accumulation in all intermediate residence points between the source region and ultimate cooling sites for new magma (i.e., sinks). In practical terms, this generally translates into specifying the net rate of magma supply from depth and the partitioning of newly-produced magma between surface extrusion, permanent intrusion, and temporary storage in one or more subsurface reservoirs. At Kilauea, such reservoirs are inferred to exist beneath the summit region and along the volcano's east rift zone. This paper is thus an extension of work by Dzurisin and others (1980), who proposed a quantitative magma budget for Kilauea based on an analysis of magma supply and storage during November 1975-September 1977.

Geologic Setting

Kilauea is an active basaltic shield volcano nestled against the southeastern flank of larger Mauna Loa volcano on the island of Hawaii (Figure 1). Salient features of Kilauea's subsurface structure and dynamics have been described in detail by earlier authors (e.g., Eaton and Murata, 1960; Eaton, 1962). Kilauea eruptions generally occur within a 3 X 5 km summit caldera or along prominent rift zones radiating eastward and southwestward from the summit. Seismic and ground deformation studies indicate that eruptions are fed from an intermediate magma storage reservoir 2-4 km beneath the caldera (Koyanagi and others, 1974), which in turn is supplied with magma from a zone of partial melting in the upper mantle (Eaton, 1962). Prior to most rift zone eruptions, a pattern of migrating seismicity and ground deformation indicates lateral transport of magma from the summit storage reservoir to the eventual eruption site via shallow rift zone conduits. The existence of subsidiary magma storage reservoirs within Kilauea's east rift zone has been inferred from ground deformation studies (Jackson and others, 1975; Swanson and others, 1976), from the petrology of east rift lavas (Wright and Fiske, 1971), and from the pattern of recent eruptions and intrusions (Dzurisin and others, 1980).

Figure 1 near here

In language appropriate to the calculation of a magma budget for Kilauea, an upper mantle "source" supplies magma at a rate balanced by available "sinks," including: 1) shallow summit storage, 2) shallow rift zone storage or permanent intrusion, and 3) surface extrusion. Evidence from a variety of sources suggests that the rate of magma supply to Kilauea from its mantle source was roughly constant during 1952-75 (Swanson, 1972; Dzurisin and others, 1980; Dvorak and Dieterich, 1981; Duffield and Christiansen, 1981). Since the November 1975 earthquake, however, the ratio of subsurface storage to surface extrusion has increased markedly, owing to frequent ruptures of the summit storage reservoir and ensuing intrusions into an enlarged reservoir within the east rift zone. Our quantitative analysis of Kilauea's magma budget is an attempt to explain this new pattern of shallow magma storage involving the summit region, east rift zone, and perhaps neighboring Mauna Loa volcano.

Background: Effects of the November 1975 Earthquake

The November 1975 M = 7.2 earthquake beneath the southeastern flank of Kilauea triggered a small-volume eruption on the floor of Kilauea caldera and within its central pit crater Halemaumau (Tilling and others, 1976). The volume of magma erupted was clearly only a small fraction of that which drained from summit storage, however, as evidenced by the second-largest summit deflation recorded at Kilauea since modern tilt measurements began there in 1956. Although masked in large part by an intense aftershock sequence, earthquakes along the volcano's east and southwest rift zones probably recorded the arrival of magma which had previously resided in summit storage. Later analysis of the regional deformation network at Kilauea revealed that the entire volcanic edifice moved differentially southeastward during the earthquake (Lipman and others, 1981). Ground displacements were most pronounced along Hawaii's southeastern coast, where movements as large as 8.8 m southeastward and 3.2 m downward were recorded. Vertical and horizontal movements generally decreased northward, but extended across Kilauea's east rift zone and onto the flank of neighboring Mauna Loa. Differential horizontal movement across the rift zone continued for several years after the November 1975 earthquake, and has resulted in more than one meter of accumulated extension across parts of the rift.

In addition to its immediate effects on Kilauea, the November 1975 earthquake substantially altered the volcano's patterns of seismic strain release and surface deformation. Prior to the M=7.2 earthquake, most Kilauea earthquakes occurred beneath the summit region or along the rift zones, presumably in direct response to magma movements into those areas. In addition to continuing seismicity from these traditionally active areas, the south flank of Kilauea has been notably more active since 1975. South flank seismicity has been more prolonged than would be expected from a typical aftershock sequence, suggesting a longer term change in the volcano's response to stress. This is most likely a reflection of continuing south flank mobility in response to gravitational and magma-related stresses caused by intrusions into the east rift zone.

This interpretation is also consistent with a distinct change in the pattern of surface deformation at Kilauea since 1975. Prior to the earthquake, horizontal and vertical deformation patterns in the summit region were typically symmetric, as the surface flexed in response to inflation or deflation of the summit magma reservoir. For more than a year following the earthquake, however, typical inflation/deflation cycles at Kilauea were largely masked by continuing seaward movement of the volcano's south flank (Lipman and others, 1981).

Finally, these seismic and deformation changes are symptomatic of a profound change in the pattern of magma movements within Kilauea. During the interval November 1975-September 1977, a single eruption along Kilauea's east rift zone was preceded by at least four distinct intrusions, as space created by earthquake-related rift zone dilation was filled with magma from the summit reservoir (Dzurisin and others, 1980). Although similar intrusions had occurred before 1975, the ratio of intrusions to eruptions increased from roughly 1:2 during 1960-75 to 4:1 during 1976-80. If we consider only the 20 events bracketing the November 1975 earthquake the intrusion/eruption ratio switched from 1:4 before the earthquake to 4:1 in favor of intrusions afterward (Table 1 of Klein, 1981). With the resumption of eruptive activity in September 1977, there was cause to believe that wounds inflicted on Kilauea by the 1975 earthquake had finally healed and that a return to more typical behavior was imminent (Dzurisin and others, 1980). Recent events argue to the contrary, suggesting that Kilauea's recovery will be a longer-term process than earlier anticipated.

CHRONOLOGY: OCTOBER 1977-AUGUST 1980

October 1977-September 1978: Summit and East Rift Inflation

The chronology of the September 1977 eruption along Kilauea's middle east rift zone has been described in detail by Moore and others (1980). Immediately following the eruption, the Kilauea summit region began to re-inflate at a relatively constant rate of 7 microradians per month. Microearthquake activity remained at a low level until September 1978, when shallow caldera quakes exceeded 500 per day on three consecutive days. By the end of the month, however, summit quakes had returned to a more typical background level of about 300/day (Figure 2).

Figure 2 near here

During this same interval, magma apparently accumulated gradually within Kilauea's middle east rift zone, as evidenced by rift inflation first noted by dry tilt surveys in January and continuing through August 1978. Combined with generally low summit seismicity, this suggests that a relief valve mechanism effectively partitioned newly supplied magma between the summit and east rift zone during this interval, at a rate such that the capacity of the summit storage reservoir was approached but not exceeded.

October-November 1978: Summit Deflation and Increased Rift Zone Storage

On 23 October 1978, the summit region entered a period of gradual, generally aseismic deflation which totalled 12.5 microradians before giving way to slow re-inflation on December 1. There was a corresponding decrease in summit microearthquake activity during late October and early November, as stresses which had accumulated during gradual re-inflation of the summit reservoir following the September 1977 eruption were relieved by slow loss of magma from the summit.

A dry tilt survey in December 1978 confirmed that magma lost from the summit reservoir had accumulated within Kilauea's middle east rift zone in the general vicinity of the September 1977 eruption site (Figure 3). Movement along and accumulation within the rift zone was essentially aseismic; no anomalous rift zone seismicity was noted during October-November 1978 (Figure 2). Combined with the pattern of summit deflation and rift inflation during this interval, this suggests that magma passageways within the rift were relatively open and that the rate of rift zone storage temporarily exceeded the rate of resupply from depth.

Figure 3 near here

December 1978-August 1979: Minimal Summit Deformation Accompanies Repeated East Rift Intrusions

The Kilauea summit region began to re-inflate at roughly 8 microradians/month during December 1978-February 1979, while summit and rift zone seismicity remained at low levels (Figure 2). Beginning in March 1979, the summit region entered a period of minimal surface deformation punctuated by small intrusions into the east rift zone on May 29, July 15, and August 12. Each event was marked by a shallow seismic swarm; the May and August swarms were accompanied by relatively rapid summit deflations. Only the May event included unambiguous harmonic tremor (Figures 4-6, Table 1). Although these events were too small to cause detectable surface deformation along the east rift zone, their character was reminiscent of larger events during 1976-77 which more clearly reflected magma movements into the rift zone (Dzurisin and others, 1980). It thus appears that the interval December 1978-August 1979 was marked by episodic injections of summit magma into the east rift, separated perhaps by periods of more gradual, quiescent magma transport from summit to rift, as evidenced by the lack of summit deformation coupled with continued inflation of the rift zone.

Figures 4-6, Table 1 near here

September-November 1979: Summit Inflation Followed by East Rift Zone Eruption

Summit inflation at roughly 10 microradians/month began again in early September 1979, culminating in a small-volume east rift eruption at Pauahi crater on November 16-17. The chronology and products of the eruption are treated in detail by Banks and others (1981). Preliminary results suggest that erupted magma was chemically differentiated, presumably during storage within the east rift zone. It appears in retrospect that magma influx to the rift zone eventually exceeded the capacity of a local storage reservoir beneath Pauahi, causing the reservoir to disgorge at least part of its contents while simultaneously refilling with fresh magma from summit storage.

December 1979-August 1980: Fluctuating Summit Tilt and More East Rift Intrusions

The summit region rapidly regained the deflation associated with the November 1979 eruption, but then deformed very little until successive rapid intrusions into the east rift zone occurred on March 2 and March 10, 1980 (Figure 2, Table 1). Both events were marked by shallow earthquake swarms (Figures 7,8) and sharp summit deflations, but only the latter included easily-recognized harmonic tremor. This second event was more prolonged and larger in magnitude, causing cracking of local roadways and vigorous volcanic gas emissions from within Mauna Ulu crater.

Figures 7 and 8 near here

Beginning in mid-April 1980, the Kilauea summit region began a series of periodic tilt oscillations which are unprecedented in the 23-year record of continuous tilt measurements at Uwekahuna. Five sequential inflation/deflation cycles had occurred by the end of June with a periodicity of roughly 14 days per cycle (Figure 9). These initial oscillations proved to be in phase with the fortnightly earth tide at Kilauea, but this pattern was not maintained during subsequent tilt excursions in July and August (F. Klein, personal communication). Observations suggest that an intimate connection existed between summit tilt cycles and east rift seismicity during this unique interval. At the beginning of each episode, summit inflation was not accompanied by anomalous seismic activity at the summit nor along the rift zone. As the capacity of the summit reservoir became more taxed with increasing storage, however, shallow summit earthquakes increased dramatically. When the summit chamber eventually ruptured, the onset of slow deflation was quickly followed by increased seismicity along the east rift zone as magma moved through fractures and accumulated within the rift. This unique episode at Kilauea graphically illustrates the close interplay possible between the summit magma reservoir and east rift zone and reaffirms the importance of relatively gradual transfer of magma from the summit chamber to storage within the rift zone.

Figure 9 near here

The pattern of oscillatory summit tilt which began in mid-April 1980 was interrupted by yet another rapid intrusion into the east rift zone on August 27. A shallow earthquake swarm began near Puhimau crater and migrated about 2 km downrift at a mean rate of 1.1 km/hour (Figure 10). Rapid summit deflation totalled 7 microradians, but this was quickly recovered as the summit chamber re-entered a period of inflation. There was no indication by the end of 1980 that the pattern of subsurface storage within the east rift zone, fed by frequent intrusions seldom culminating in eruptions, had been altered in any significant way.

Figure 10 near here

PROPOSED MAGMA BUDGET

Theoretical Considerations

We assume that Kilauea's mantle source, summit magma reservoir, and rift zones form a closed system for magma supply and storage. In other words, the volume of magma supplied from the volcano's mantle source region must be balanced by surface extrusion, storage changes within the summit reservoir, and storage changes along the volcano's rift zones. We suspect that this magma balance is not instantaneously reflected in Kilauea's geodetic response to rapid magma movements, and will therefore restrict our discussion to intervals longer than the average duration of typical intrusions and eruptions (hours to weeks).

As noted above, several independent estimates of the mantle supply rate for Kilauea are available in the literature. Swanson (1972) calculated the rate of extrusion during three long-lived Kilauea eruptions during 1952-71 to be remarkably constant at roughly 9×10^6 m^3/month. He argued from the lack of net surface deformation (suggesting minimal subsurface storage) and from the phenomenology of the eruptions (long-term steady extrusion via well-established feeding conduits) that the extrusion rate accurately reflected the rate of supply from depth during these three eruptions. This contention was generally supported by Dzurisin and others (1980), who modelled simultaneous gravity and vertical deformation measurements to calculate a supply rate of 6-13 $\times 10^6$ m^3/month during December 1975-June 1976. More recently, Dvorak and Dieterich (1981) used a least-squares inversion technique to model Kilauea summit deformation during October 1966-September 1970. They estimated a mean supply rate of 6×10^6 m^3/month during this 4-year interval by calculating the rate of volume change at the summit and adding the observed rate of surface extrusion. Finally Duffield and Christiansen (1981) used a similar approach to calculate a mean supply rate of 6×10^6 m^3/month during June 1971-January 1972. It thus appears that magma was delivered to Kilauea's shallow storage system at a relatively constant rate of 6-12 $\times 10^6$ m^3/month during 1952-75.

We can calculate the average magma supply rate to Kilauea as a function of time if we can specify the mean extrusion rate and the rates of change in summit and rift zone storage, each as a function of time. Such changes can be derived from the measured rate of surface deformation at Kilauea's summit, subject to the following assumptions: 1) any increase in summit storage is uniquely reflected by inflation of the summit region; 2) any decrease in summit storage as evidenced by summit deflation is accompanied by a corresponding increase in rift zone storage or by surface extrusion; and 3) the relationship between summit storage volume and measured surface deformation is linear and constant. Extruded volume as a function of time does not enter explicitly into this scheme, but is included by way of eruption-related summit deformation. Note that this approach yields a *minimum* supply rate to the rift zones, because magma may be delivered there at an equilibrium rate, with no corresponding summit deformation. We also point out that our first assumption was clearly violated immediately after the November 1975 M = 7.2 earthquake, while quake-induced voids refilled with magma without appreciably inflating the summit region. This process was reflected by a relative increase in local gravity in excess of that which could plausibly be attributed to measured ground deformation (Dzurisin and others, 1980). However, we regard this as a relatively unique event in recent Kilauea history and feel that our first assumption is generally valid for the interval under discussion.

The major advantage of this approach to calculating magma supply rates at Kilauea lies in its ability to estimate storage changes within the volcano's rift zones from deformation changes measured in the summit region. Kilauea's summit is easily accessible and therefore intensely monitored, but relatively little geodetic control exists along the volcano's largely inaccessible east rift zone. Our approach is to quantify the volume of magma which is lost from the summit reservoir and assume that this is a reliable measure of magma delivered to the rift zones. This assumption is justified for the most part by observed seismic or geodetic changes along the rift zone during periods of rapid summit deflation.

The most convenient deformation parameter from which to estimate changes in summit magma storage is near-summit ground tilt as monitored by a 3-meter baselength water-tube tiltmeter in Uwekahuna Vault (Figure 1). A continuous daily record from this instrument has been maintained at the Hawaiian Volcano Observatory since July 1956. The tiltmeter is generally read once each day, with an uncertainty of less than 1 part per million, or 1 microradian. Changes in summit and rift zone magma storage can be inferred from the Uwekahuna tilt record by assuming that net summit inflation reflects increased summit storage, and cumulative summit deflation records increased rift zone storage. Net summit deflation during any interval $\Delta t = t_2 - t_1$ is simply the algebraic difference between summit tilt values bracketing the interval. That is: $\Delta\tau_{net} = \tau_2 - \tau_1$, where τ is any representative measure of summit tilt (in this case, the Uwekahuna water-tube tilt record). Cumulative summit deflation is defined here as the sum of all deflations during Δt which exceed some arbitrary noise threshold. For the Uwekahuna water-tube tilt record, we adopt 2 μrad as a conservative threshold; experience shows that small changes in threshold do not significantly alter our results. This approach is illustrated graphically for the period March-August 1980 in Figure 11. The Uwekahuna water-tube tilt data for this interval is shown at the bottom of the figure (A). We interpret this record as an approximate measure of summit magma storage versus time. Next is shown the cumulative deflation of the summit region versus time, interpreted as a record of increased rift zone storage during this 6-month interval (B). We then sum the summit and rift zone storage records to obtain an approximate history of magma supply to Kilauea during March-August 1980 (C). For completeness, we also show the inferred magma supply rate as a function of time (D), for which a derivation will be discussed shortly.

Figure 11 near here

We stress that the major strengths of this approach are its simplicity and ease of application. Our results are admittedly subject to several assumptions and uncertainties, and are not intended to supercede more detailed analyses for specific intervals by other authors (e.g., Dvorak and Dieterich, 1981). We assume that the sensitivity of the Uwekahuna tiltmeter to magma storage changes is constant through time even though the center of summit deformation is known to shift with time. For this reason, it is preferable to compute volume changes from a data base which spans the entire deforming area. Results from standard levelling surveys are perhaps the best example of such an areally complete data base. However, calculations of volume changes from levelling data suffer from serious drawbacks which generally limit their utility: 1) data collection is manpower intensive, typically requiring 20 man-days per summit survey; 2) the resulting record is not continuous in time and may therefore fail to record short-term deformation events; and 3) data reduction is tedious, and calculation of volume changes generally requires computer analysis. In contrast, the Uwekahuna tilt record: 1) requires only about 1 man-day/month to acquire; 2) has been continuous since July 1956; and 3) can be directly converted to a record of magma storage changes, assuming that an appropriate conversion factor can be specified. Thus, although the Uwekahuna tilt record does not provide a complete picture of magma movements within Kilauea, it offers utility in data acquisition and a long-established, essentially continuous record for analysis.

In order to convert the summit deformation record in Figure 11 into a true record of magma supply, we need to specify an empirical relationship between summit tilt change at Uwekahuna and the corresponding volume change in the summit magma reservoir. This problem has been addressed by Eaton (1962), who modelled tilt changes during the 1959-60 Kilauea Iki/Kapoho eruption using a formalism developed by Mogi (1958). The following treatment parallels that of Eaton (1962) as corrected by Jackson and others (1975, p. 15) and is based on the semi-infinite elastic model of Mogi (1958).

If we assume that ground tilting reflects volume changes in a spherical chamber of radius a centered at depth f, the ground tilt at a point separated by distance d from the deformation center is given by:

$$\tau = 3.5 \frac{d/f}{(1+d^2/f^2)^{5/2}} \tau_{max} \qquad (1)$$

where: τ_{max} = maximum tilt at $d = f/2$.

According to this model, the volume swept out by the surface during a tilt event characterized by maximum tilt τ_{max} is given by:

$$\Delta V = 2.32\pi f^3 \tau_{max} \qquad (2)$$

Combining equations 1 and 2, we obtain:

$$\Delta V = 0.66 \frac{\pi f^4}{d} (1+d^2/f^2)^{5/2} \tau \qquad (3)$$

We adopt for our purposes f = 2-4 km, which is representative of results obtained by modelling Kilauea levelling data (Swanson and others, 1976). The distance from Uwekahuna Vault to the center of summit deformation varies with time as the deformation center typically shifts between a position near the center of Kilauea caldera and a site south of Halemaumau (see Figure 3 of Swanson and others, 1976, or Figure 5 of Fiske and Kinoshita, 1969). Accordingly, we let d = 2-4 km. Substituting these values into equation 3, we obtain the results shown in Table 2. Permissible values of $\Delta V/\Delta\tau_{uwe}$ range from 0.09 to 0.75 X 10^6 m^3/μrad.

This range can be narrowed considerably by making use of the observation that the depth and lateral position of the summit chamber are seemingly linked, such that the chamber often migrates upward and southward as inflation progresses. This pattern favors the values connected by the dotted line in Table 2 ($\Delta V/\Delta\tau_{uwe}$ = 0.32-0.46 x 10^6 m^3/μrad). Combined with the conclusion of Fiske and Kinoshita (1969) that "...the magma reservoir probably lies at depths of 2 to 3 kilometers, the overall average of the depth determinations being close to 3 kilometers.", this suggests that $\Delta V/\Delta\tau_{uwe}$ = 0.32 X 10^6 m^3/μrad best approximates the average deformation pattern at Kilauea. We point out that the relationship $\Delta V/\Delta\tau_{uwe}$ = 0.35 X 10^6 m^3/μrad is implicit in Figure 13 of Eaton (1962), which is based in part on an independent measurement of ground tilts at Kilauea summit during January-April 1960.

Table 2 near here

Another approach to the same problem is to empirically compare observed tilt changes at Uwekahuna with surface volume changes derived from levelling results, preferably for well-defined intervals of rapid deformation. Such a comparison for four summit deflation episodes ranging in magnitude from -17 μrad in July 1963 to -205 μrad during September 1975-January 1976 is provided in Table 3. The measured ratio of volume change to summit tilt change, $\Delta V/\Delta\tau_{uwe}$, for these four cases varies between 0.23 and 0.45 X 10^6 m^3/μrad with a mean value of 0.33 X 10^6 m^3/μrad.

Table 3 near here

A final estimate of the relationship between summit storage volume and tilt changes can be obtained by comparing observed tilt changes with the volume of magma extruded during the early phases of the Mauna Ulu eruption of 1969-74. Table 4 includes tilt and extruded volume data for the first 12 phases of the Mauna Ulu eruption during 24 May-31 December 1969. Swanson (1972) noted that this early part of the 5-year eruption was characterized by close interplay between summit storage and rift extrusion, and by negligible net summit deformation. In this case, the measured ratio $\Delta V/\Delta\tau_{uwe}$ ranges from 0.19 to 0.50 X 10^6 m^3/μrad, with a mean value of 0.34 X 10^6 m^3/μrad.

Table 4 near here

Although each of these calculations suffers from its own limitations, we regard the remarkable agreement between the result of Eaton (1962; 0.35 X 10^6 $m^3/\mu rad$), the theoretical Mogi model calculation (0.32 X 10^6 $m^3/\mu rad$), the summit volume change vs. tilt comparison (0.33 X 10^6 $m^3/\mu rad$), and the Mauna Ulu extruded volume vs. summit tilt comparison (0.34 X 10^6 $m^3/\mu rad$) as compelling (Table 5). Accordingly, we adopt for our purposes:

$$\Delta V/\Delta \tau_{uwe} = 0.33 \text{ X } 10^6 \ m^3/\mu rad. \qquad (4)$$

Table 5 near here

We attribute observed deviations from this generalized result to: 1) lateral shifts of the summit deformation center with respect to Uwekahuna; 2) departures from elasticity during exceptionally large summit deflations; 3) the possibility of steady state delivery of magma directly to the rift zones with no related summit deformation; and 4) other unmodelled complexities of the Kilauea system.

Magma Supply During Two Intervals of Oscillatory Summit Tilt

The approach outlined above is most directly applicable when: 1) the center of summit deformation does not shift laterally with respect to Uwekahuna, and 2) the pathway for mobile magma includes sufficient residence time in the summit reservoir so that magma movements into the rift zone are well-recorded by summit deflations. Both criteria were satisfied during periods of oscillatory summit tilting in May-December 1969 and March-August 1980.

The first interval includes phases 1-12 of the Mauna Ulu eruption from Kilauea's upper east rift zone during 1969-74. These early phases were characterized by close interplay between summit magma storage and east rift extrusion, as periods of sustained summit inflation and weak eruption alternated with rapid summit deflation and strong eruption (Swanson and others, 1979). Swanson (1972) pointed out that a negligible amount of net summit deformation occurred during these 7 1/4 months, and combined that fact with observed volumes of extrusion to calculate an average magma supply rate of 8.5 X 106 m3/month. Application of our technique to this same interval serves two purposes. First, it allows a direct comparison of our result with that of Swanson (1972), thereby providing a calibration of our technique against a known standard. Second, it forms the basis for a comparison of supply rates to Kilauea for two similar intervals separated by 11 years, which in turn will be used to assess the effect on the Kilauea magma supply of the November 1975 earthquake and July 1975 reawakening of neighboring Mauna Loa volcano.

A second interval of interest is March-August 1980, during which summit tilting oscillated between steady inflation and gradual deflation with no surface extrusion. As noted in the chronology section, the close interplay between summit tilt and east rift zone seismicity during this interval suggests that magma delivered to the summit reservoir was episodically **leaked** into the east rift zone during gradual summit subsidence events. In this respect, the period March-August 1980 was similar to May-December 1969, except that in the first case magma was intruded and stored in the east rift zone rather than being extruded at Mauna Ulu.

We calculate from the Uwekahuna short base watertube tilt record that the cumulative summit deflation along a N 60^{o} W radial vector from Uwekahuna during 24 May-31 December 1969 was 234.5 μrad. During the same interval, the net summit inflation was 5.5 μrad. From equation 4, we infer that 77.4 X 10^6 m^3 of magma was added to the east rift zone, and that summit storage increased by 1.8 X 10^6 m^3 during this 7 1/4 month interval. This implies a mean supply rate of (77.4 + 1.8)/7.25 = 10.9 X 10^6 m^3/month. For the same interval, Swanson (1972) calculated a mean extrusion rate of 9.9 X 10^6 m^3/month, which he adjusted to 8.5 X 10^6 m^3/month to account for 15% vesicularity in surface flows. The two approaches can be further reconciled by allowing for a small, unmonitored increase in rift zone storage during this interval. If we exclude for this reason those summit deflations which were not associated in time with the 12 eruptive phases listed in Table 4, the cumulative deflation is reduced to 188.5 μrad. This implies a mean supply rate available for extrusion of 8.8 X 10^6 m^3/month, in good agreement with Swanson's (1972) corrected result. Thus, at least for periods of oscillatory summit tilting which satisfy the two criteria listed at the beginning of this section, our technique produces results which can be directly compared with those of Swanson (1972), and which presumably are a reliable indicator of the true rate of magma supply from depth.

The same technique applied to the interval March 1-August 31, 1980 yields a cumulative summit deflation of 104.6 μrad and a net deflation of 14.1 μrad. This implies a mean suply rate of (34.5 - 4.7)/6 = 5.0 X 10^6 m^3/month, or roughly half of the rate calculated for May-December 1969. As noted earlier, our supply rate calculations are generally unreliable for intervals shorter than a few months, but for the interval March-August 1980 the inferred rate was remarkably constant (Figure 11, D). This is probably a true reflection of relatively uniform transfer of magma from depth to the summit magma reservoir and thence to rift zone storage during this unique period of oscillatory tilting.

Minimum Magma Supply During October 1977-August 1980

We can now extend this approach to include the 35-month interval since Kilauea's last major eruption in September 1977, subject to the qualifications discussed above. Probably the most important of these is our assumption of zero magma supply during periods of negligible summit tilting. We suspect that an unknown volume of magma has been delivered to the east rift zone either directly from depth, or from the summit reservoir at a sufficiently low rate that recharge from depth was able to keep pace and thereby nullify associated summit deflation. We therefore assume that the Uwekahuna tilt record in Figure 2 is a reasonable reflection of net changes in summit magma storage and minimum increases in east rift storage during October 1977-August 1980.

Net inflation at Uwekahuna of 106.4 μ rad during October 1977-August 1980 suggests an increase in summit storage by 35.1 X 10^6 m^3;

cumulative deflation of 426.3 μrad corresponds to an increase in rift zone storage by 140.7 X 10^6 m^3. Taken together, this implies a minimum supply rate of (35.1 + 140.7)/35 = 5.0 X 10^6 m^3/month (Figure 12). This is the same rate calculated above for the March-August 1980 period of oscillatory summit tilt, which leads us to conclude that 5 X 10^6 m^3/month is a reasonable estimate of the supply rate to Kilauea during the entire 3-year interval since the September 1977 eruption.

Figure 12 near here

Minimum Magma Supply Since 1956

Encouraged by the somewhat surprising agreement between: 1) our calculated supply rate for May-December 1969 and Swanson's (1972) estimate for the same interval; and 2) our results for March-August 1980 and October 1977-August 1980, we have extended our calculations to include the entire Uwekahuna water tube tilt record for July 1956-August 1980. We emphasize from the outset that this application to a complex 25-year interval at Kilauea is simplistic and especially subject to the limitations discussed earlier. Nevertheless, the results are useful for comparative purposes in assessing the constancy of magma supply to Kilauea.

Our results for July 1956-August 1980 are summarized in Figure 13. During July 1956-December 1975, summit storage seemingly increased by 69 X 10^6 m^3, and roughly 1,770 X 10^6 m^3 of magma entered the east and southwest rift zones combined. For comparison, roughly 130 X 10^6 m^3 and 590 X 10^6 m^3 of basalt were extruded during the same interval from Kilauea's summit area and rift zones, respectively. The minimum monthly supply to Kilauea during July 1956-December 1975 is thus: (1,770 + 69)/233 = 7.9 X 10^6 m^3/month, within 15% of the long-term rate proposed by Swanson (1972).

Figure 13 near here

During January 1976-August 1980, our technique suggests that summit storage decreased by roughly 7 X 10^6 m^3, while roughly 281 X 10^6 m^3 were delivered to the east rift zone. No extrusion occurred in the summit area during this interval; a combined total of roughly 35 X 10^6 m^3 were extruded during the September 1977 and November 1979 eruptions along the east rift zone. The minimum monthly supply during January 1976-August 1980 is thus: (281 - 7)/56 = 4.9 X 10^6 m^3/month, essentially the same rate derived for October 1977-August 1980 and March-August 1980, but only 60% of the pre-1976 result.

In detail, the apparent magma supply rate to Kilauea fluctuated considerably during 1956-80 (Figure 13,D). The relatively high apparent rate prior to 1960 may be partly an artifact of the higher average noise level in the early Uwekahuna tilt record, but in large measure reflects rapid re-inflation of Kilauea's summit following the large 1960 Kapoho eruption. Eliminating the pre-1960 data set reduces the mean supply rate during 1961-75 to 6.8 X 106 m3/month, still significantly above the post-1975 rate of 4.9 X 106 m3/month. Other prominent peaks in apparent supply correlate with: 1) early phases of Mauna Ulu extrusive activity in 1969-70; 2) a sharp increase in summit storage associated with the September 1971 summit and southwest rift eruption; and 3) two periods of rapid summit inflation during 1974-75 which culminated in the December 1974 southwest rift eruption and large intrusion, and in the November 1975 M = 7.2 earthquake. The existence of such peaks in near-surface supply suggests that some large eruptions at Kilauea may be triggered by pulses in magma generation at depth, as proposed by Wright and others (1979). The small peak in apparent supply in 1971 may be an artifact caused by a permanent positive offset in the Uwekahuna tilt record during the September 1971 eruption. However, the rapid summit inflations during 1960-61, 1969-70, and 1974-75 which give rise to other peaks in apparent supply strongly suggest that magma is occassionally supplied to Kilauea's shallow summit reservoir at rates in excess of 10 X 106 m3/month for intervals of months to years.

DISCUSSION

One straightforward interpretation of our results is that the average magma supply rate to Kilauea has diminished by roughly 40% since the M = 7.2 earthquake and Mauna Loa eruption during 1975. However, alternate interpretations are also possible, including: 1) the November 1975 earthquake caused new leaks in Kilauea's near-surface plumbing system, so that proportionally more magma now escapes geodetic detection; 2) the earthquake temporarily disrupted feeding conduits from depth, so that proportionally more magma now resides in deep storage; or 3) Kilauea's former magma supply may now be tapped in part by neighboring Mauna Loa volcano. Each possibility is treated in more detail below, following a discussion of recent geodetic and inferred magma storage changes along Kilauea's east rift zone.

Is Our Estimate of Rift Zone Storage During October 1977-August 1980 a Plausible One?

Inherent in our proposed magma budget for October 1977-August 1980 is the assumption that roughly 140 X 106 m3 of magma could plausibly have been added to subsurface storage along the east rift zone during this interval. Unfortunately, much of the east rift zone is carpeted with dense tropical jungle which severely limits geodetic monitoring efforts aimed at assessing magma storage changes. A relatively complete network of seismographs in the area provides a qualitative indication of magma movements into the rift zone, but cannot provide quantitative estimates of stored magma volume. Similarly, an array of dry tilt stations on the rift zone's flanks provides a reliable indicator of rift inflation or deflation, but is inadequate to support calculations of stored volume. At present, our best source of quantitative information about magma storage changes along the east rift zone is a precise distance monitor which spans the rift from Puu Huluhulu 5 km southwestward to station Goat II, roughly 10 km downrift from Kilauea caldera (Figure 3). This line has been a reliable indicator of rift zone expansion/contraction since 1974; changes in the line's southward extension to Apua Point contributed to a forewarning of the November 1975 earthquake by Swanson, Duffield, and Fiske (1976).

The Puu Huluhulu-Goat II line extended by roughly 70 cm during or immediately after the November 1975 earthquake, as Kilauea's south flank moved differentially seaward. The resulting volume increase along the east rift zone was presumably filled with newly-delivered magma prior to the September 1977 eruption (Dzurisin and others, 1980). Dilation of the rift zone continued after the eruption, however, presumably driven by continuing magma delivery from the summit reservoir. During the 3-year interval since September 1977, the Puu Huluhulu-Goat II line has extended an additional 60 cm. We are forced to assume that this result is representative of the 30 km of rift between the summit and Heiheiahulu, which is the extent of the actively deforming area delineated by dry tilt measurements (Figure 3). We can therefore accomodate 140 X 10^6 m^3 of newly-stored magma by extending the measured surface extension to a depth of (140 X 10^6 m^3)/(30 X 10^3 m X 0.6 m) = 7.8 km. This is not unreasonable, given that the rift zone has been seismically active to a depth of at least 7 km during recent intrusive episodes (Koyanagi and others, 1974; HVO unpublished data). This constraint is further relaxed if the unknown volume of surface uplift implied by net inflation of the rift zone since 1977 is taken into account. Our assertion that roughly 140 X 10^6 m^3 of magma were delivered to the east rift zone during October 1977-August 1980 is therefore consistent with the (admittedly weak) constraints imposed by rift zone deformation measurements.

Is the Magma Supply Rate Since 1975 Demonstrably Lower Than During 1952-1975?

As noted in the Introduction, four independent approaches have yielded an average magma supply rate to Kilauea of 6-12 X 10^6 m^3/month for several intervals during 1952-1975. Our result for the same interval is roughly 8 X 10^6 m^3/month, compared with 5 X 10^6 m^3/month since January 1976. Taken at face value, these calculations suggest that the supply rate to Kilauea has diminished by roughly 40% since 1975. However, these results are subject to several challenges and alternate interpretations.

First, the various approaches to magma supply calculations may not be directly comparable, given that each independent measure is sensitive to different geophysical parameters or processes (e.g., gravity, surface deformation, extrusion). We have gone to some length to demonstrate that this objection is not a serious one for our purposes. A specific comparison of our results with those derived from other approaches is provided in Table 6. Swanson (1972) proposed a mean supply to Kilauea during 1952-71 of 8.5 X 10^6 m^3/month; our minimum estimate for July 1956-December 1975 is 7.9 X 10^6 m^3/month. For the specific interval 24 May-31 December 1969, Swanson (1972) calculated 8.5 X 10^6 m^3/month compared with our estimate of 8.8 X 10^6 m^3/month. Dvorak and Dieterich (1981) estimated a mean supply during October 1966-September 1970 of 6 X 10^6 m^3/month, in reasonable agreement with our estimate of 7.3 X 10^6 m^3/month. Finally, Dzurisin and others (1980) proposed a mean supply rate during November 1975-June 1976 of 6-13 X 10^6 m^3/month, whereas our estimate for the same interval is 5.7 X 10^6 m^3/month.

Table 6 near here

Admittedly, it would be possible to make comparisons for other time periods during which the various approaches would differ substantially. This is especially true during intervals of steady state delivery of magma to a vent area, with little or no associated summit deformation. However, the nearly exact correspondence between our results for March-August 1980 (5.0 X 10^6 m^3/month) and January 1976-August 1980 (4.9 X 10^6 m^3/month) argues that the resulting uncertainty is relatively small. This is because the shorter interval encompasses only a well-behaved pattern of oscillatory summit tilt, but the longer interval includes several episodes of more complex summit deformation including several extended periods of negligible summit tilt change.

A second major objection to a possibly diminished magma supply since 1975 is that the November 1975 earthquake may have altered the relationship between storage changes in the summit reservoir and resulting tilt changes at Uwekahuna. Lipman and others (1981) noted that rates of horizontal and vertical deformation at Kilauea were comparable prior to the 1975 earthquake, but that horizontal changes have dominated since 1975. If this were a purely structural change unrelated to a changed supply rate, our (incorrect) assumption of a constant relation between supply and summit tilt changes would give rise to an apparent decrease in supply since 1975.

The contention that the November 1975 earthquake may have substantially altered the rules by which Kilauea behaves is difficult to evaluate, because the five years since the earthquake have provided relatively limited opportunity to verify results accumulated during the previous three decades. For example, there has been no event comparable to the 1969-74 Mauna Ulu eruption, which would provide a post-earthquake supply estimate for direct comparison with that by Swanson (1972). However, the September 1977 eruption does provide an indirect check of the post-earthquake relation between magma supply and summit tilt changes. Roughly 35 X 106 m3 of differentiated basalt were forced out of rift zone storage during this eruption, while Uwekahuna tilt dropped by 120 μrad. If we assume that this volume of extruded basalt was displaced by an identical volume of magma from summit storage, we calculate $\Delta V/\Delta \tau_{uwe}$ = (35 X 106 m3)/120 μrad) = 0.29 X 106 m3/μrad. Dry tilt measurements recorded net rift zone inflation during the eruption (Dzurisin and others, 1980), so this should be regarded as a minimum value. This post-earthquake result is remarkably close to our adopted figure of 0.33 X 106 m3/month, but the significance of this comparison is admittedly open to question. Pending a more detailed analysis of this alternative, we are disposed toward a real decrease in magma supply since 1975.

How Has The Magma Budget Changed Since 1975?

A significant change in the measureable magma supply to Kilauea's shallow summit reservoir implies a corresponding change in the rate of magma generation at depth, a change in the location or style of subsurface magma storage, or both. The best available monitor of magma generation beneath Hawaii's volcanoes is the time-averaged seismic energy output of sporadic harmonic tremor episodes which originate in Kilauea's inferred magma source region at 40-50 km depth. (Figure 14). Observations since 1962 suggest that the rate of magma generation has been relatively constant, with perhaps a small increase during 1968-73 corresponding to long-lived lava lake activity in Halemaumau (1967-68) and the construction of Mauna Ulu shield along the east rift zone (1969-74). More specifically germane to the issue at hand, magma generation as reflected in deep tremor episodes has been remarkably constant since 1973, and may in fact have increased slightly since 1975. It thus appears that the apparent decrease in supply since 1975 more likely reflects a change in the details of magma storage rather than in production rate at depth.

Figure 14 near here

It is possible that magma could be hidden from our calculations during accumulation in a relatively deep storage reservoir beneath the Kilauea summit region. One scenario in which deep storage might plausibly have increased since 1975 involves disruption of feeding conduits from depth by the November 1975 earthquake. Mogi (1958, p. 117) initially proposed the existence of a large reservoir at 20-30 km depth based on far-field levelling results at Kilauea, but this interpretation was later called into question by Eaton (1962). Ellsworth and Koyanagi (1977) modelled the three-dimensional seismic structure beneath Hawaii and concluded that large-volume concentrations of magma are absent in the mantle to depths of at least 40 km. However, neither seismic nor ground deformation results currently available are of sufficient resolution to unambiguously refute the existence of a modest magma storage reservoir in the upper mantle beneath Kilauea. We must therefore entertain the possibility that the apparent decrease in magma supply to Kilauea since 1975 may simply reflect a corresponding increase in deep storage in response to the 1975 earthquake.

Another viable interpretation of the apparent decrease in magma supply since 1975 is that the M = 7.2 earthquake caused new leaks in Kilauea's near-surface plumbing system, so that proportionally more magma now escapes geodetic detection. The earthquake clearly had a profound effect on shallow magma storage at Kilauea, as evidenced by the large summit deflation triggered by the quake, and by frequent post-earthquake intrusions into the east rift zone. If in fact the magma supply rate to Kilauea has been relatively constant at roughly 8 X 10^6 m^3/month since 1975, then our result of 5 X 10^6 m^3/month implies than an additional 3 X 10^6 m^3/month was leaked into the east rift zone or other shallow storage. During the 5 years since 1975, this corresponds to roughly 180 X 10^6 m^3 of additional storage. Given that the observed dilation of the east rift zone is barely adequate to accommodate 5 X 10^6 m^3/month (as discussed above), this hypothesis is difficult to justify quantitatively.

It is tempting and in our view equally plausible to relate an apparently diminished rate of supply to Kilauea since 1975 to the resumption of eruptive activity at neighboring Mauna Loa volcano in July 1975. Several writers have noted an apparent inverse relationship between eruptive activity at Kilauea and Mauna Loa (e.g., Moore, 1970; Klein, 1981), and there is seismic evidence to suggest that the two volcanoes may be fed from a common source in the upper mantle (Ellsworth and Koyanagi, 1977). If this is the case, then Mauna Loa may have begun to pirate some fraction of the available magma supply shortly before its most recent eruption in July 1975. Recent dry tilt and laser geodimeter measurements on Mauna Loa show that the summit region inflated at a relatively constant rate during 1975-80, suggesting that Mauna Loa may continue to tap some fraction of the magma supply previously available exclusively to Kilauea. It is a fact that Kilauea was vigorously active during Mauna Loa's 1950-1975 repose, and that extrusive activity at Kilauea has diminished considerably during 1975-1980. However, this observation is clouded by the near coincidence of the July 1975 Mauna Loa eruption and November 1975 M = 7.2 earthquake. Both events could plausibly have affected the rate of magma supply to Kilauea, and the earthquake has in addition tipped the scales toward subsurface magma storage in the east rift zone at the expense of surface extrusion. A strong argument against a single source region for Kilauea and Mauna Loa can be made from petrochemical evidence, but this does not preclude some physical explanation for their seemingly antithetic behavior.

What are the Prospects for Future Activity at Kilauea?

Any attempt to forecast future activity at Kilauea is hampered by the lack of a unique interpretation for the apparent decrease in magma supply since 1975. The trend toward increased subsurface magma storage initiated by the 1975 earthquake clearly decreased the likelihood of frequent surface eruptions, but simultaneously increased the potential for a large volume eruption should the enlarged east rift reservoir eventually be tapped. Although it is not possible to specify any single course of events which is most likely to occur at Kilauea during the next few years, various factors which will influence the ultimate outcome can be identified. To the extent that Kilauea's south flank continues to move seaward in response to the November 1975 earthquake, continued subsurface storage within the east rift zone will be favored over surface extrusion. Relatively quiescent delivery of magma from the summit chamber to the rift zone may occasionally be punctuated by forcible injections marked by rapid summit deflation and shallow earthquake swarms in the intrusive zone. The ultimate fate of magma stored along the east rift zone will be critically affected by the future behavior of Kilauea's south flank. Should the entire area remain mobile for the foreseeable future, magma intruded into the east rift may remain in subsurface storage indefinitely. On the other hand, magma stored in the rift zone since 1975 represents a large reservoir (at least 240 X 106 m3) potentially available for surface extrusion. This reservoir will more likely be tapped if: 1) the south flank again becomes rigid, thereby limiting the capacity of the east rift zone for future magma storage; or 2) stored magma somehow gains access to the lower east rift zone near or below sea level, where an eruption could tap parts of the rift zone reservoir by a gravity feed mechanism. Recent south flank geodimeter measurements suggest a stick-slip mechanism since 1975, in which temporary stress accumulations in a quasi-rigid flank are episodically released by renewed seaward mobility. It is not possible to assess with available information when the flank will again be sufficiently rigid to limit the storage capacity of the east rift zone and thereby increase the likelihood of surface extrusion. Likewise, structural changes which could allow access for stored magma to the lower east rift zone cannot be foreseen at this time. Earthquake swarms occasionally occur downrift from the principal zone of magma accumulation along the middle east rift zone, but their significance in terms of magma movements is not fully understood.

Another factor which could potentially influence activity at Kilauea in the near future is the continuing inflation of neighboring Mauna Loa. To the extent that both volcanoes tap a single magma source at depth, the recent reawakening of Mauna Loa may foretell a period of diminishing activity at Kilauea. To the extent that: 1) Mauna Loa continues to tap part of the magma supply which had previously been accessible exclusively to Kilauea and, 2) continued structural adjustments in response to the November 1975 earthquake enhance the likelihood of subsurface storage relative to surface extrusion, the next few years at Kilauea may extend the relative quiescence of 1975-80. However, the volume of magma stored along the east rift zone since 1975 is comparable to the volume extruded during Kilauea's largest historic eruptions. The potential therefore exists for an event of major proportions should the east rift reservoir be tapped in the near future by a vent along the middle or lower rift zone.

In summary, the scenario for minimal Kilauea eruptions during the next few years would involve a resurgence of activity at Mauna Loa and continuing seaward movement of Kilauea's south flank. The opposite extreme would most likely result from diminished activity at Mauna Loa and healing of Kilauea's south flank and/or summit reservoir, from structural changes to permit access of stored magma to Kilauea's lower east rift zone, or from a pulse in magma generation at depth. Simple extrapolation of events since 1975 favors the less active scenario, but the potential exists for a major east rift eruption comparable in magnitude to the largest event in Kilauea's recorded history.

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Table 1. Kilauea intrusions and eruptions during September 1977 - August 1980

Date	SEISMIC: Time, HST: Total Interval	Time, HST: peak of activity	Size of Earthquakes: magnitude max (M_L)	Size of Earthquakes: number ($1.0<M_L<4.0$)	energy release (ergs) $x10^{15}$	felt earthquakes at epicentral distances: >10km	>3 0km	60km	Location of Swarm: center (Lat N, Long W, depth)	depth range (Km)	hypocentral volume (Km^3)	Harmonic Tremor (intensity and duration)	Migration Pattern: rate (km/hr)	Migration Pattern: direction	SUMMIT TILT UWEKAHUNA IDEAL-AEROSMITH (E-W): Time Interval	amount deflation (μ rad)	max rate deflation (μ rad/hr)	VOLUME OF LAVA ERUPTED ($10^6 m^3$)	GAS EMISSION 1	SELF-POTENTIAL AND ELECTROMAGNETICS 2
Sept. 12-Oct. 1, 1977	2130, 9/12 1610,10/1 (end of eruption weak tremor continues 1 week)	0700-0800, 9/13	4.0	514	945	>40	14	1	19°22',155°07' near Puu Kamoamoa depth = 4	<1-8	1250	Moderate to Strong, 20 days; weak 10 days	.9	E-down-rift	2145, 9/12 to 2045, 9/17	80	3	35	No data	Self-potential changes on Escape Road monitor line.
May 29-30, 1979	1708, 5/29 0400, 5/30	1700-1800 5/29	3.2	51	22	12	0	0	19°22',155°12' SE of Mauna Ulu	<1-8	70	Moderate <1 day	0.6	E-down-rift	1710, 5/29 to 0200, 5/30	3	0.3	——	No data	Insufficent data
July 15-16, 1979	1642, 7/15 1100, 7/16	0400-0500, 7/16	3.6	9	33	1	1	0	19°23',155°06 near Puu Kamoamoa	<1-3	11	——	——	——	7/10 to 7/15	5	0.04	——	No data	Insufficient data
Aug. 12, 1979	0602 - 1654, 8/12	1100-1200	2.7	56	4	10	0	0	19°24,155°15' near Puhimau	<1-4	14	——	1.4	SE-down-rift	0900-1200	1	——	——	No data	Small self-potential increases on Escape Road monitor near (NE side) old Chain of Craters Road.
Nov. 15-17, 1979	2100, 11/15 2000, 11/17	0000-0100, 11/16	3.8	117	50	25	2	0	19°22',155°14' SW of Pauahi depth = 2km	<1-4	30	Strong 2 days	1.1; 0.9	SE-down-rift; upward	2130,11/15 to 0300,11/17	7	0.5	0.5 - 0.7	usual eruptive gas emission	New 700 mv SP anomaly coincident with eruptive fissure on Escape Road. Transient SP anomalies associated with magma emplacement and migration both at Pauahi and on the Escape-Ainahou roads.
Mar. 2, 1980	0751-1700	0800-0900	3.1	90	6	6	0	0	19°22',155°14' S of Hiiaka depth = 3km	1-4	3	Weak <1 day	——	——	0758-1600	2	0.3	——	no known gas events	no known events
Mar. 10-12, 1980	2157-0800	2200-2300	3.9	88	92	15	1	0	19°22',155°13' S of Mauna Ulu depth = 2km	<1-4	50	Strong <1 day	0.5; 0.2	E-down-rift; W	2206-1630	16	0.9	——	abundant H_2O, CO_2, SO_2 from Mauna Ulu crater and a new fissure between Mauna Ulu and Makaopuhi.	no known events
Aug. 27-28, 1980	1413-0300	1700-1800	3.4	151	30	12	0	0	19°23',155°15' Puhimau depth = 3km	<1-4	37	Moderate 1 day	1.1; 1.0	SE-down-rift; upward	1500-1900	7	2.5	——	transient SO_2 detected at Puhimau thermal area.	Transient amplitude and phase increases coincident with earthquake swarms at Outlet vault and Keanakakoi electromagnetic monitors.

Table 2

Depth (km)	Distance (km) 2.0	3.0	4.0
2.0	.09	.21	.46
3.0	→ .21	.32	.54
4.0	.46	.54	.75

Values of $\Delta V/\Delta\tau_{uwe}$ in units of 10^6 $m^3/\mu rad$ derived by substitution of the indicated depths and lateral distances into equation 4. The dotted line represents an observed pattern of upward and southward migration of deformation centers; the arrow indicates the average magma chamber depth favored by Fiske and Kinoshita (1969). Taken together, these constraints suggest a preferred value of $\Delta V/\Delta\tau_{uwe} = 0.32 \times 10^6\ m^3/\mu rad$.

Table 3

$\Delta V/\Delta\tau_{uwe}$($10^6$ $m^3/\mu rad$) from measured volume and tilt changes

Date	ΔV (106 m3)	$\Delta\tau_{uwe}$(μrad)	$\Delta V/\Delta\tau_{uwe}$ (106 m3/μrad)
5/ 9/63	-7.6	-33	0.23
7/ 1/63	-7.6	-17	0.45
10/ 5/63	-22.9	-75	0.31
9/23/75 - 1/8/76	-66.8	-204.7	0.33
		Average =	0.33

Comparison of tilt changes measured at Uwekahuna Vault along a N 60° W azimuth and volume changes derived from repeat levelling surveys on the indicated dates. N 60° W is representative of the azimuth from Uwekahuna Vault to the typical deformation center observed by levelling after major summit deflations.

Table 4

Date (1969)	Volume Erupted (X106 m3)	Uwekahuna Tilt Change (μrad)	$\Delta V/\Delta\tau_{uwe}$ (106 m3 μrad)
May 24-25	4.5	-23.1	0.19
May 27-29	3.5	7.4	0.47
June 12-13	4.0	-15.1	0.26
July 15	4.0	-13.7	0.29
August 3-4	3.5	-12.1	0.29
August 5-6	4.0	-12.6	0.32
August 22	3.5	11.1	0.32
September 6-7	12.0	-29.9	0.40
October 10-13	4.0	11.1	0.36
October 20	10.5	-21.0	0.50
December 30	11.0	-24.7	0.45
		Average =	0.34

Table 4. Extruded volume and summit tilt changes during the 12 eruptive phases at Mauna Ulu during 1969. Tilt changes are from the Uwekahuna short base water-tube tiltmeter, computed along a N 60^{o} W azimuth from Uwekahuna to the average center of summit deformation. Erupted volumes are from Table 5 of Swanson and others (1979).

Table 5

Source	Range	Average
	(X 106 m3/μ rad)	(X 106 m3/μ rad)
Eaton (1962)	-	0.35
Mogi (1958) model	0.09 - 0.75	0.32
Summit levelling	0.23 - 0.45	0.33
Mauna Ulu extrusion	0.19 - 0.50	0.34
		AVERAGE = 0.33

Comparison of the relationship between volume and tilt changes at the Kilauea summit derived from four independent sources discussed in the text.

Table 6. Magma supply estimates for Kilauea volcano, Hawaii

Source	Method	Interval	Supply (m3/month)
Swanson (1972)*	Rate of extrusion during long-lived eruptions	27 June 1952 -10 November 1952	8.3 X 10^6
		5 November 1967 - 13 July 1968	8.7 X 10^6
		24 May 1969 - 31 December 1969	8.5 X 10^6
		1 January 1970 - 30 June 1970	7.1 X 10^6
		1 July 1970 - 31 May 1971	8.9 X 10^6
	Extrapolation of above results	June 1952 - May 1971	8.5 X 10^6
Dzurisin and others (1980)	Gravity and vertical deformation model	29 November 1975 - 21 June 1976	6-13 X 10^6
Dvorak and Dieterich (1981)	Summit deformation model	October 1966 - September 1970	6 X 10^6
Duffield and Christiansen (1981)	Extrusion plus summit deformation	June 1971 - January 1972	6 X 10^6
This work**	Summit model	July 1956 - December 1975	7.9 X 10^6
		January 1961- December 1975	6.8 X 10^6
		October 1966 - September 1970	7.3 X 10^6
		24 May 1969 - 31 December 1969	10.9 x 10^6
		June 1971 - January 1972	9.6 X 10^6
		November 1975 - June 1976	5.7 X 10^6
		January 1976 - August 1980	4.9 X 10^6
		October 1977 - August 1980	5.0 X 10^6
		March 1980 - August 1980	5.0 X 10^6

*Swanson's (1972) results corrected for 15% vesicularity
**Minimum estimateS

FIGURE CAPTIONS

Figure 1 - Sketch map of Kilauea summit region and rift zones. Locations of the Hawaiian Volcano Observatory (HVO) and Uwekahuna vault (UWE) are indicated along the western rim of Kilauea caldera in the upper left. Also shown schematically are the Koae and Hilina fault systems, plus prominent pit craters and recent vent areas along the east rift zone. The epicenter of the 29 November 1975 earthquake beneath Kilauea's southeastern flank is indicated by the star. The quake occurred at roughly 10 km depth and effectively decoupled the entire volcanic edifice along a nearly horizontal slip plane. Resulting differential movements to the southeast produced more than 1m of extension along much of the east rift zone, thereby increasing its magma storage capacity and opening passageways for magma transport from a shallow summit magma reservoir.

Figure 2 - Geophysical overview of activity at Kilauea during October 1977 - August 1980. Earthquake counts in the summit region (top) and along the upper east rift zone (bottom) are shown together with the Uwekahuna short-base water-tube tiltmeter record (middle). Relatively high quake counts and declining tilt during October 1977 are a reflection of the east rift eruption and rapid summit deflation during September 13 -October 1. Note the dramatic decrease in summit quake activity during gradual summit deflation in October-November 1978. Lack of a corresponding increase in rift seismicity suggests that magma drained from the summit region into the rift zone through relatively open passageways during this interval. A similar episode occurred during August-September 1976, but these two events are unique during 25 years of daily tilt monitoring at Kilauea. They presumably reflect opening of the east rift zone by differential movements associated with the November 1975 M = 7.2 earthquake. Forcible intrusions into the rift zone on 29 May, 15 July, 12 August, 16 November (eruption) 1979; 2 March, 10 March, and 27 August 1980 were marked by rapid summit deflations and east rift seismic swarms.

Figure 3 - Results of dry tilt surveys along Kilauea's middle east rift zone during July - December 1978. Inflation of the rift zone reflects relatively passive, steady magma transfer from the summit reservoir to the rift zone which has become more prevalent since the November 1975 earthquake.

Figure 4 - Epicenter and cross-section plots for the 29 May 1979 intrusion into the upper east rift zone.

Figure 5 - Epicenter and cross-section plots for the 15 July 1979 earthquake swarm along the middle east rift zone.

Figure 6 - Epicenter and cross-section plots for the 12 August 1979 intrusion into the upper east rift zone.

Figure 7 - Epicenter and cross-section plots for the 2 March 1980 intrusion into the upper east rift zone.

Figure 8 - Epicenter and cross-section plots for the 10 March 1980 intrusion into the upper east rift zone.

Figure 9 - Summary of oscillatory summit tilting during April - August 1980. During this unique interval, episodes of steady summit inflation as recorded by an Ideal-Aerosmith mercury capacitance tiltmeter (middle) were accompanied by corresponding increases in summit earthquakes (top). With the onset of gradual deflation, summit quakes decreased and east rift quakes increased markedly (bottom). This close interplay between summit and east rift magma storage demonstrates the importance of relatively gradual transfer of magma from summit to rift.

Figure 10 - Epicenter and cross-section plots for the 27 August 1980 intrusion into Kilauea's upper east rift zone.

Figure 11 - Inferred magma supply to Kilauea during March-August 1980. The Uwekahuna water-tube tiltmeter record (A) reveals a sequence of summit tilt oscillations interpreted to reflect episodic magma transfer from summit to east rift storage. Calculated storage changes along the rift zone are shown in (B), and the net magma supply as a function of time (A+B) is shown in (C). The time derivative of the net supply is plotted in units of average monthly supply rate in (D).

Figure 12 - Inferred magma supply to Kilauea during October 1977 - August 1980. The Uwekahuna water-tube tilt record (A) reveals a general trend of summit inflation punctuated by frequent small deflations and intrusions into the east rift zone. We interpret this record as an approximate measure of magma storage changes within a near-summit reservoir. The calculated rate of magma delivery to the east rift zone is shown in (B), and the inferred net supply (A+B) is given by (C). Finally, the time derivative of the net supply is presented as a monthly magma supply rate in (D).

Figure 13 - Inferred magma supply to Kilauea during July 1956 - August 1980. (A) Summit storage changes as recorded by Uwekahuna water-tube tiltmeter; (B) calculated magma delivery to Kilauea's east rift zone; (C) net magma supply (A+B); and (D) monthly magma supply rate. Supply rates prior to 1960 are probably too high owing to noise in the Uwekahuna tilt record.

Figure 14 - Cumulative seismic energy release of deep harmonic tremor episodes beneath Kilauea. Deep tremor typically occurs at 40-50 km depth and is assumed to originate within or immediately above a zone of partial melting in the upper mantle. We infer a relatively constant magma production rate at depth, with perhaps a slight increase during sustained eruptions in 1967-73. Note that there is no evidence for a decrease in production rate since 1975, even though the supply rate to Kilauea has seemingly decreased by roughly 40%. This suggests that partitioning of the shallow magma supply has changed since 1975. Most likely recipients of the missing magma are Kilauea's east rift zone and/or neighboring Mauna Loa.

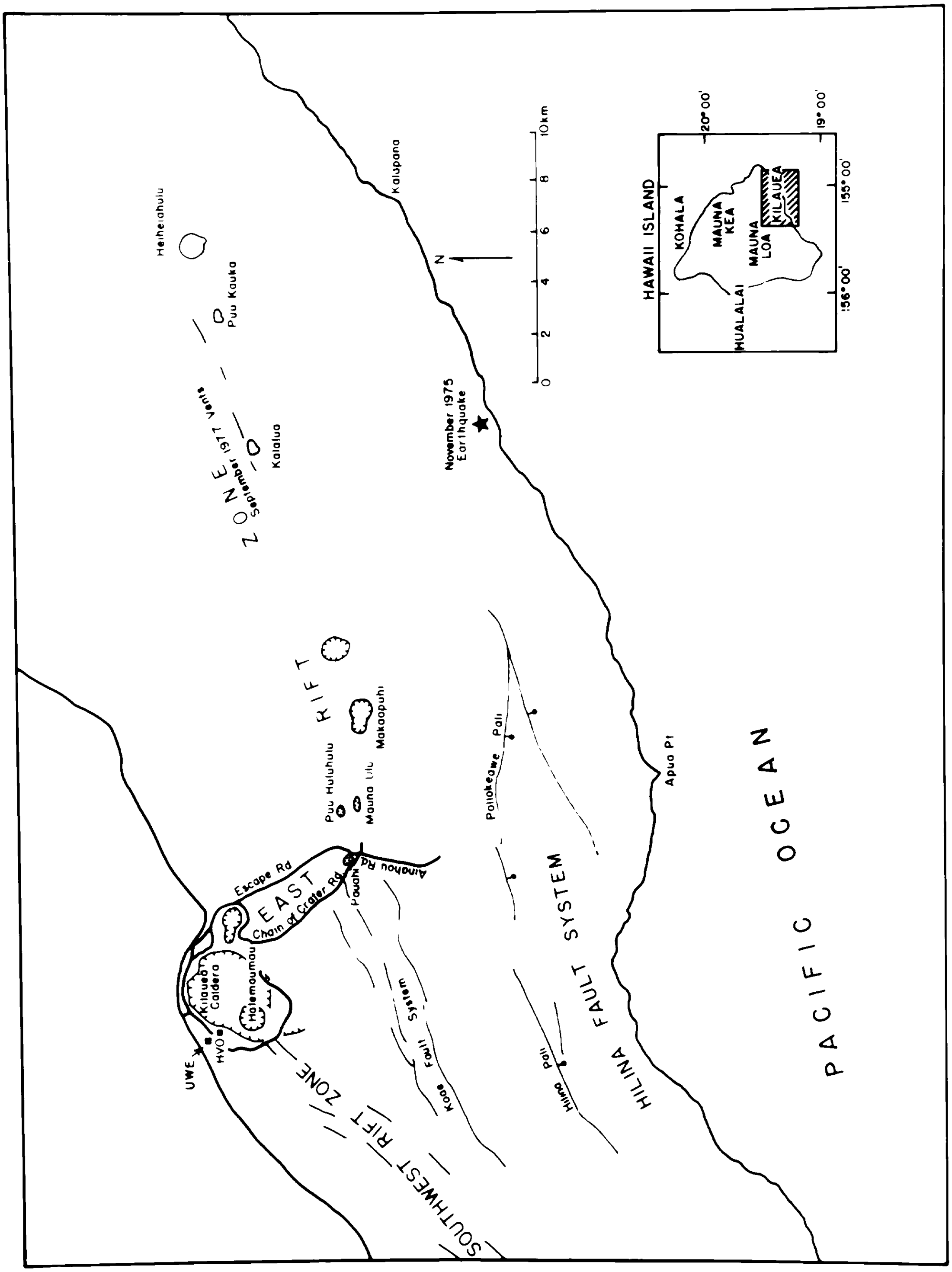

EAST RIFT ZONE
SOUTHWEST RIFT ZONE
HILINA FAULT SYSTEM
Koae Fault System
PACIFIC OCEAN
Kilauea Caldera
Halemaumau
HVO
UWE
Escape Rd
Chain of Craters Rd
Ainahou Rd
Pauahi
Puu Huluhulu
Mauna Ulu
Makaopuhi
Poliokeawe Pali
Hilina Pali
Apua Pt
Kalapana
November 1975 Earthquake
Kalalua
September 1977 Vents
Puu Kauka
Heiheiahulu
N
0 2 4 6 8 10km
HAWAII ISLAND
KOHALA
MAUNA KEA
MAUNA LOA
HUALALAI
KILAUEA
20°00'
19°00'
156°00'
155°00'

Figure 1

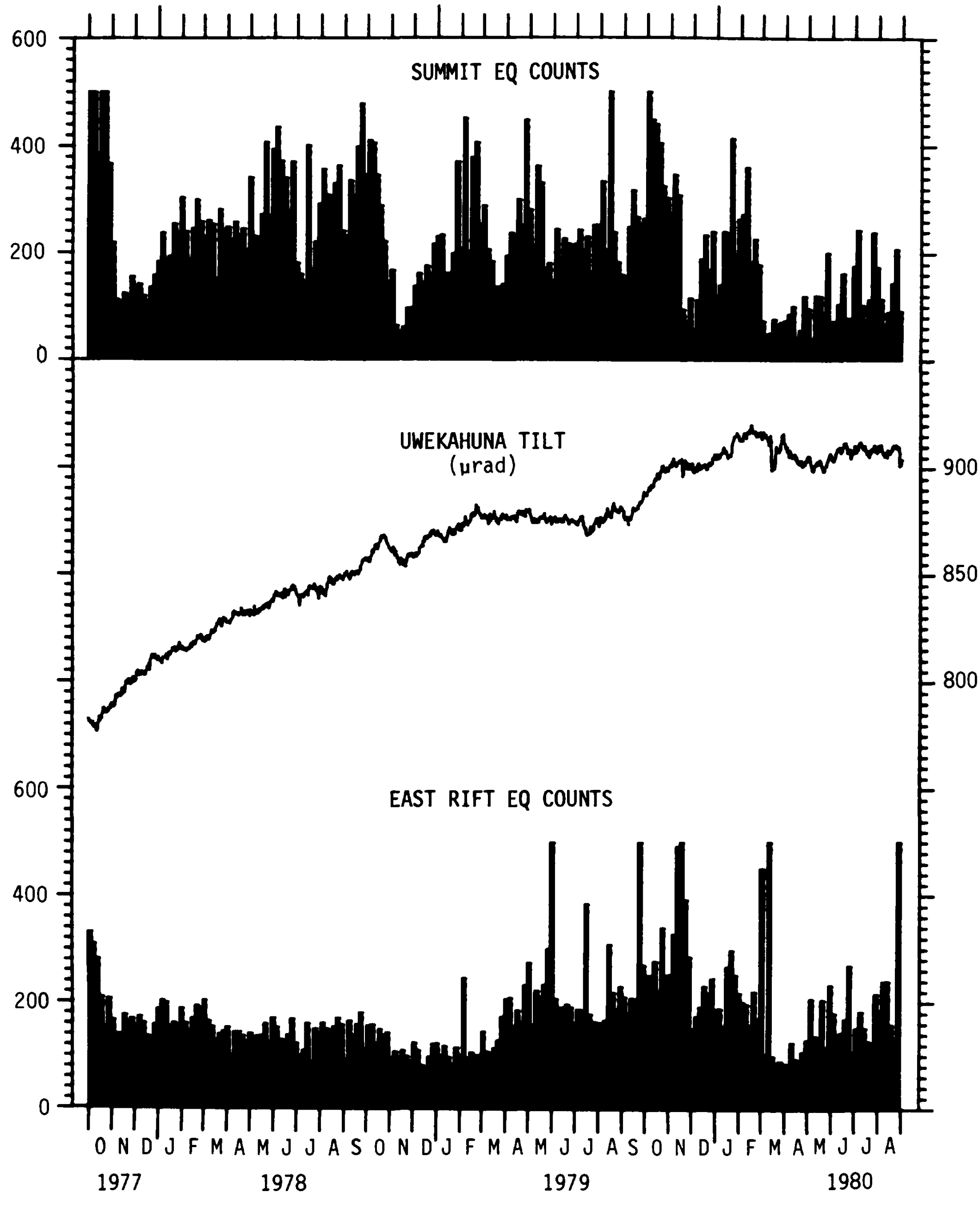
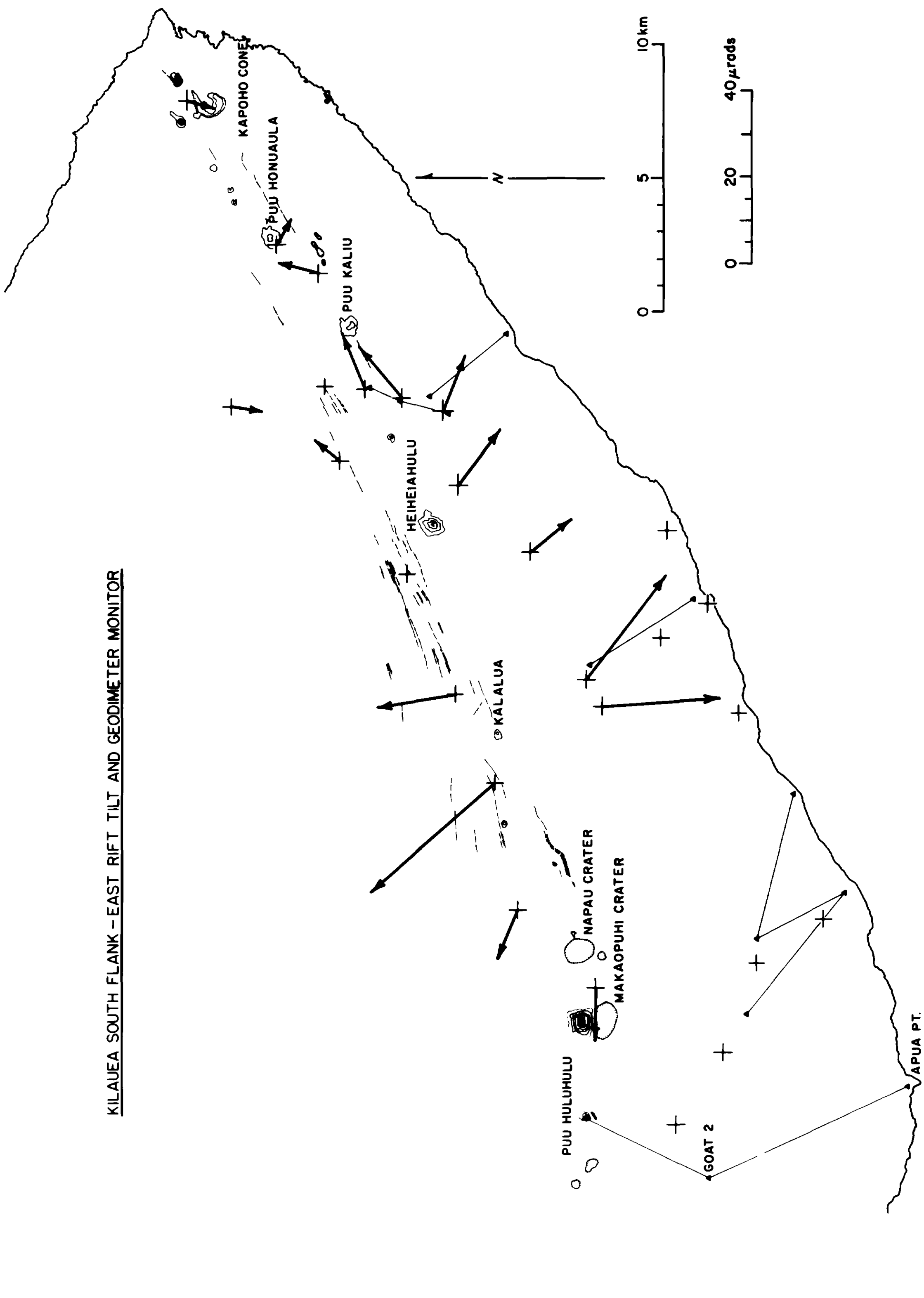

SUMMIT EQ COUNTS
600
400
200
0
UWEKAHUNA TILT
(μrad)
900
850
800
EAST RIFT EQ COUNTS
600
400
200
0
O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A
1977
1978
1979
1980

Figure 2



KILAUEA SOUTH FLANK-EAST RIFT TILT AND GEODIMETER MONITOR

Figure 3

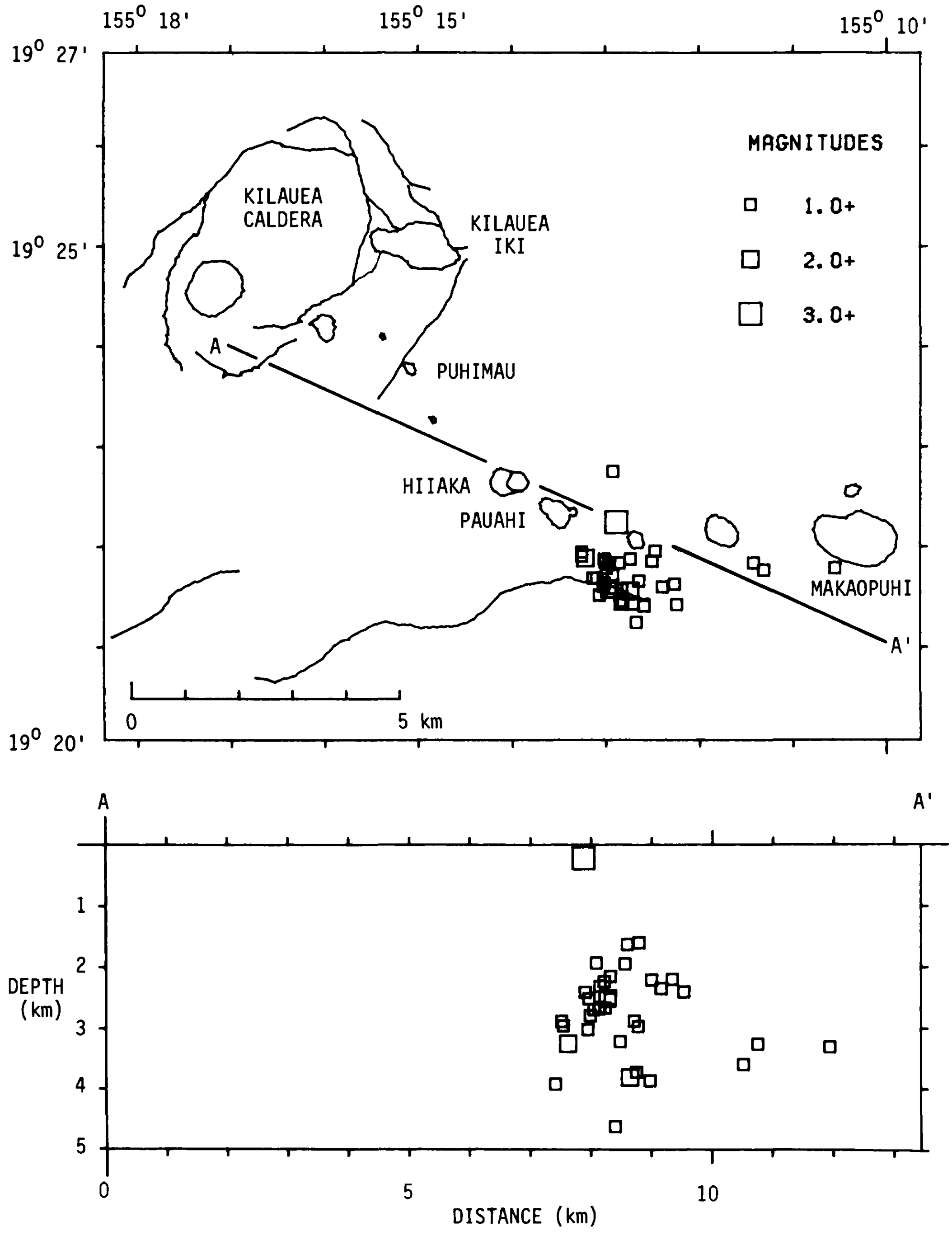

155° 18'
155° 15'
155° 10'
19° 27'
19° 25'
19° 20'
MAGNITUDES
1.0+
2.0+
3.0+
KILAUEA
CALDERA
KILAUEA
IKI
PUHIMAU
HIIAKA
PAUAHI
MAKAOPUHI
A
A'
0
5 km
DEPTH
(km)
1
2
3
4
5
0
5
10
DISTANCE (km)

Figure 4

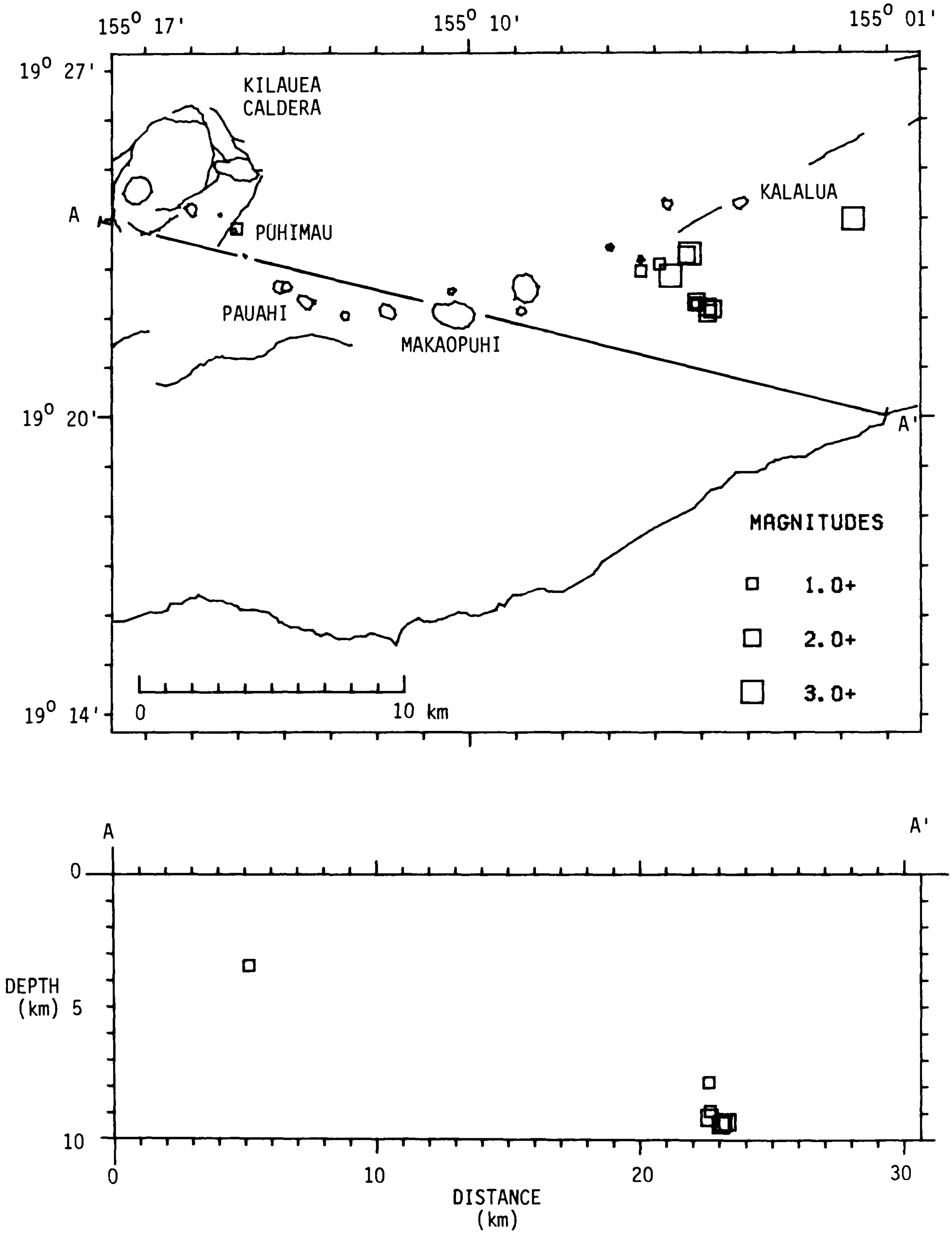

155° 17'
155° 10'
155° 01'
19° 27'
19° 20'
19° 14'
KILAUEA
CALDERA
A
PUHIMAU
KALALUA
PAUAHI
MAKAOPUHI
A'
MAGNITUDES
1.0+
2.0+
3.0+
0
10 km
A
A'
0
DEPTH
(km) 5
10
0
10
20
30
DISTANCE
(km)

Figure 5

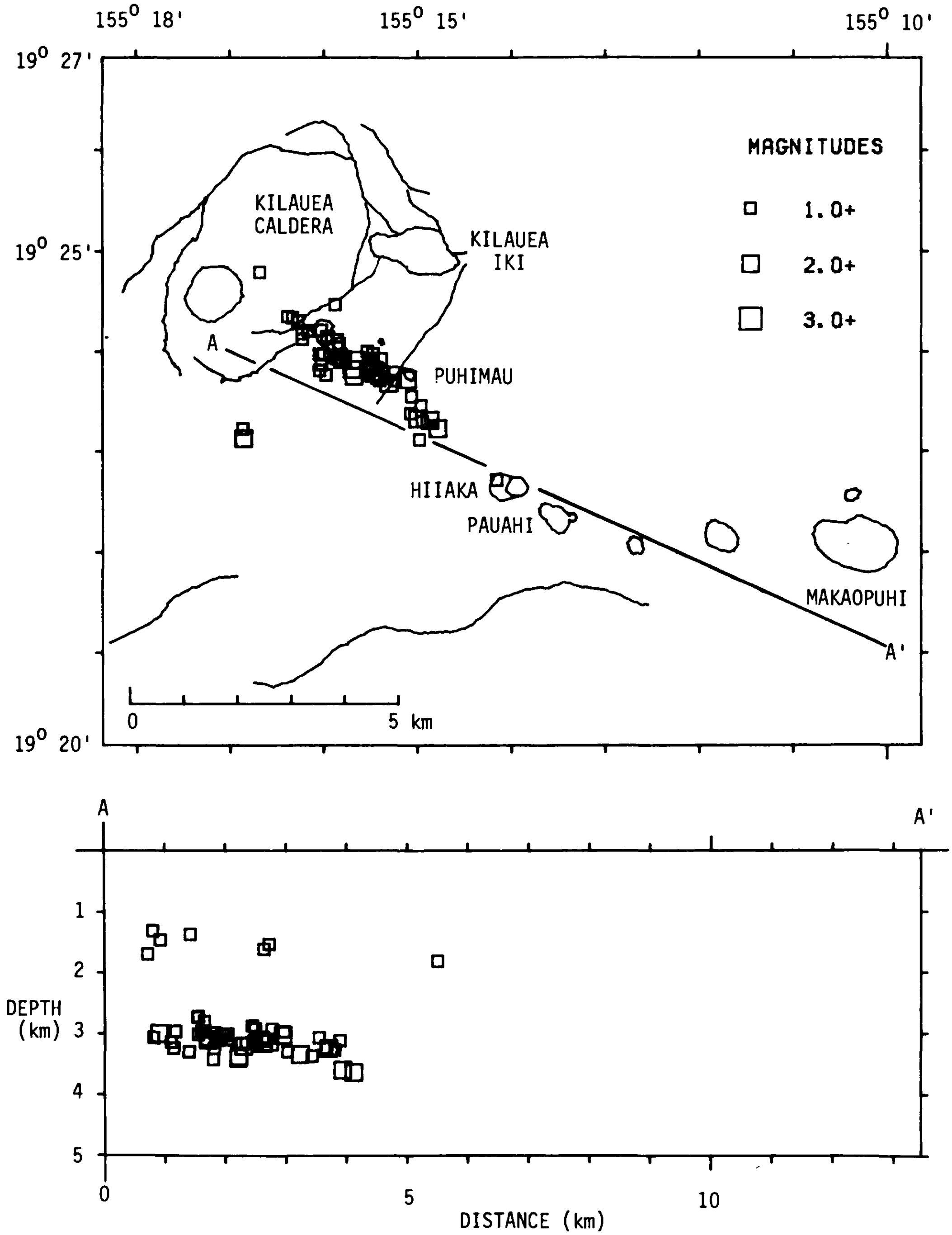

155° 18'
155° 15'
155° 10'
19° 27'
19° 25'
19° 20'
MAGNITUDES
1.0+
2.0+
3.0+
KILAUEA
CALDERA
KILAUEA
IKI
A
PUHIMAU
HIIAKA
PAUAHI
MAKAOPUHI
A'
0
5 km
A
A'
1
2
DEPTH
(km) 3
4
5
0
5
10
DISTANCE (km)

Figure 6

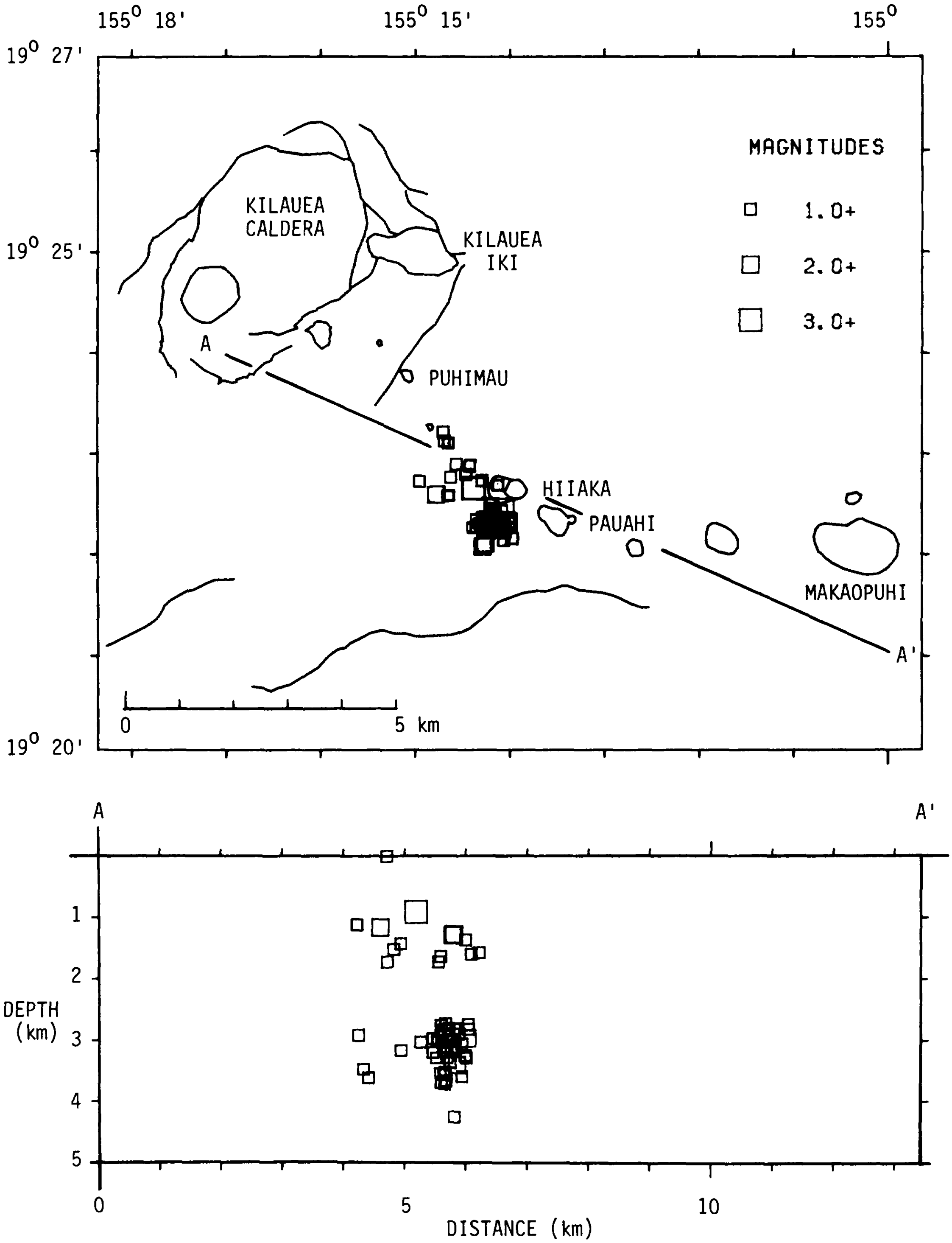

155° 18'
155° 15'
155°
19° 27'
19° 25'
19° 20'
MAGNITUDES
1.0+
2.0+
3.0+
KILAUEA
CALDERA
KILAUEA
IKI
A
PUHIMAU
HIIAKA
PAUAHI
MAKAOPUHI
A'
0
5 km
A
A'
1
2
DEPTH
(km)
3
4
5
0
5
10
DISTANCE (km)

Figure 7

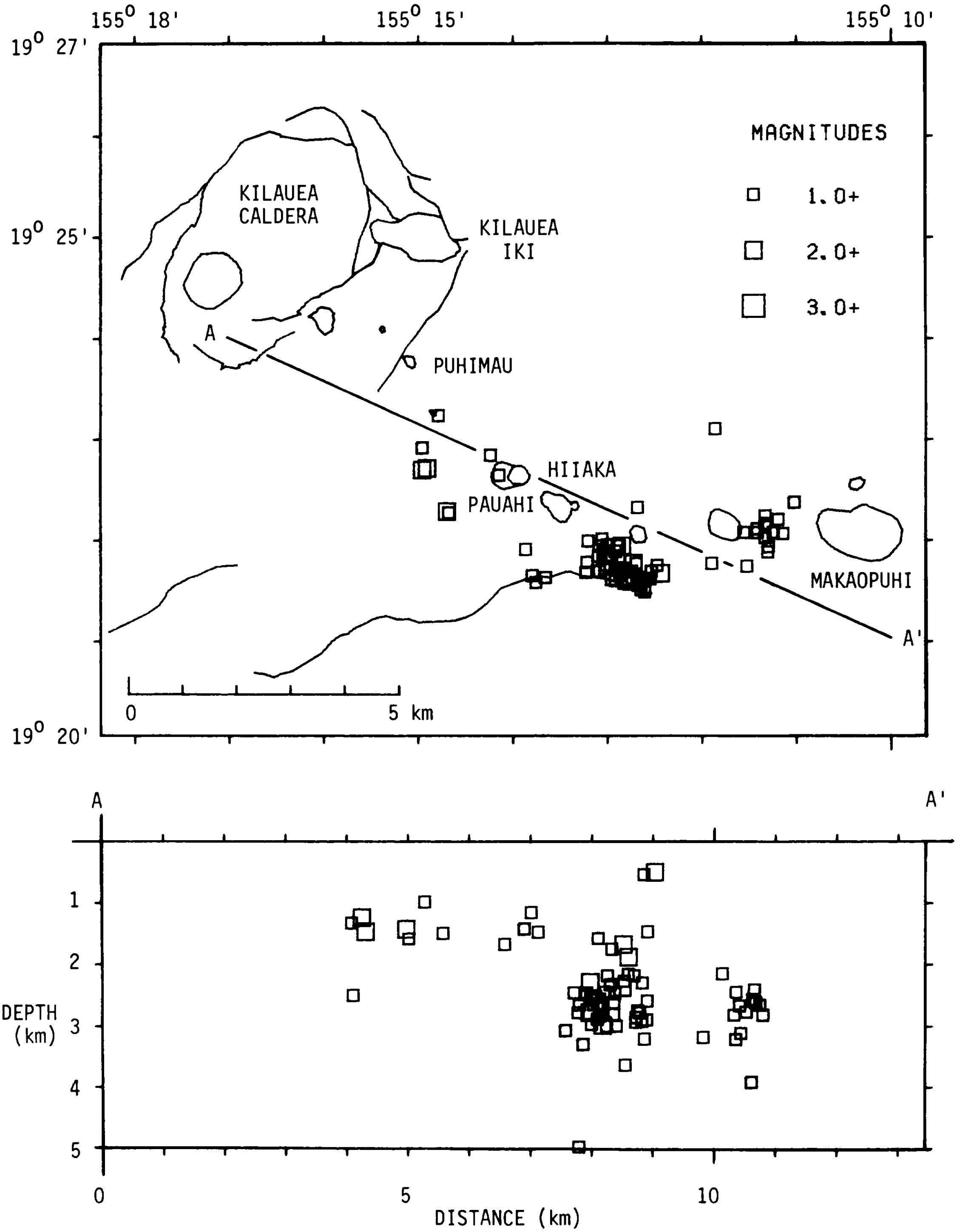

155° 18'
155° 15'
155° 10'
19° 27'
19° 25'
19° 20'
MAGNITUDES
1.0+
2.0+
3.0+
KILAUEA CALDERA
KILAUEA IKI
PUHIMAU
HIIAKA
PAUAHI
MAKAOPUHI
A
A'
0
5 km
A
A'
1
2
3
4
5
DEPTH (km)
0
5
10
DISTANCE (km)

Figure 8

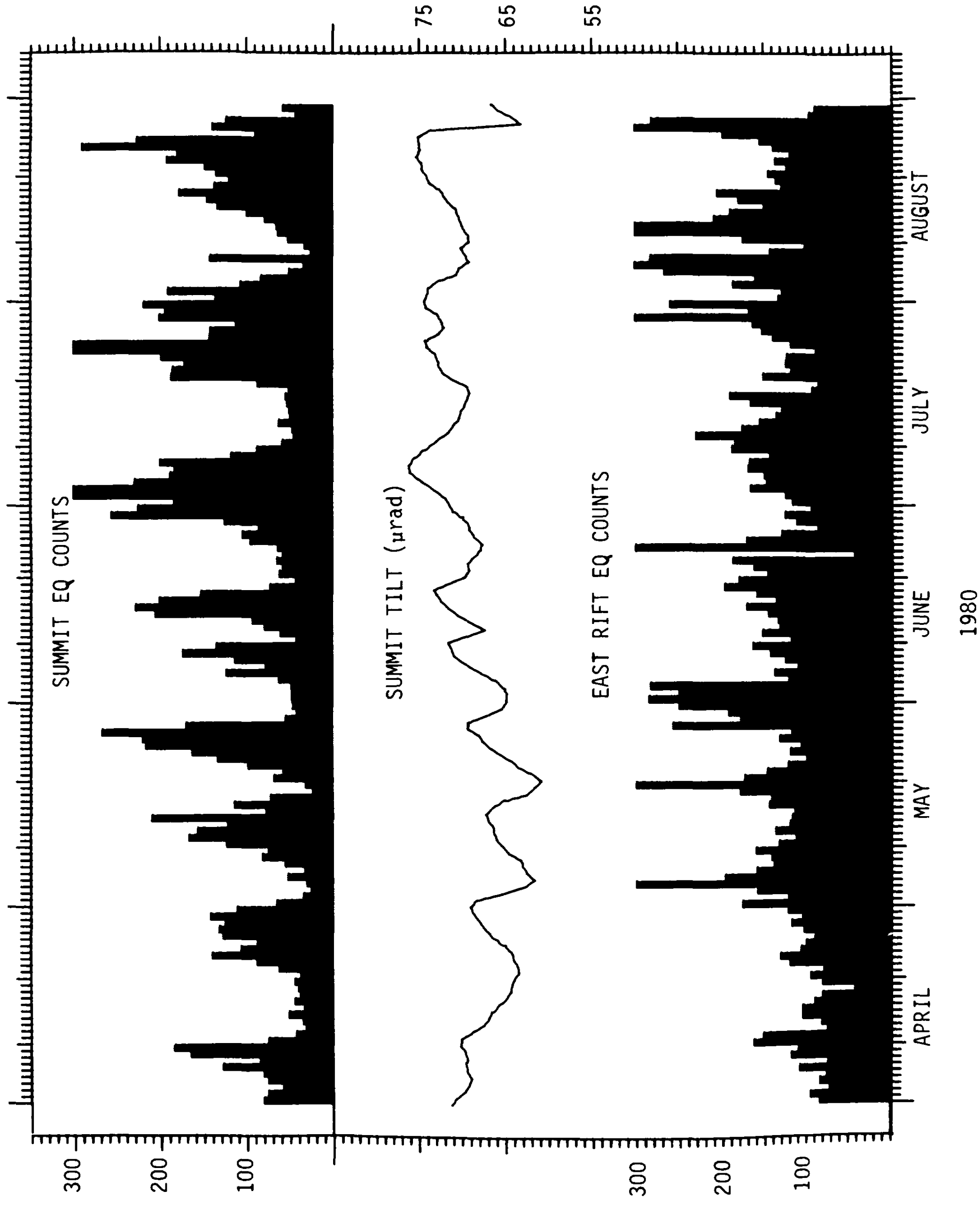

SUMMIT EQ COUNTS
SUMMIT TILT (μrad)
EAST RIFT EQ COUNTS
300
200
100
75
65
55
300
200
100
APRIL
MAY
JUNE
JULY
AUGUST
1980

Figure 9

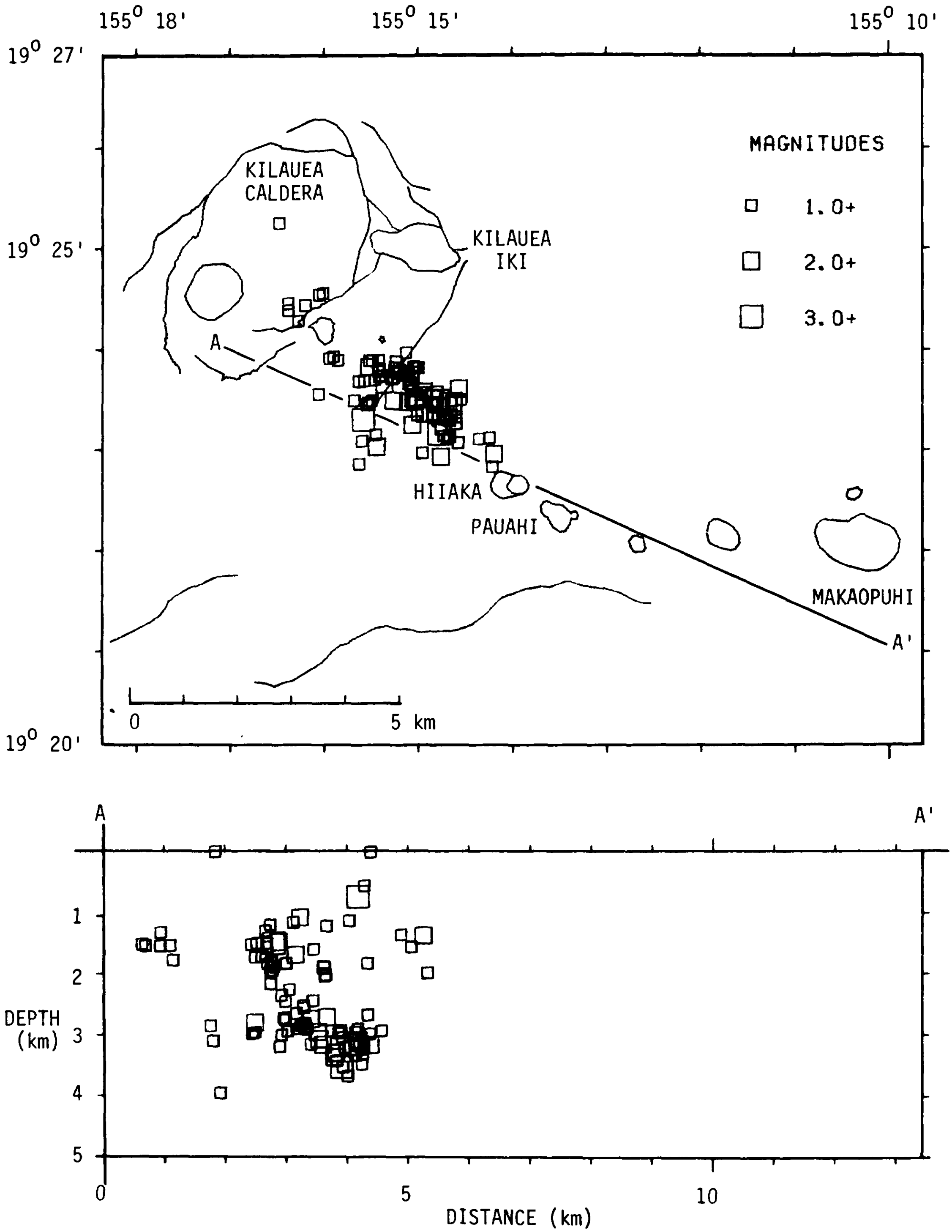

155° 18'
155° 15'
155° 10'
19° 27'
19° 25'
19° 20'
KILAUEA
CALDERA
KILAUEA
IKI
MAGNITUDES
1.0+
2.0+
3.0+
A
A'
HIIAKA
PAUAHI
MAKAOPUHI
0
5 km
A
A'
1
2
3
4
5
DEPTH
(km)
0
5
10
DISTANCE (km)

Figure 10

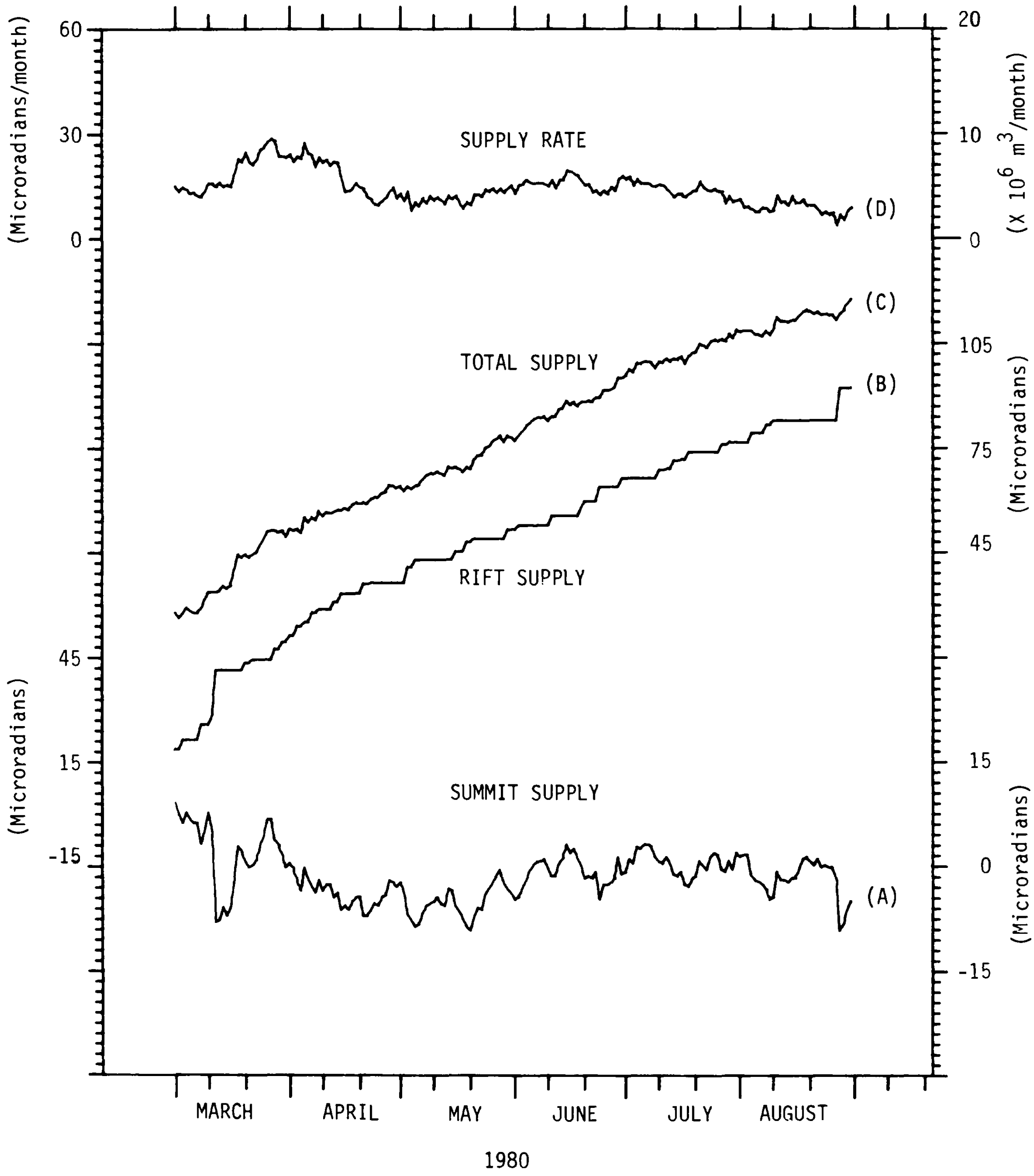

(Microradians/month)
60
30
0
SUPPLY RATE
(D)
20
10
0
(X 10^6 m^3/month)
TOTAL SUPPLY
(C)
105
(B)
75
(Microradians)
45
RIFT SUPPLY
45
15
(Microradians)
15
SUMMIT SUPPLY
-15
0
(A)
-15
(Microradians)
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
1980

Figure 11

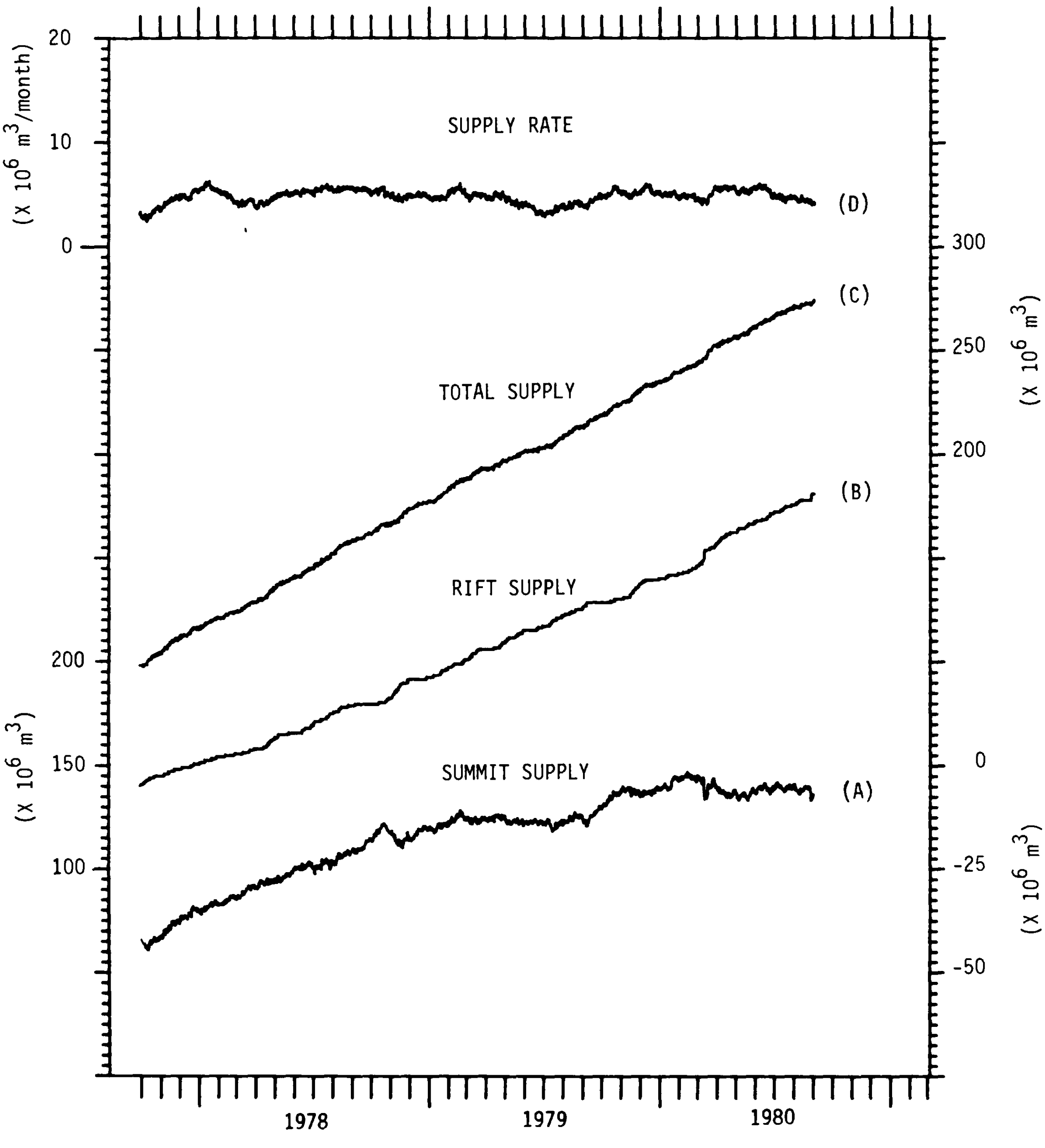
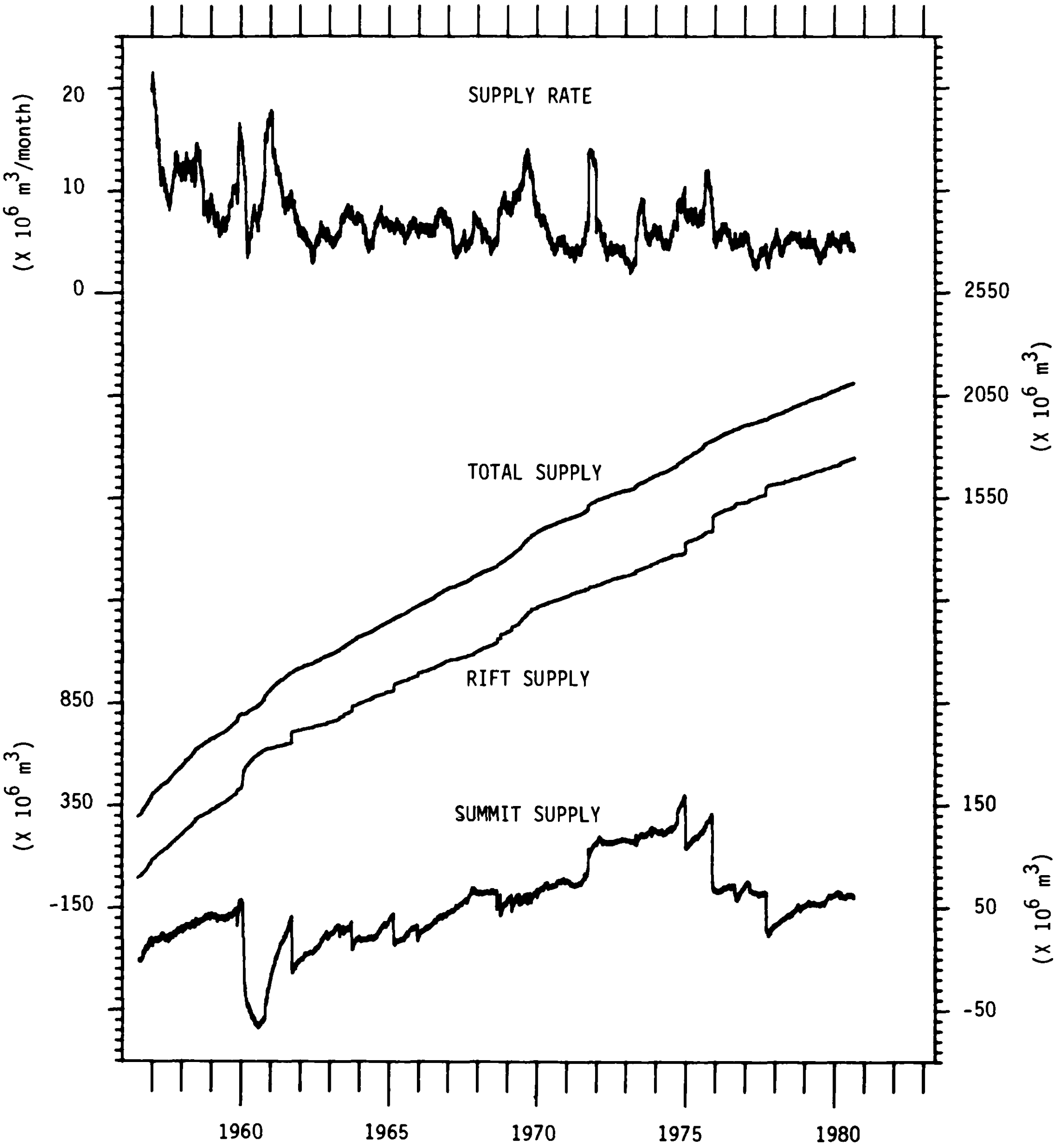

20
10
0
(X 10^6 m^3/month)
SUPPLY RATE
(D)
300
(C)
250
(X 10^6 m^3)
TOTAL SUPPLY
200
(B)
RIFT SUPPLY
200
150
100
(X 10^6 m^3)
0
SUMMIT SUPPLY
(A)
-25
(X 10^6 m^3)
-50
1978
1979
1980

Figure 12



SUPPLY RATE
TOTAL SUPPLY
RIFT SUPPLY
SUMMIT SUPPLY
(X 10^6 m^3/month)
20
10
0
850
350
-150
(X 10^6 m^3)
2550
2050
1550
(X 10^6 m^3)
150
50
-50
(X 10^6 m^3)
1960
1965
1970
1975
1980

Figure 13

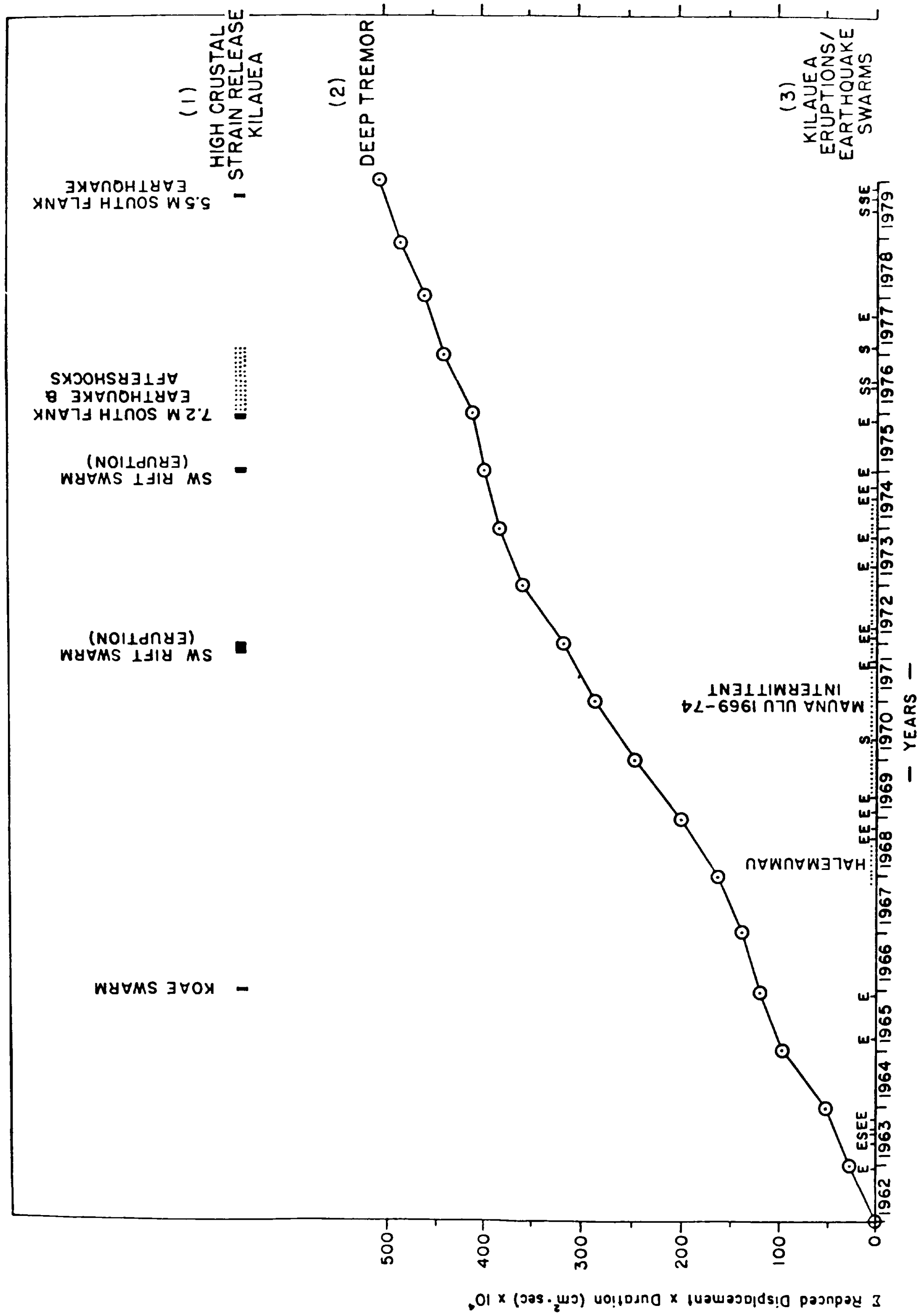

(1) HIGH CRUSTAL STRAIN RELEASE KILAUEA
(2) DEEP TREMOR
(3) KILAUEA ERUPTIONS/ EARTHQUAKE SWARMS
5.5 M SOUTH FLANK EARTHQUAKE
7.2 M SOUTH FLANK EARTHQUAKE & AFTERSHOCKS
SW RIFT SWARM (ERUPTION)
SW RIFT SWARM (ERUPTION)
KOAE SWARM
HALEMAUMAU
MAUNA ULU 1969-74 INTERMITTENT
1962 1963 1964 1965 1966 1967 1968 1969 1970 1971 1972 1973 1974 1975 1976 1977 1978 1979
— YEARS —
0 100 200 300 400 500
Σ Reduced Displacement x Duration (cm²·sec) x 10⁴

Figure 14