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Volcanic Activity and Ground Deformation Hazard Analysis for the Hawaii Geothermal Project Environmental Impact Statement

By

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1.0 Introduction

As conceived in a 1990 proposal to Congress by the State of Hawaii, the Hawaii Geothermal Project would involve the development of a geothermal resource for electrical power production within three legislatively-defined (Act 296, Session Laws of Hawaii, 1983) geothermal subzones on the east rift zone of Kilauea volcano. The Project would include overland transmission of this power to the west coast of Hawai'i (Fig. 1). From there to O'ahu, the power would be transmitted principally via submarine cable. In this report, lava flow and ground deformation hazard are evaluated for the three legislatively-defined geothermal subzones and the three proposed overland transmission routes (Stroud, 1993, written communication). The time interval for evaluating hazards was chosen as 50 years because that is consistent with seismic design standards in the Uniform Building Code, and because of limited information on occurrence dates.

The geothermal subzones and the first leg of the overland transmission routes are located on the east rift zone (ERZ) and northeast flank of Kilauea Volcano. Kilauea is an active volcano that has been erupting continuously for the past 11 years from vents a few kilometers west of the western geothermal subzone. The overland transmission routes then continue across the northeast flank of the active volcano Mauna Loa and the dormant volcano Mauna Kea to their ultimate destination on the western flank of the extinct volcano of Kohala. Neither Mauna Kea nor Kohala has been active in the past several thousand years.

2.0 Methods

The primary basis for estimating potential hazards posed by volcanic activity or ground deformation in any area is the record of past volcanic activity or deformation in that area. Accordingly, the type and frequency of volcanic activity and deformation that have occurred in each of three broad areas - the northeast flank and lower east rift zone (LERZ) of Kilauea volcano, the north and east flank of Mauna Loa volcano, and the flanks of Mauna Kea and Kohala volcanoes - are reviewed.

2.1 Estimation of volcanic hazard potential:

2.1.1 Previous estimates: Previous volcanic hazard analyses for Hawai'i rated relative severity of hazard in a qualitative fashion. Lava flow hazard zones in Hawai'i (Fig. 2) have been defined by Mullineaux et al. (1987), Heliker (1990), and Wright et al. (1992) on the basis of volcanic structure, terrain, and degree of coverage by lava flows. Fig. 2 shows the Hazard Zone map of Hawai'i from Wright et al. (1992). Hazard Zone 1 includes the summit calderas and rift zones of Kilauea and Mauna Loa volcanoes. More than 25% of Hazard Zone 1 has been covered by lava in the past 200 years (Heliker, 1990). Between 15% and 25% of Hazard Zone 2 has been covered by lava in the past 200 years and less than 5% of Hazard Zone 3 has been covered by lava in the same period. Hazard Zones 4 through 9 reflect decreasing frequency of eruptions or areas shielded from lava flows by topography.

As a general rule, the area covered by lava flows increases with time on active volcanoes (Wright and others, 1992; Heliker, 1990). More than 65% of Hazard Zone 1 has been covered in the past 750 years. More than 90% of Kilauea's surface in any Hazard Zone has been covered in the past 1500 years, or approximately since the time of first Polynesian contact (Kirch, 1985). If desired, these figures could be used to estimate an average rate of coverage of greater than 10% per century in Hazard Zone 1, 5-10% per century in Hazard Zone 2 and less than 5% per century in Hazard Zone 3.

There are difficulties with using either rate or percentage of coverage as a measure of potential hazard. First, coverage percentages can be misleading if the areas of the zones are significantly different. For example, if the areas covered by lava are measured (Table 1), we see that more area in Hazard Zone 2 was covered by lava than Hazard Zone 1 in this period in both the Kilauea east rift zone and the Mauna Loa northeast rift zone. Rates of areal coverage are maximum for Hazard Zone 2, not Hazard Zone 1. Almost ten times as many km^2 were covered within the past 150 years in the Mauna Loa northeast rift zone section of Hazard Zone 2 than 1, yet Hazard Zone 1 has a higher Hazard Zone rating based on percentage coverage. Second, measuring coverage using data from the most recent past can be misleading because it is a measure of land *not already covered within that period.* If the first lava flow within this period covers, for example, 10% of an area and a subsequent lava flow completely covers the first, the combined coverage by the first and second flows is still 10%. Unfortunately, estimates of areal rate of lava coverage cannot be converted to a probability of lava flow coverage. A measure more relevant to lava flow hazard would be the number of times a given region is affected by lava within a given period of time.

Table 1: Coverage by lava within the last 200 (Kilauea) and 150 (Mauna Loa) years.

Hazard Zone	Kilauea (%)	Kilauea (km^2)	Mauna Loa (%)	Mauna Loa (km^2)
1	39.9	110	57.3	20.2
2	34.4	144	33.1	186
3	2.9	20.4	1.6	15.5

Volcanic hazard assessments have been part of Environmental Impact Statements (EIS) for various projects in Hawai'i. The EIS for the Kahauale'a Geothermal Project (True/Mid-Pacific Geothermal Venture, 1982) divided up the Campbell Estate's Kahauale'a tract into four zones of relative volcanic hazards potential, qualitatively rated from highest to low (Figure 3). The zone of highest volcanic hazards potential was about 2 km wide and the northernmost boundary was coincident with the northernmost eruptive fissures that were active in the early- to mid-1960s. This assessment is particularly interesting because the ongoing eruption of the Pu'u 'O'o and Kupaianaha vents began in 1983 within this zone of highest volcanic hazards potential. The areal distribution of this eruption shown on Figure 3 can be used to calculate that, as of 1993, (1) 100% of the zone of "highest" volcanic hazards potential, (2) 75% of the zone of "high" volcanic hazards potential, and (3) 5% of the zone of "moderate" volcanic hazards potential, has been covered. The hazard assessment for this area was unusually prophetic.

A more quantitative hazard assessment has recently been completed for the draft EIS covering the Conceptual Plan for the Commercial Satellite Launching Facility at Palima Point on the southwest rift zone (SWRZ) of Kilauea Volcano (Legg, 1993). The area downslope of the SWRZ is concluded to have the highest potential for burial by lava flows at about 50 percent for a 50-year time span. The area to the north and west of the SWRZ is estimated to have a probability of burial by lava of less than 5 percent for a 50-year time span. Although not specifically relevant to the Hawaii Geothermal Project because of its location, this assessment is of interest because of the use of probabilistic methods on Kilauea.

2.1.2 Probabilistic estimates of volcanic hazard: Ideally, hazards posed by volcanic activity should be analyzed in terms of probability of occurrence, which is most useful for planning purposes. Theoretical probability of inundation by lava can be calculated using the equation (Kilburn, 1983)

$$Prob=\sum P_v(t)\times P_v(b)\times P(c)\times T_c\times D_v \quad (1)$$

where $P_v(t)$ is the probability of an eruption for each vent within the catchment area;
$P_v(b)$ is the probability of burial of the catchment area by the flows from each vent;
$P(c)$ is the proportion of catchment area covered by vents with density, D_v;
T_c is the total size of the catchment area; and
D_v is the vent density (vents/unit area) within each vent area of the catchment region.

Inundation by lava is defined as a lava flow covering part or all of a selected area. A catchment area is defined by topography as the region in which an eruption could conceivably affect the area of interest, usually a town or development. For the purpose of estimating the lava flow hazard for a specific area, attention is confined to that area's catchment only. For example, Kilauea southwest rift eruptions are unimportant when assessing the lava flow hazard in the vicinity of the Kilauea east rift zone because the southwest rift zone is not within the catchment of the east rift zone.

For any selected area within a catchment area, equation (1) simply states that the probability of lava inundation is proportional to the probability of an eruption within the catchment within the time period of interest, $P_v(t)$, reduced by the probability that any lava flow produced by such an eruption will reach that area, $P_v(b)$. Although this is a complete formulation for estimating potential lava flow hazard, it is more direct to estimate probability of inundation by lava directly from the frequency of lava flows which have inundated the region of interest in the past.

A probability of inundation by lava flows for any specified region can be evaluated using an estimate of the recurrence interval of inundation for that region (Kauahikaua et al., 1993). Using local information about the frequency of lava flows that have already reached the selected area in the past is more direct than the theoretical approach of eq. (1) which predicts the probability of a number of various factors influencing whether a lava flow will reach the selected area. Assuming that time intervals between lava flows are randomly distributed in a Poisson fashion, the probability of inundation by *n* lava flows within a given time interval, t_i , can be estimated from the mean recurrence interval, *T*, of past inundation in an area as

$$Prob_n = \left(\frac{t_i}{T}\right)^n \frac{e^{-\frac{t_i}{T}}}{n!} \qquad (2)$$

(Scheidegger, 1975, p. 71). The probability of occurrence of a lava flow within the time interval, *t*, which is the same as the probability of having a recurrence interval shorter than *t* or one minus the probability of having no eruptions (equation 2 with n=0), is

$$Prob(t) = 1 - e^{-\frac{t}{T}} \qquad (3)$$

(Klein, 1982). In any given region, the probability of inundation by lava flows will increase with decreasing recurrence interval, *T*, and increasing evaluation interval, *t*.

Estimation of recurrence interval, *T*, is therefore the most crucial step. A number of papers have been written on the estimation of recurrence intervals and the appropriateness of Poisson distributions for eruption intervals of volcanoes (Wickman, 1966; Klein, 1982). These techniques should apply equally well to the estimation of recurrence intervals for lava flows covering a limited area on a volcano. Recurrence intervals for limited areas should be longer than those for all eruptions of the respective volcano because not all eruptions of a given volcano will affect the limited area.

The most statistically-sound method of estimating the probability of lava inundation within 50 years would be to determine the number of lava flow occurrences in 50-year intervals as far back into the past as possible, obtain an average frequency per 50-year interval (equivalent to 1/T), and then use equation (2) to estimate the probability of a single eruption within the next 50-year interval (de la Cruz-Reyna, 1991). With this type of information, we can further examine the manner in which the flow frequencies are distributed [i.e., check whether they are really Poissonian and thereby justifying the use of equations (2) and (3)]. Ideally, thee calculations would be based on a complete list of all lava flows that have flowed into the selected area for several thousand years into the past and their ages. Such a list is not obtainable, but more limited information is available from other sources including drill holes with detailed lithologic logs and geologic maps of individual surface flows. Unfortunately, even though all discernible flow units may have been mapped individually in the study area or have been logged in a drill hole, rarely are all units dated. Almost all events after 1790 have good dates, but few prior events can be accurately dated with less than 50-year error. Therefore, it is not possible to obtain lava flow frequencies in suitably short, uniform-length time intervals for much of the geologic record. The smallest intervals for the recent past in which flow ages can be lumped confidently are generally 200 to 1,000 years.

Given the type of data available, the most direct way of estimating a recurrence interval is to divide the age of the oldest flow by the number of flows within the chosen area. Mathematically, this is exactly equivalent to taking the reciprocal of the mean of the number of flows within 50-year intervals (Ho et al., 1991). If any bias is present in this estimation, it would be due to some flow units being completely covered and not represented at the surface. The number of flows within the area would be underestimated and the recurrence interval would be overestimated.

The inability to compare flow frequency distributions with the theoretical Poisson distribution is a problem. Both Mauna Loa and Kilauea have erupted at highly variable intervals during their geologic histories. Mauna Loa may have been more active within the past 1,000 years than in any similar length period within the past 20,000 years (Lockwood and Lipman, 1987). The lower east rift zone of Kilauea, on the other hand, has been less active in the past 200 years than previously (Moore, 1992). Guidance is not completely absent on this point because the eruption records of both Kilauea and Mauna Loa are distinctly random over portions of the past 200 years (Wickman, 1966; Klein, 1982). Lacking a way to compare our specific distributions with a Poisson or any other theoretical distributions, we will arbitrarily assume Poisson distributions for flow frequencies, estimate a long-term and a most-recent-past recurrence interval, and choose the shorter of the two recurrence interval estimates in order to yield the highest probabilities.

The distribution and age of many lava flows has been determined for the lower east rift zone (LERZ) of Kilauea (Moore and Trusdell, 1991) and the northeast flank of Mauna Loa (Buchanan-Banks, 1993; Lockwood et al., 1992). Hagstrum and Champion (1994) recently revised the chronology of the Kilauea LERZ mapping of Moore and Trusdell (1991) based on paleomagnetic correlations between units which reduced the total number of unique lava flow events in this area. Both chronologies are used below in an example to bracket probabilities. The maps of Moore and Trusdell (1991), Buchanan-Banks (1993) and Lockwood et al. (1992) for Kilauea and Mauna Loa have been converted to digital form so that the Geographic Information System (GIS) software packages ARC/INFO and MapInfo could be used to count all flow units within a selected region. The most detailed geologic maps of Mauna Kea and Kohala are those of Wolfe and Morris (1989); however, these do not distinguish all individual flow units.

The use of equation (3) allows the calculation of probabilities for any time interval given the recurrence interval. For example, a recurrence interval of 25 years means that there is a probability of 86% that at least one event will occur in 50 years, 70% in 30 years, and 4% in one year. Use of equation (3) is essential to extrapolate to other time intervals because, as can be seen from this example, probabilities based on a Poisson distribution cannot be linearly interpolated. For example, linearly extrapolating, a 4% probability of at least one event in one year into a 100% probability of at least one event in 25 years is clearly erroneous; the correct probability of at least one event in 25 years is 63% using equation (3).

An example of this type of lava flow hazard assessment illustrates the relationship between the hazard zones of Wright and others (1992) and calculated probabilities of inundation. It also shows the effect of lava flow chronology on hazards estimation. For the Kilauea LERZ (east of 155° longitude), the hazard zonation of Wright et al. (1992) does reflect a difference in frequency of coverage by lava flows over the past 2400 years. Table 2a shows the tabulation of flows found within each Hazard Zone of Wright et al. (1992) using the flow units of Moore and Trusdell (1991). Table 2b uses the revised LERZ chronology of Hagstrum and Champion (1994) for most units and that of Moore and Trusdell (1991) for all units not identified by Hagstrum and Champion (1994). Using the recurrence intervals in table 2a and equation (3), the probability of inundation by a lava flow at least once within a 50 year time span is 92% for Hazard Zone 1, 71% for Hazard Zone 2, and 22% for Hazard Zone 3. Using table 2b, the probability of inundation by a lava flow at least once within a 50 year time span is 72% for Hazard Zone 1, 64% for Hazard Zone 2, and 22% for Hazard Zone 3.

Table 2a: Calculation of recurrence interval using flow units of Moore and Trusdell (1991)

Range, years before present	No. of lava flows in Hazard Zone 1	No. of lava flows in Hazard Zone 2	No. of lava flows in Hazard Zone 3
0-200	5	4	0
200-400	13	10	1
400-750	37	30	6
750-1500	21	21	1
1500-3000	0	1	0
TOTAL	76	66	8
Average recurrence interval	19.7 years	35.8 years	187.5 years

Table 2b: Calculation of recurrence interval using flow units of Hagstrum and Champion (1994) and Moore and Trusdell (1991).

Range, years before present	No. of lava flows in Hazard Zone 1	No. of lava flows in Hazard Zone 2	No. of lava flows in Hazard Zone 3
0-200	5	4	0
200-400	10	6	1
400-750	23	14	6
750-1500	20	20	1
1500-3000	3	5	0
TOTAL	61	49	8
Average recurrence interval	>39 years	>49 years	187.5 years

The probability differences based on the two data sets range from dramatic in Hazard Zone 1 to insignificant in Hazard Zone 3 depending on which chronology is used.

The revision by Hagstrum and Champion (1994) used in Table 2b results in average recurrence intervals for the whole 2400 years represented in the Kilauea LERZ that agree with recurrence intervals calculated from the best dated flows in the last 200 years. Using the chronology of Moore and Trusdell (1991) alone results in average recurrence intervals for 2400 years which are significantly shorter than for the past 200 years. Taking this line of reasoning further, the probability of having the specific number of flows within each time interval in either Table 2a or 2b can be calculated with the respective average recurrence intervals to qualitatively assess which chronology fits a Poisson distribution best. If this is done for Hazard Zones 1 and 2 in both Tables 2a and 2b, the probabilities of having the distribution of flows in Table 2b are higher with one exception indicating a closer conformance to a Poisson distribution. Based on this analysis and comparison, the chronology of Moore and Trusdell (1991) as modified by Hagstrum and Champion (1994) will be used in analyses of Kilauea LERZ hazard.

2.1.3 Uncertainties: Uncertainties in probability estimates are due to uncertainties in the estimation of the recurrence intervals and/or inappropriateness of the Poisson distribution. The latter factor has already been discussed. The recurrence interval, *T*, is the age of the oldest flow divided by the total number of exposed flows; therefore, errors in *T* are due to errors in either of these quantities. The ages of flows less than 200 years old are known to within a few years from historical records. Radiocarbon ages used by Moore and Trusdell (1991) are quoted with standard errors of 60 years for dates between 340 to 490 years before present and 90 years for the oldest flow dated at 2360 years before present. If the number of exposed flows is equal to the number of flows which have inundated the selected area, these errors would automatically result in σ_T values of 60 to 90 years divided by the number of flows within the area. Because a few flows may be buried by younger flows, the number of exposed flows may underestimate the number of flows within the selected area, which would cause the recurrence interval to be overestimated. This in turn would result in the probability of inundation being underestimated. As has already been shown by the Hagstrum and Champion (1994) revision of the chronology of Moore and Trusdell (1991), the number of distinct flows in an area may also overestimate the number of eruptive events.

In light of these potential errors, it seems prudent to view our recurrence interval estimates as having a typical estimated error of about 1.5 to 2 years for 40-50 year recurrence intervals (Hazard Zones 1 and 2 in Table 2b) and 11 years for a 187.5 year recurrence interval (Hazard Zone 3 in Table 2b). Using these values for σ_T, the uncertainty of the probability estimates can be obtained by differentiating equation (3) with respect to T,

$$\sigma_{Prob} = \sqrt{\left(\frac{\partial Prob(t)}{\partial T}\right)^2 \sigma_T^2} = \frac{te^{-t/T}}{T^2}\sigma_T. \quad (4)$$

For t=50 years and T=40 years, the probability estimate would be 71% with an uncertainty of 1.7%. For t=50 years and T=187.5 years, the probability estimate would be 23% with an uncertainty of 1.1%.

2.2 Estimation of Ground Deformation Hazard:

There are two types of crustal motion that occur in Hawai'i categorized by rate of deformation. Vertical and horizontal motions of as much as 3-5 m occur rapidly during large earthquakes and during shallow migration and eruption of magma. These infrequent, sudden events are associated with considerable ground shaking. By contrast, motions at much more modest rates are nearly continuous, occurring at rates of as much as about 20 cm/yr near Kilauea's summit, the region of greatest deformation in Hawai'i. In the following text, both kinds of ground deformation are summarized.

The Hawaiian Territorial Survey completed triangulation of most coastal areas for horizontal control on the island of Hawai'i between 1893 and 1914. Some of these stations in east Hawai'i were reoccupied in 1949. Other stations across the entire island were reoccupied during the late 1950s and early 1960s in preparation for publication of modern USGS topographic maps. The data used for topographic maps have not been archived with the National Geodetic Survey (NGS) and are thus not available for determination of 20th century horizontal crustal motions.

Vertical control, in the form of level data, is also sparse in Hawai'i. At this time, the USGS leveling of 1957-1958 in east Hawai'i has not been archived with the NGS. Results of reoccupation of benchmarks established in the early 20th century are not readily available.

Accordingly, much of the summary presented here focuses upon data collected by the Hawaiian Volcano Observatory (HVO). These data are comprised of (1) tilt, (2) electronic distance measurement (EDM), and (3) leveling, mostly collected since the late 1960s or early 1970s. Tilt is a shear strain at a point, and tilt units of micro(μ)radians can be equated with micro(μ)strain. Similarly, distance changes can be divided by distance to obtain normal strain. Level data, the differences in height between adjacent benchmarks, can be divided by the distance between those benchmarks to obtain a tilt or shear strain. Wherever possible, data are displayed with error bars of 2 standard errors, as estimated by Delaney et al. (1993). Not enough data exist documenting ground deformation to make probabilistic estimates. Therefore, we will simply describe the types and magnitudes of deformation hazards.

3.0 RESULTS

3.1 EAST RIFT ZONE AND NORTHEAST FLANK OF KILAUEA VOLCANO

3.1.1 Types of volcanic activity

Various types of eruptions on the east rift zone (ERZ) of Kilauea volcano produce deposits of spatter and ash, littoral cones, and ‘a‘a and pahoehoe flows. Sustained eruption of spatter may build large cones around source vents. More typically, however, eruptions on the ERZ have been of short duration and only low (3-10 m) spatter ramparts have formed. Commonly, small spatter ramparts are broken apart and partly rafted by associated lava flows hundreds of meters from their original position.

Only two tuff (consolidated ash) deposits (Moore, 1983, 1992; Moore and Trusdell, 1991) are exposed on the surface of the ERZ.A single unit of tuff surrounding Pu‘ulena, Pawai, and Kahuwai craters on the LERZ was deposited by vigorous phreatic and phreatomagmatic eruptions between 1,270 and 490 years B.P. The tuff of Kapoho Crater was deposited between 340 and 200 years B.P. Both deposits covered areas of at least 4-6 km^2. Deep well SOH-1 encountered 13 ash units in the top 748 m of the drillhole (Novak and Evans, 1991), and SOH-4 encountered 19 ash units (each less than 15 cm thick) in the 2001 m core hole (Trusdell et al., 1992) within the LERZ.

Littoral cones form where lava flows enter the ocean. This interaction of lava and seawater is frequently explosive and potentially threatens the lives of the unwary, but the effects of the explosions rarely extend more than a few hundred meters.

‘A‘a and pahoehoe flows are the most voluminous and extensive eruptive products on the east rift zone. The subaerial parts of flows on the LERZ range from a few tens of meters to more than 9 km in length, from a few meters to as much as 3 km in width, and from 1 to 20 m in thickness (Moore 1983, 1992; Moore and Trusdell, 1991). The speeds of advancing flow fronts generally are slow -- tens to hundreds of meters per hour; however, ‘a‘a flows on steep slopes have been observed to surge at rates of as much as 33 m/minute (Neal and Decker, 1983).

The northeast flank of Kilauea is underlain chiefly by pahoehoe flows erupted 260-450 years before present from the ‘Ai-la‘au shield on the eastern side of Kilauea’s summit caldera (Holcomb, 1987). By analogy with observations of recent shield eruptions of Kilauea (e.g., Mauna Iki from 1919-1920, Rowland and Munro, 1993; Mauna Ulu from 1969-1974, Swanson et al., 1979; Tilling and others, 1987; and Kupaianaha from 1986-1991, Heliker and Wright, 1991), tube-fed flows from the ‘Ai-la‘au shield probably moved relatively slowly, posing little or no threat to life. However, their great volume and lengthy period of eruption ensured that most of the northeast flank was buried. Any man-made structures that may have existed eventually were overwhelmed by lava.

3.1.2 Frequency of eruption

Holocene time: The frequency of eruption on the LERZ east of 155°W longitude during Holocene time has been studied in some detail (Moore, 1992; Hagstrum and Champion, 1994). The oldest radiometrically-dated lava flow on the LERZ was erupted 2,360$\pm$90 years B.P. From anomalous paleomagnetic inclinations, Hagstrum and Champion (1994) suggest that a few of the lava flows on the LERZ are older than 2400 years. In addition, the number of flows is reduced using the Hagstrum and Champion chronology. Fifty-four of the 112 surface flow units of Moore and Trusdell (1991) are combined into only 22 paleomagnetically-distinct units. With the remaining 58 units for which no paleomagnetic determinations were made, the average dormant interval during the period represented by surface flows is greater than 30 years (2400 years / 80 surface flow units).

Post-Western contact time (A.D. 1790 and younger): A general recurrence interval distribution for all Kilauea eruptions during the past 200 years has been estimated by Wickman (1966) to be bimodal with the component intervals being about 1.3 and 27.8 years. In the past 200 years, eruptions on the portion of the ERZ which includes the geothermal subzones occurred in 1790, 1840, 1955, 1960, 1961, 1977, and the current eruption which began in 1983. Eruptions have averaged nearly 43 years apart for this part of the volcano, but the range has been 1 to 115 years.

3.1.3 Mitigation Procedures:

Mullineaux and others (1987) discussed various methods to mitigate the hazards associated with volcanic eruptions and related phenomena. One of the most effective procedures is land-use zoning that prevents structures in areas of high risk. However, since geothermal wells must be drilled at the heat source within the ERZ, other means of mitigation are necessary. The most effective strategies, none of which would guarantee protection from inundation by a lava flow, include placing structures on topographically high areas and building barriers or channels to divert flows away from valuable property. Another technique, perhaps less desirable, involves the use of explosives to disrupt lava channels and tubes. Spraying the flow front with water can cool it and slow its progress, but a large supply of water may be unavailable except near the ocean.

Mitigation of the hazards associated with the rare pyroclastic-flow and -surge eruptions on the LERZ is not possible. Evacuation is the only recourse.

3.1.4 Types and rates of ground deformation

3.1.4.1 Northeast flank of Kilauea:

None of the 20th century triangulation archived with the NGS has been repeated on Kilauea northeast flank. As discussed below in the section on the LERZ, Swanson et al. (1976) used data not presently available from the NGS to analyze motions along the LERZ, eastern south flank, and Kilauea's summit relative to stations to the north.

HVO reoccupied parts of its EDM trilateration network intermittently after 1970 (Fig. 4). The baseline, HALONA-KALOLI, shows 108 $\pm$ 34 mm of extension (Fig. 5) associated with the M7.2 earthquake of 1975. Data for the other baselines, even one from KEAAU to HALONA, do not show the effects of this event (Fig. 5). Over the period 1970-1990, the average rate of extension for the HALONA-KEAAU baseline is 3.3 $\pm$ 1.5 mm/yr or 0.18 μstrain/yr, but the KALOLI-KEAAU baseline contracted 2.4 $\pm$ 1.4 mm/yr or −0.22 μstrain/yr.

HVO reoccupies levelling profiles first established by the USGS in 1957 and 1958 for preparation of topographic maps. Repeat leveling from the tide-gauge datum in Hilo was carried out in 1976, 1979, 1986, 1988, and 1989. Profiles of height changes (Fig. 6) were constructed along an azimuth perpendicular to Kilauea LERZ from Hilo to Kea'au, to Pahoa, and to Kaimu (Fig. 4). From Hilo to just north of the east rift zone (up to distances of about 25 km in Fig. 6), height changes have generally been negligibly small, with apparent changes in height probably reflecting error accumulated along the traverse.

3.1.4.2 Lower East Rift Zone:

Ground deformation indicated by the formation of grabens has frequently occurred in the vicinity of active eruptive vents and above near-surface intrusions. For example, grabens with bounding fault scarps as high as 4 m formed when an intrusion apparently occurred beneath Kapoho village in 1924 (Macdonald and others, 1983), and subsidence of 1 to 4 m occurred when the magma column withdrew below the 1977 eruptive vents (Moore and others, 1980). Systematic deformation measurements of various types made on Kilauea in the past 35 years allow overall patterns of deformation to be established.

Repeated triangulations, covering epochs 1896-1914, 1949, 1958, and 1970, were examined by Swanson et al. (1976, p. 10), who estimated station displacements after assuming certain stations to the north were immobile. From epoch 1896-1914 to epoch 1970, there were horizontal motions of 2-3 m, perpendicular to the rift axis, among LERZ stations; this is an approximate measure of rift zone extension during this time. Concurrently, coastal stations along the eastern south flank, south of the LERZ, migrated seaward 2-3.5 m. These motions reflect about 1-1.5 m of extension during the dike emplacement and eruption of 1955, as documented by the 1949 and 1958 epochs. Extensions during the 1960 dike intrusion and eruption and the possible intrusive activity of 1924 have not been documented but are likely to have contributed to the overall displacements from the triangulation data.

Level data along the LERZ is somewhat sparse. Some of the earliest releveling (Finch, 1925) spanned the 1924 intrusive activity near Kapoho, and documents up to 2.5 m of graben subsidence between two fault scarps more than 1 km apart. Displacements returned to negligible values about 1 km south of the fault scarp, suggesting tilts, or shear strains, of about 2500 μradians across the rift axis.

As described for the northeast flank, extensive leveling was completed from 1958 onward (Figs. 4, 6). Most of the LERZ motion is attributable to the M7.2 earthquake of 1975, which caused up to 70 cm of subsidence on the LERZ. From the "stable" north flank, the deformation occurred across a 6-7 km wide zone implying 100-150 μradian of tilt to the south. Since the 1975 earthquake, deformation along the south edge of the rift zone has continued, although many important benchmarks have not been reoccupied. Between 1976 and 1989, the rift zone subsided up to about 15 cm, accompanied by tilts of up to 5-10 μradians/yr. South of the rift zone, deformation near the sea coast at Kaimu during the 1975 earthquake was followed by gradual uplift, as much as 10-15 cm (Delaney et al., 1990). Delaney et al. (1990, 1993) and Arnadottir et al. (1991) report 25 cm of rift deformation attributable to the M6.1 south flank earthquake of June 1989.

The rates of LERZ deformation and eastern south flank uplift are constrained by records of depth-to-water-table recorded at three wells -- Kapoho, Malama-Ki, and Pulama (Fig. 7). Because these wells are within unconfined aquifers, their water level is primarily dictated by sea level. Fresh water, if present, must float on seawater with 40 meters of fresh water below sea level for every meter of fresh water above sea level. Fluctuations in the elevation of fresh water above sea level would therefore be only 1/40th of the fluctuation in the thickness of fresh water penetrated by each of these wells, making the water table elevation insensitive to long-term changes in groundwater supply. Pulama and Malama-Ki wells do not have a well-developed thickness of fresh water, making their water levels even more stable indicators of sea level. Variations in water level (Fig. 8) are predominantly local variations directly related to seasonal changes in rainfall. Each of the wells records deformation associated with the 1975 M7.2 earthquake (Fig. 8) that matches quite well with deformation measured by conventional techniques (Lipman et al., 1985). Records from the two wells in the LERZ, Kapoho and Malama-Ki, also indicate ongoing subsidence of 18 mm/yr and 19 mm/yr, respectively (Fig. 8A, 8B). (Two measurements of the Malama-Ki well taken at the time of the 1977 LERZ intrusive and eruptive activity, appear to indicate an anomalous short-term drop of the water table.) The Pulama well records an average uplift of 42 mm/yr between 1976 and 1986 (Fig. 8C). Starting in the mid 1980s, data collected at Pulama appears to have become noisier and by mid 1986, lava flows from the current eruption of Kilauea began surrounding the well. Delaney et al. (1993) propose that the apparent deformation of the ground surface near the well in the late 1980s was caused by loading from the nearby accumulation of lava. The well was covered by lava in 1989.

Measurements of line-length changes were collected along baselines northward and southward from rift zone stations and along the rift zone (Fig. 7). Based on the observation that level data (Fig. 6) show that the ground surface north of the rift zone is stable, it is reasonable to assume that most of the measured extensions (Fig. 9A) measured northward from the rift zone stations actually occurred within a few kilometers of the rift zone stations. In general, the extensions increase westward along the rift zone. The baseline KALOLI-KAPOHO, for instance, extended 325±56 mm during the 1975 M7.2 earthquake and extended at a rate of 7.4±4.3 mm/yr until the M6.1 earthquake of 1989, which did not noticeably affect the length of that baseline. Farther west, the baseline KEAAU-KALIU extended 681±68 mm during the 1975 earthquake and extended 20.0±5.3 mm/yr until the time of the 1989 M6.1 earthquake, which caused an additional 107±59 mm of extension. Still farther west, the baseline KULANI-KALALUA extended 339±85 mm during the 1975 earthquake and underwent an additional 3200±85 mm of extension until the most recent measurement in early 1990.

Baselines measured southward from stations downrift (east) of KALIU (Fig. 7) have generally contracted since 1976 (Fig. 9B) and were little affected by the M7.2 earthquake of 1975. For instance, the baseline KAPOHO-POHOIKI contracted at a rate of 6.7±2.0 mm/yr, and this is one of the few baselines to show an abrupt change in length spanning that earthquake. Westward from KALIU, the effects of the 1975 earthquake are much more pronounced. The baseline HEIHEIAHULU-HAKUMA, for instance, extended 849±37 mm and 57±23 mm during the 1975 and 1989 earthquakes; during the 13.5 years between these events, the baseline extended an additional 738±37 mm.

Baselines directed along the rift zone (Fig. 7) also show changes in length that have typically increased westward (Fig. 9C). This pattern of increased deformation westward reflects that there have been no eruptions or other significant magmatic or seismic events downrift of HEIHEIAHULU since 1960.

3.1.5 Hazard Analysis of geothermal subzones and Kilauea transmission routes:

The data discussed above can be used to assess the hazards from volcanic activity and ground deformation for the geothermal subzones:

Lava flows: Table 3 shows the number of distinct lava flow units subdivided by age category within each geothermal subzone and within 1 km of the transmission routes across Kilauea (Moore and Trusdell, 1992; as revised by Hagstrum and Champion, 1994; Richter et al., 1964; Jackson et al., 1975; Moore and Koyanagi, 1969) .

Table 3: Number of Kilauea lava flow units within geothermal subzones and within 1 km of transmission routes.

Age	Kapoho Subzone	Kama'ili Subzone	Kilauea MERZ Subzone	All Subzones	Proposed Trans. Route	1st and 2nd Alternate
0-200 yrs	4	3	6	9	3	3
200-400 yrs.	4	4	5	10	2	2
400-750 yrs.	8	9	4	19	13	3
750-1500 yrs.	6	9	5	19	9	7
1500-3,000 yrs.	4	1	0	5	0	1
TOTAL	26	26	20	62	27	16

The oldest surface flow in the subzones has not been dated, but is more than 2,400 years old (Hagstrum and Champion, 1994). Based on the long-term record, the average recurrence intervals over the last 2400 years are more than 92 years for Kapoho and Kama'ili geothermal subzones and less than 75 years for Kilauea MERZ subzone. The calculated probability of inundation by lava within the next 50 years is no more than 42% for Kapoho and Kama'ili subzones, and at least 49% for Kilauea MERZ subzone. The average recurrence interval for all three subzones together is more than 39 years for a probability of inundation by lava within 50 years of 72%. The western edge of the Kilauea Middle East Rift subzone was partly covered by lavas from both Pu'u 'O'o and Kupaianaha vents (Fig. 3) in the past 11 years (Heliker and Wright, 1991). The Pu'u 'O'o - Kupaianaha eruption is on-going.

If only the last 750 years are considered, the recurrence intervals for the three geothermal subzones are remarkably consistent at 47 years for Kapoho and Kama'ili and 50 for Kilauea MERZ subzone. These estimates are almost half what they were based on the 2400-year surface flow record, but they are consistent whether intervals of the past 200, 400, or 750 years are chosen. It is only the inclusion of the older, possibly undersampled flows that brings the long-term recurrence interval up to 75 - 92 years. The probabilities of inundation for the subzones based on the past 750 years are 63%-65% for the subzones individually and 90% for the subzones together. The most recent past is probably the best indicator of the immediate future, therefore, these probabilities are perhaps more relevant than those based on the longer-term recurrence intervals.

The planned transmission corridors cross Kilauea along two routes (Fig. 1). The proposed route goes nearly due west from the Kama'ili subzone before veering to the northwest whereas the first and second alternate routes both head directly northwest. Table 3 shows the number of distinct LERZ lava flow units within 1 km of each route. The oldest flow is less than 2,400 years old, and the estimated recurrence intervals for lava inundation are less than 55 and 150 years for the proposed and alternate routes, respectively. Therefore, the calculated probabilities of a lava flow cutting across either transmission corridor within 50 years is 60% and 28%, respectively. Based on the last 750 years, the recurrence intervals are 42 and 94 years which correspond to slightly higher calculated probabilities of 70% and 41%. A combined probability for both routes was not estimated because only one of the two routes is to be used.

The generality of our approach easily allows for calculating the probability of inundation by lava for any size area. If the Kilauea LERZ region is split up into 1 km square cells, the maximum number of flows per square kilometer is 8. The range of recurrence intervals for the cells within any of the geothermal subzones is 30 to 600 years. More than half of these cells have recurrence intervals between 100 and 200 years, giving a range of probabilities of inundation by lava within 50 years of 22% to 39% per km^2.

Phreatic or Phreatomagmatic eruptions: The probability of explosive eruptions is relatively low but is not zero. Two such eruptions occurred within the Kama'ili and Kapoho subzones; the earliest is between 490 and 1,270 years old. Based on this information, the probability of another such eruption within 50 years would be between 8% and 19%. A longer record would, of course, allow a better estimate of the long-term recurrence interval. The identification of ash horizons in deep drill holes SOH-1 and SOH-4 located within the geothermal subzones, together with preliminary dates on a few of the lavas in SOH-4 could yield a long-term perspective. Guillou et al. (1993) report lava ages of 42,000±15,000 and 61,000±34,000 years before present at a depth of 472 m, 201,000±31,000 years before present at a depth of 609 m, and 395,000±75,000 years at a depth of 1646 m in SOH-4. The range of accumulation rates are 3 to 11.2 m/1,000 years. If we assume a similar range of accumulation rates for SOH-1, each of the 13 ash layers within the first 748 m (Novak and Evans, 1991) would have occurred on average every 5,000 to 19,000 years. Each of the 19 ash layers in the upper 1685 m of SOH-4 (Trusdell et al., 1992) would have occurred on average every 8,000 to 29,000 years. The range of recurrence intervals from these deep cores is much less frequent than the recurrence of ash now exposed at the surface in the LERZ. Perhaps the layers in the deep cores represent explosive events which are much more pervasive than the more spatially-limited Pu'ulena or Kapoho events. In any case, all available information suggests that the probability of a moderate to large ash-producing volcanic event is less than 1.0% within 50 years. The probability of a smaller ash-producing volcanic event might be as high as 8% to 19%.

Intrusions intersecting Geothermal Wells: So far, no dikes or sills have intersected a geothermal well in Hawai'i, probably because deep wells have only been in the east rift zone of Kilauea since 1976 (Kingston Reynolds Thom & Allardice Limited, 1976). However, intrusions and eruptions similar to those in Hawai'i have affected geothermal wells in Iceland (Elsworth and Voight, 1992; Stefansson, 1981; Larsen et al., 1979). Three Scientific Observation Holes drilled within the geothermal subzones to depths of approximately 2 km each encountered numerous dikes from old intrusions (Trusdell et al., 1992; Novak and

Evans, 1991; Evans, 1992) and demonstrated that intrusions do occur within the depth interval exploited by typical geothermal production holes. Therefore, it is possible that an intrusion will intersect a geothermal well in Hawai'i in the future.

Because not all intrusions result in eruptions but all eruptions are preceded by intrusions, the probability of an intrusion within a subzone must be somewhat greater than the probability of an eruption. However, this higher probability of intrusion will be offset by the low likelihood of that intrusion actually intersecting a vertical well bore. Hawaiian dikes are typically 1 m in width and are nearly vertical; the chances of intersecting a vertical well bore less than 1 m in diameter are probably small. The probability of a dike intersecting a non-vertical, or directional, well would be greater. Further, the development of fields of wells around several power plants additionally increases the probability of at least one well being damaged by an intrusion. Calculation of this probability depends on the specific pattern of well development and cannot be calculated at this time.

Ground Deformation: Deformation appears to be insignificant for most of the northeast flank of Kilauea Volcano, at least since levelling measurements began in 1957. Horizontal extensions and contractions near Kea'au (see Fig. 4) between major earthquakes are minimal and amount to just a few mm/yr. Only rapid extension during major Kilauea south flank earthquakes appears to be significant (108 mm over a distance of about 8 km for HALONA-KALOLI line in Fig. 5); however, the deformation effects of these earthquakes become much more pronounced closer to the east rift zone.

Along the LERZ, slow deformation occurs at rates of 12 to 19 mm/yr east of Heiheiahulu, with uplifts of 42 mm/yr measured to the southwest. The deformation results in tilt rates of 5-10 μradians/yr. Horizontal extension rates also have been smaller east of Heiheiahulu. Rates are approximately 7 to 20 mm/yr compared to over 200 mm/yr west of Heiheiahulu. Subsidence and extension are expected to continue at comparable rates. Measured deformation on the north flank of Kilauea is less than 10 mm (Fig. 6).

Both volcanic events and earthquakes can cause rapid and localized deformation. Deformation during eruptions and intrusions can exceed 2-3 m locally over a small area or near the source forming grabens within the rift zone. The last two major earthquakes have contributed less than 1 m of deformation each over the rift zone and south flank. Frequency of sizeable earthquakes is beyond the scope of this report.

3.2 NORTHEAST FLANK OF MAUNA LOA VOLCANO

3.2.1 Types of volcanic activity

The northeast flank of Mauna Loa is underlain by 'a'a and pahoehoe flows and a few spatter ramparts and cones mostly of late Holocene age (Lockwood and Lipman, 1987; Lockwood and others, 1988). Most flows were erupted from vents on the northeast rift zone of the volcano. In addition, some eruptive vents in and near the Humu'ula Saddle are radial to

Mauna Loa's summit caldera, Moku'aweoweo. Eruptions in the past 200 years typically have lasted weeks to months and have produced flows that generally are larger and more voluminous than those of Kilauea.

3.2.2 Frequency of eruption

The map of Lockwood et al. (1988) indicates that virtually all volcanic rocks on the northern side of Mauna Loa are of Holocene age. Lockwood and Lipman (1987) point out that 90 percent of Mauna Loa's surface is covered with flows less than 4,000 years old. A recurrence interval for all Mauna Loa eruptions based on those between 1832 and 1950 is 3.6 years (Wickman, 1966). Of those, eruptions whose flows covered large areas on the north side of Mauna Loa occurred in 1843, 1852, 1855-56, 1859, 1880-81, 1899, 1935, and 1942. The most recent eruption, in 1984, produced a lava flow that covered more of the northeast flank (Lockwood et al., 1988). The average recurrence interval for northeast flank flows from 1843 to 1984 was about 17 years (9 flows in 150 years).

3.2.3 Previous Assessments of Volcanic hazards and Mitigation Procedures

Lava flows are the principal volcanic hazard on the north side of Mauna Loa; scoria falls would probably affect only small areas. Mullineaux and others (1987), Heliker (1990), and Wright and others (1992) indicate that most of the north side of Mauna Loa lies in Hazard Zones 2 and 3, and <5 to 25 percent of the land surface has been covered by lava during the last 200 years.

The Mauna Loa Weather Observatory, operated by the National Center for Atmospheric Research (National Oceanic and Atmospheric Administration), is protected from potential inundation by lava flows by earth barriers on its upslope side (Lockwood et al., 1987). No other artificial barriers are known to exist on Mauna Loa's north side. Macdonald (1958) suggested building barriers to protect Hilo, but the idea foundered because of technical and economic problems (J.P. Lockwood, 1994,written communication).

Aerial bombing of active flows on Mauna Loa's flank was carried out in 1935 and 1942, during attempts to protect the city of Hilo from possible inundation. Results were insignificant (Lockwood and Torgerson, 1980), and the eruptions ended before the flows reached Hilo. Improvements in bomb delivery may make this mitigation technique more feasible in certain situations than past trials have indicated (Lockwood, 1994, written communication).

The north side of Mauna Loa lacks sufficient water, except near the ocean, for use in slowing or diverting flows by cooling.

3.2.4 Types and rates of ground deformation:

Few 20th century triangulation data exist for the northeast flank of Mauna Loa, and no angles listed in the NGS archive have been repeated. HVO has completed a series of ground-surface tilt measurements in the Humu'ula Saddle (Fig. 10) since 1976. Station VANCE, located at 6500 feet elevation on Mauna Loa, about 7 km south of the Saddle Road, shows no significant long-term motion (Fig. 11). During the Mauna Loa northeast rift zone eruption of 1984, the station recorded a sudden northward tilt of 30 ± 16 μradians. The station is about 10 km from the eruptive fissures of the northeast rift zone, and so the co-eruptive tilts farther away near the Saddle were certainly much less than those at VANCE. In fact, between 1981 and 1986, seven tilt measurements were also completed at HUMUULA TILT (Fig. 10), located in the Saddle. Aside from one apparently spurious measurement, apparent tilt variations, even spanning the 1984 eruption, are smaller than the 2σ measurement uncertainty of 11 μradians recorded over six years. This provides a maximum admissible strain rate of about 2 μstrain/yr.

HVO completed a series of electronic distance measurements in the Humu'ula Saddle region (Fig. 10) since 1976. Selected EDM measurements along seven baselines spanning the Saddle are shown in Fig. 12. Aside from one, apparently, spurious measurement along the baseline HUMUULA-PUU OO, virtually all changes in distance are less than the 2σ measurement uncertainty, even those spanning the northeast rift zone eruption of 1984. Some of the baselines show extensions, OMAOKOILI-PUU KOLI at 3.5±1.9 mm/yr (±2σ) or 0.35 μstrain/yr and PUU OO-VANCE at 5.83 mm/yr, or 0.42 μstrain/yr. One baseline, PUU OO-BOULDER, showed a contraction of 4.8 ± 2.8 mm/yr, or -0.70 μstrain/yr.

3.2.5 Hazard Analysis

Lava Flows: Mauna Loa flows do not threaten the geothermal subzones, but pose a significant hazard to the proposed transmission route. Table 4 shows the total number of lava flow units subdivided by age within 1 km of the three possible routes.

Table 4. Number of Mauna Loa flows within 1 km of Geothermal Energy Transmission Routes.

Age range	Proposed route	1st Alternate Route	2nd Alternate Route
0-150 yrs.	6	3	1
151-999 yrs.	5	1	0
1,000-1,999 yrs.	3	2	2
2,000-2,999 yrs.	4	1	0
3,000-3,999 yrs.	0	1	1
4,000-4,999 yrs.	2	1	0
5,000-5,999 yrs.	3	2	1
6,000-6,999 yrs.	0	0	0
7,000-7,999 yrs.	1	0	0
8,000-8,999 yrs.	0	0	0
9,000-9,999 yrs.	1	2	2
10,000-14,999 yrs.	1 (10,400 yrs.)	3 (>14,000 yrs.)	3 (>14,000 yrs.)
TOTAL	26	16	10

Estimated recurrence intervals for lava flows crossing each of the three routes are 400, 875, and 1,400 years, respectively. These recurrence interval estimates seem low compared with the occurrence of up to 11 lava flows within the past 1,000 years. Either the past 1,000 years have been a period of unusually frequent activity in Mauna Loa's eruptive history, or our algorithm for counting individual flow units within a region over-sampled recent flows and under-sampled older flows. To explore these possibilities, buffers of 2 and 5 km were computed for the proposed route and flows were counted. The results remained unchanged from those in table 4.

Most probably, older flows are under-sampled because they are progressively buried by younger flows. If older flows that had crossed the proposed route had been buried by the more recent flows near the route, they may still be visible downslope (to the east on this flank of Mauna Loa). The final tabulation of flow units was therefore counted within a region which included the route to be evaluated and all Mauna surface flows downslope and to the east. Table 5 shows the results of this modified approach.

Table 5: Number of lava flows downslope of Geothermal Energy Transmission Routes.

Age Range	Proposed Route	1st Alternate Route	2nd Alternate Route
0-150 yrs.	6	3	1
151-999 yrs.	5	1	0
1,000-1,999 yrs.	3	2	2
2,000-2,999 yrs.	4	3	0
3,000-3,999 yrs.	2	2	1
4,000-4,999 yrs.	3	1	0
5,000-5,999 yrs.	5	3	3
6,000-6,999 yrs.	0	0	0
7,000-7,999 yrs.	2	0	0
8,000-8,999 yrs.	0	0	0
9,000-9,999 yrs.	3	3	2
10,000-14,999 yrs.	8	6	3
15,000-19,999 yrs.	1	0	0
> 20,000 yrs.	1 (28,000 yrs.)	1 (28,000 yrs.)	0
TOTAL.	41	25	24

The recalculated recurrence intervals are 680, 1100, and 625 years, respectively for the three routes if all flow units are included. If the 28,000 year old flow is excluded, the recurrence intervals are 500, 600, and 625 years, respectively. These estimates are not significantly different from those using the counts in table 4. Either the undersampling of older flows is not significant or this approach to overcoming that limitation does not work.

The past 1,000 years has been a period of anomalous activity in Mauna Loa's history with 12-15 flows per century compared to less than 7 per century more than 1,000 years ago (Fig. 18.9 in Lockwood and Lipman, 1987). In the past 150 years, the mean recurrence intervals have been about 25, 50, and 150 years, respectively, for the three transmission routes. Obviously, probabilities based on these two sets of recurrence intervals will be quite different, and our preference is to choose the shorter recurrence intervals on which to base probabilities. It seems more relevant to consider a volcano's behavior in the most recent past to forecast events within the immediate future. Likewise, one would use a volcano's long-term behavior to estimate the long-term future behavior. Therefore, estimates of the probability of inundation by Mauna Loa lava flows for the three transmission routes within the next 50 years are 86%, 63%, and 28%, respectively.

If the first alternate transmission route were shifted northward through the Saddle area between Mauna Loa and Mauna Kea so that it was well on Mauna Kea lavas west of Hilo (i.e., shift the route into lava flow hazard zone 7 and 8), the probability of inundation by Mauna Loa lavas within 50 years would drop from 63% to 28%.

Ground Deformation: No vertical deformation measurements have been made in this region. From the few EDM and tilt measurements, it appears that ground deformation, in general, is minor.

3.3 FLANKS OF MAUNA KEA AND KOHALA VOLCANOS

3.3.1 Types of volcanic activity

The most recent eruptions of Mauna Kea have built cinder cones and extruded ‘a‘a and pahoehoe flows. Although most flows extend only a few kilometers from their vents, the flow that forms Laupahoehoe Point, on the Hamakua coast, extends about 22 km from its source cone, Pu‘u Kanakaleonui. The most recent eruptions of Kohala volcano have also built cinder cones and extruded short ‘a‘a and pahoehoe flows.

3.3.2 Holocene frequency of eruption

Wolfe and Morris (1989) show 14 vents and associated flows of probable Holocene age on the north and south flanks of Mauna Kea. Seven of these eruptive units have been dated by radiocarbon (Wolfe and others, in press). Mean ages range from 4,400 to 7,100 years B.P., which yields an average frequency of eruption during this period of about 450 years. Several eruptions occurred about 4,400-4,500 years B.P., which suggests that recent Mauna Kea activity may be characterized by several eruptions over periods of decades to centuries, followed by dormant periods lasting thousands of years.

3.3.3 Previous Assessment of Volcanic Hazards and Mitigation Procedures:

Mullineaux and others (1987), Heliker (1990), and Wright and others (1992) indicate that the summit area and upper slopes of Mauna Kea, extending down to the Humu‘ula Saddle, fall in Hazard Zone 7. Twenty percent of the land surface was covered between about 4,400 and 4,500 years ago, and no eruptions have occurred since. The rest of Mauna Kea is in Hazard Zone 8, where no lava flows have been erupted for at least 10,000 years. Kohala volcano is in Hazard Zone 9, where no lava flows have been erupted for the past 60,000 years.

Techniques for mitigating the effects of possible Mauna Kea eruptions would be similar to those discussed for Kilauea and Mauna Loa. However, all recent eruptive products of Mauna Kea have been hawaiite, which often forms thick, viscous flows that would be difficult to divert.

3.3.4 Types and rates of ground deformation:

No reoccupations of geodetic stations in this area have been published or are presently available from the NGS. HVO has made no repeat measurements in this area.

3.3.5 Hazard Analysis of Mauna Kea and Kohala Volcanoes:

Because of length of time since the most recent eruptions of Mauna Kea and Kohala, the probability of inundation by lava flows from either of these volcanoes is expected to be very low but not zero. There is no information with which to assess the ground deformation hazard for these areas.

4.0 SUMMARY

Mean recurrence intervals for specific areas of the Hawaii Geothermal Project have been estimated and converted to probability estimates of lava flow inundation using Poisson distribution statistics. The information available with which to estimate deformation hazard is much more limited and can only be used to suggest ranges of rates in the recent past. Table 6 summarizes these estimates of lava flow inundation probability and deformation rates.

Table 6: Probabilities of lava flow inundation within 50 years and estimated deformation rates

	Kilauea lava flow	Mauna Loa lava flow	steady subsidence	eruption or earthquake subsidence
Geothermal Resource Subzones	63-65%[1], 90%[2]	0%	12-19 mm/yr	>2 m
Proposed Transmission Route	60%	86%	<1 mm/yr	<10 mm
1st Alternate Route	28%	63%	<1 mm/yr	<10 mm
2nd Alternate Route	28%	28%	<1 mm/yr	<10 mm

[1] per subzone, [2] combined subzones

Because Mauna Loa and Kilauea eruptions are not clearly related and therefore independent, the combined probability of lava flow inundation for either the geothermal subzones or any of the three transmissions line routes from Mauna Loa, Mauna Kea, Kohala, or Kilauea is the higher of the probabilities separately estimated for each volcano.

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LIST OF FIGURES

1. Map of the island of Hawai'i showing boundaries of the five volcanoes, the three geothermal subzones, and the three transmission line routes (labelled proposed, first alternate, and second alternate).

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open triangles in Fig. 4. Horizontal axis is distance from northernmost levelling benchmark with positive southward for locations projected onto 155°W longitude..

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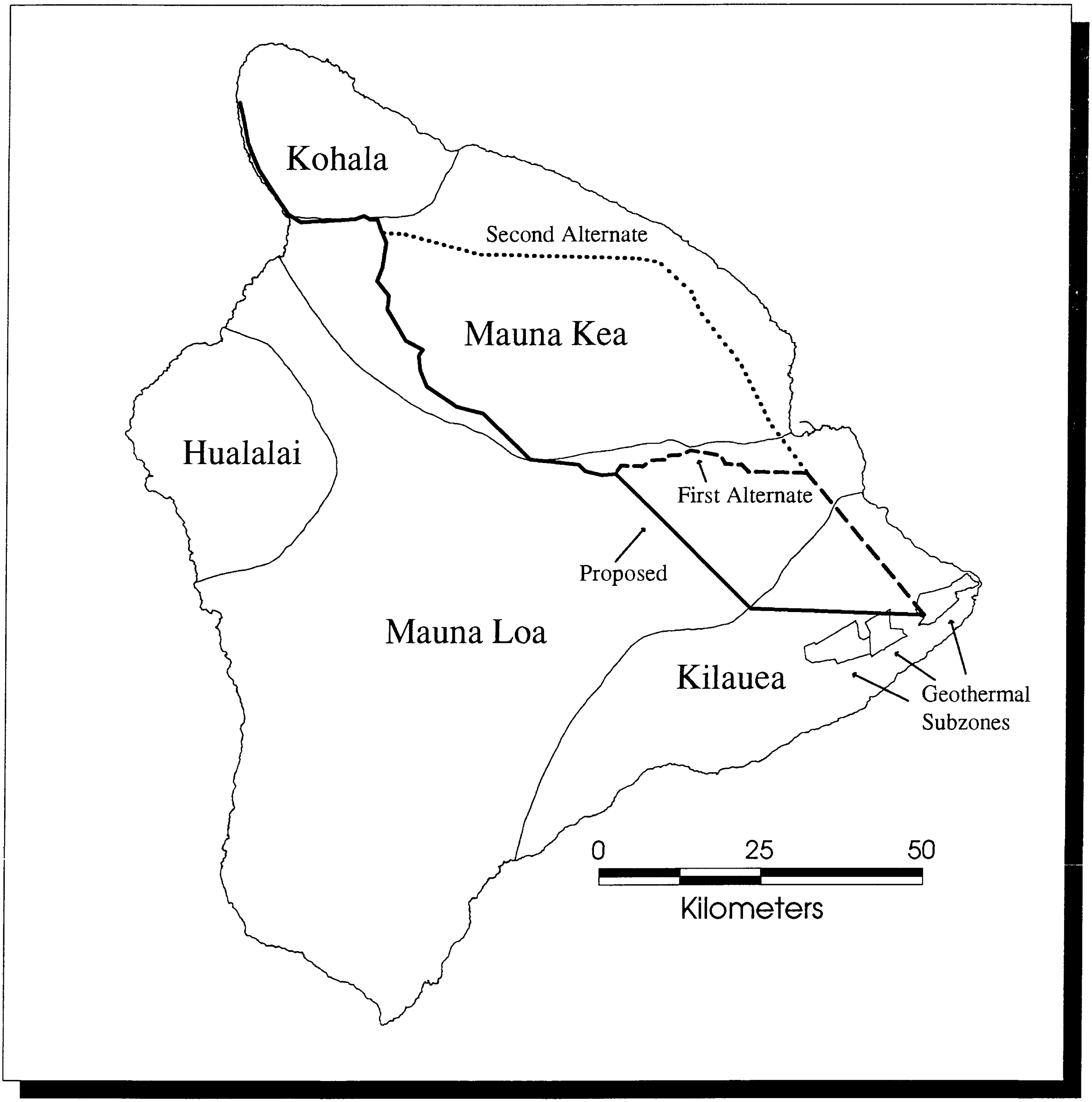
10. Map showing locations of EDM lines and HUMUULA and VANCE tilt station on the north flank of Mauna Loa.

11. Time series plot of tilt changes at HUMUULA and VANCE spirit-level tilt stations. The time series are offset along the vertical axis for visibility. The first data point on each line indicates the first measurement and, therefore, zero for that line

12. Time series plot of EDM line length changes for stations on north flank of Mauna Loa. The time series are offset along the vertical axis for visibility. The first data point on each line indicates the first measurement and, therefore, zero for that line


Kohala
Second Alternate
Mauna Kea
Hualalai
First Alternate
Proposed
Mauna Loa
Kilauea
Geothermal
Subzones
0
25
50
Kilometers

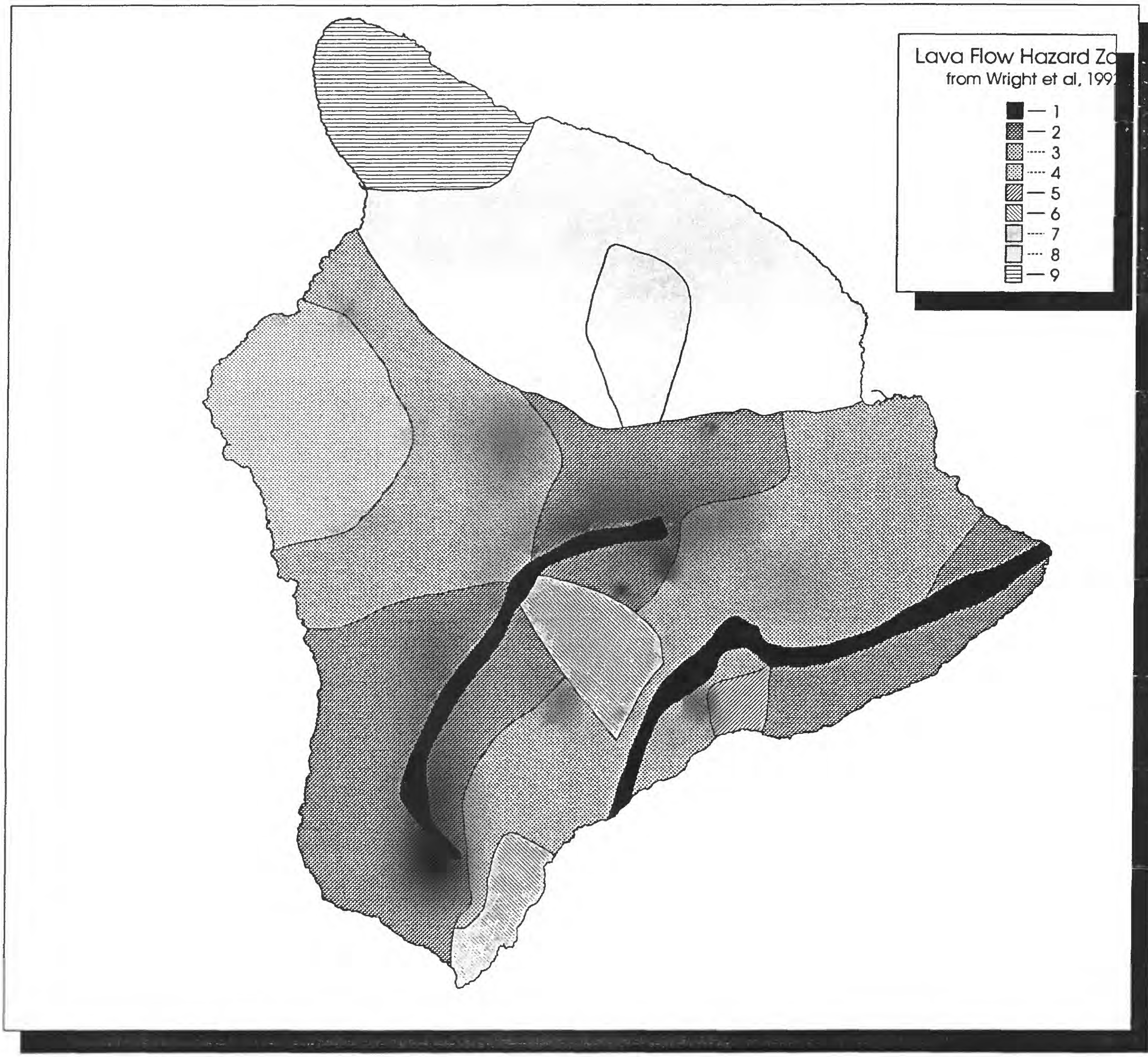


Figure 2. A map of the Island of Hawai`i showing the lava flow hazard zones from Wright et al. (1992) .

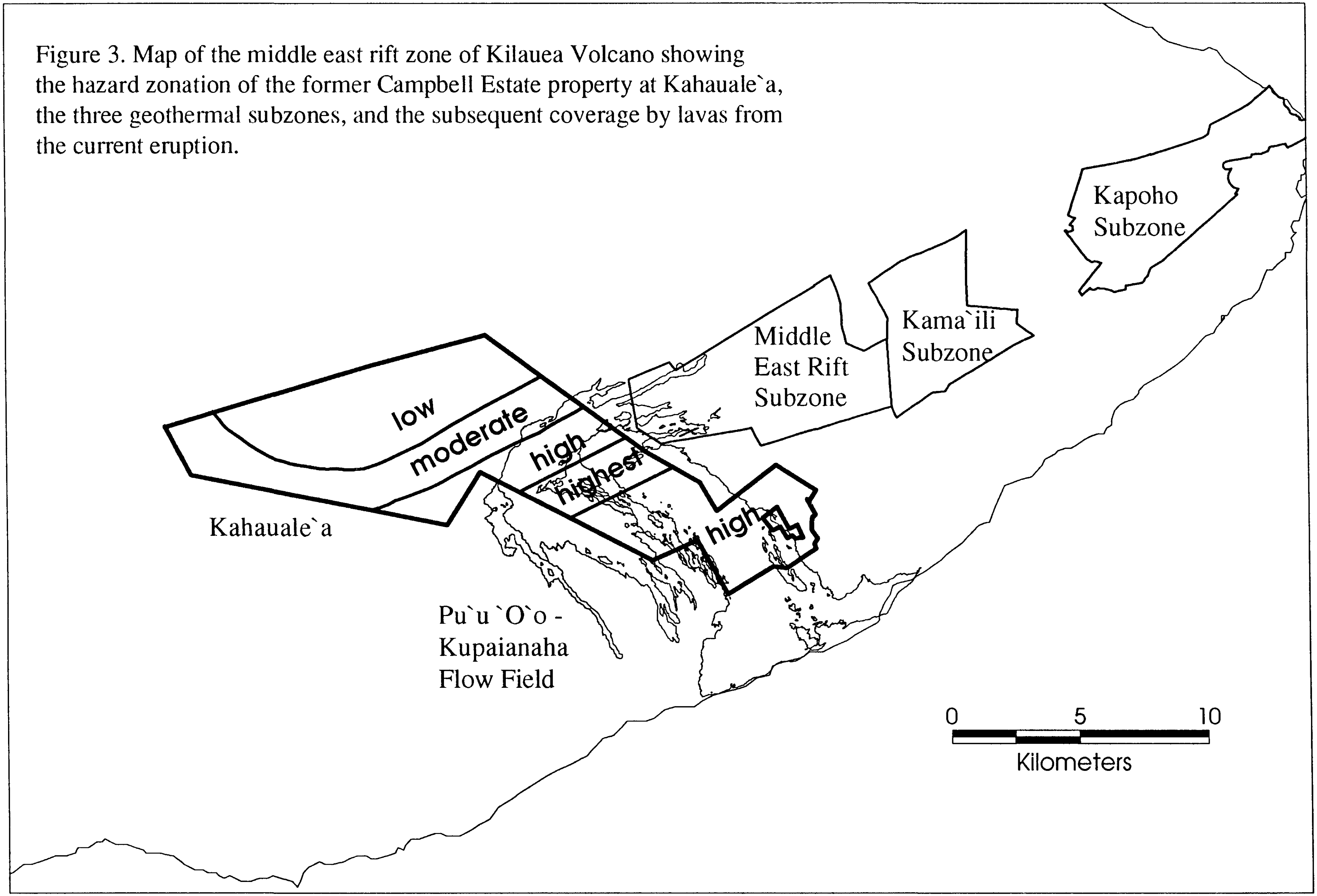


Figure 3. Map of the middle east rift zone of Kilauea Volcano showing the hazard zonation of the former Campbell Estate property at Kahauale`a, the three geothermal subzones, and the subsequent coverage by lavas from the current eruption.

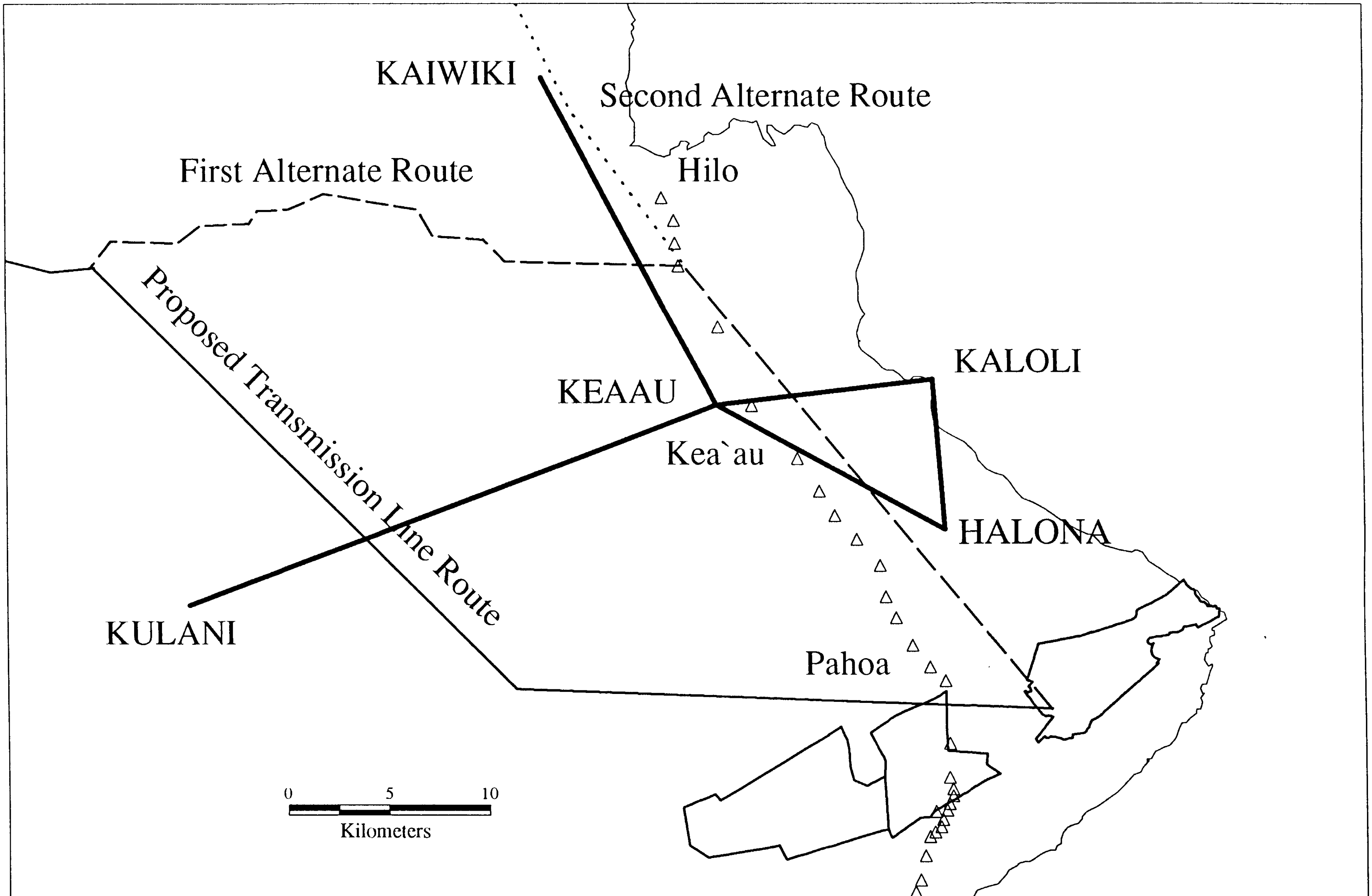


Figure 4. Map showing the EDM lines (heavy) and the cross-rift levelling profile (open triangles indicate major benchmark locations) for the north flank and east rift zone of Kilauea Volcano.

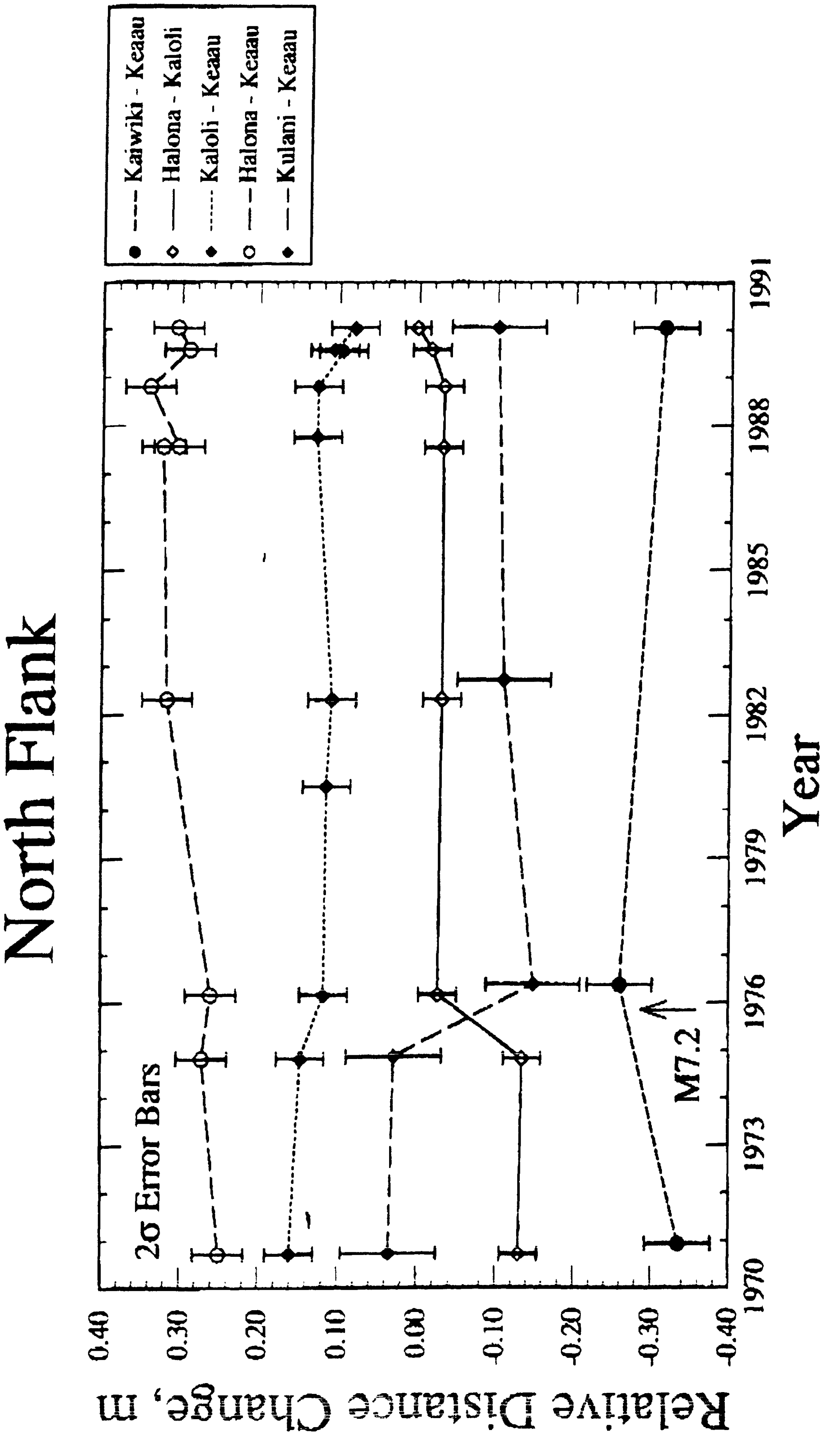

North Flank
Relative Distance Change, m
Year
2σ Error Bars
M7.2
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
1970
1973
1976
1979
1982
1985
1988
1991
Kaiwiki - Keaau
Halona - Kaloli
Kaloli - Keaau
Halona - Keaau
Kulani - Keaau

FIG.5

Middle East Rift Zone Level Profile

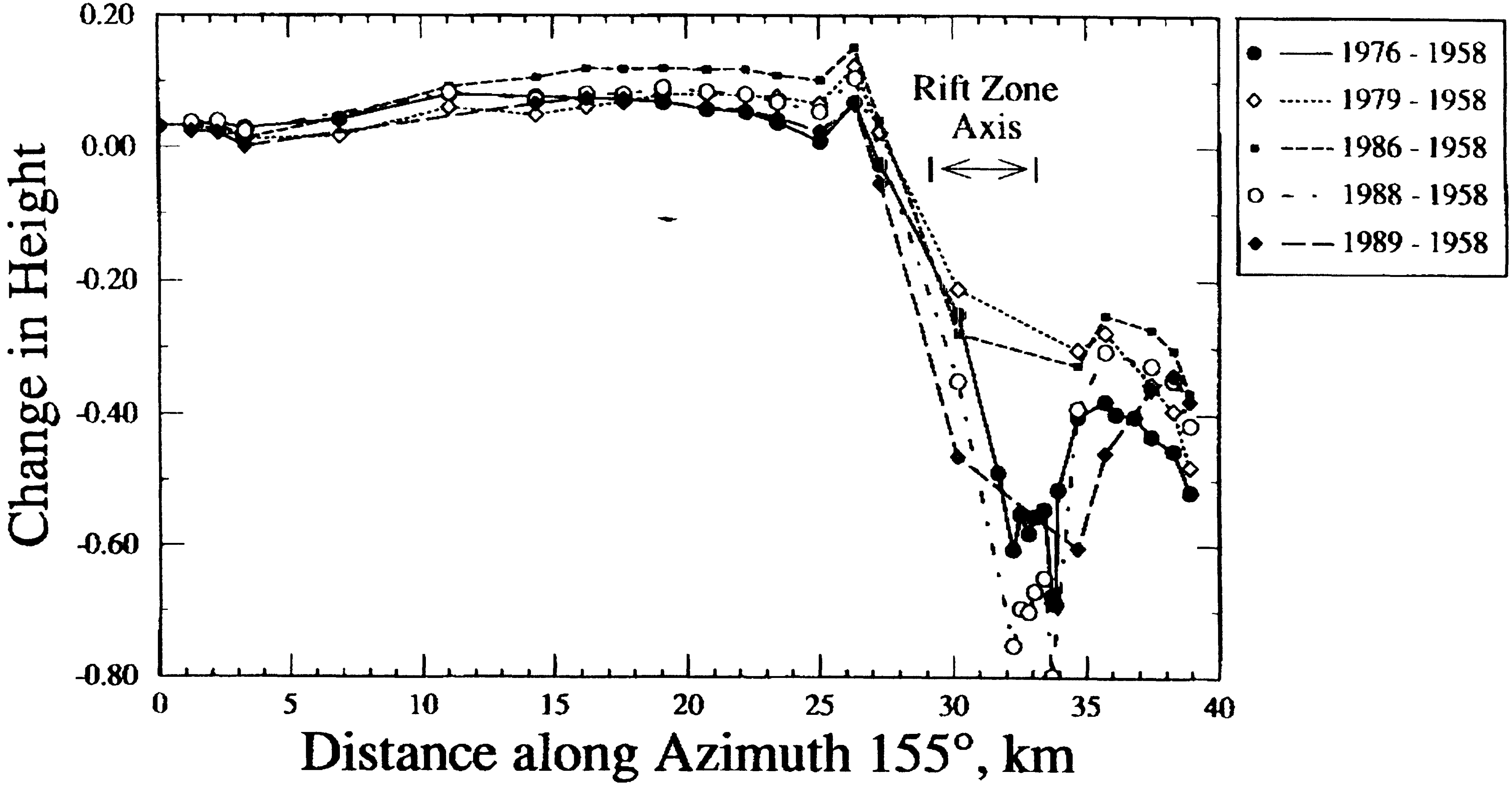


FIG 1

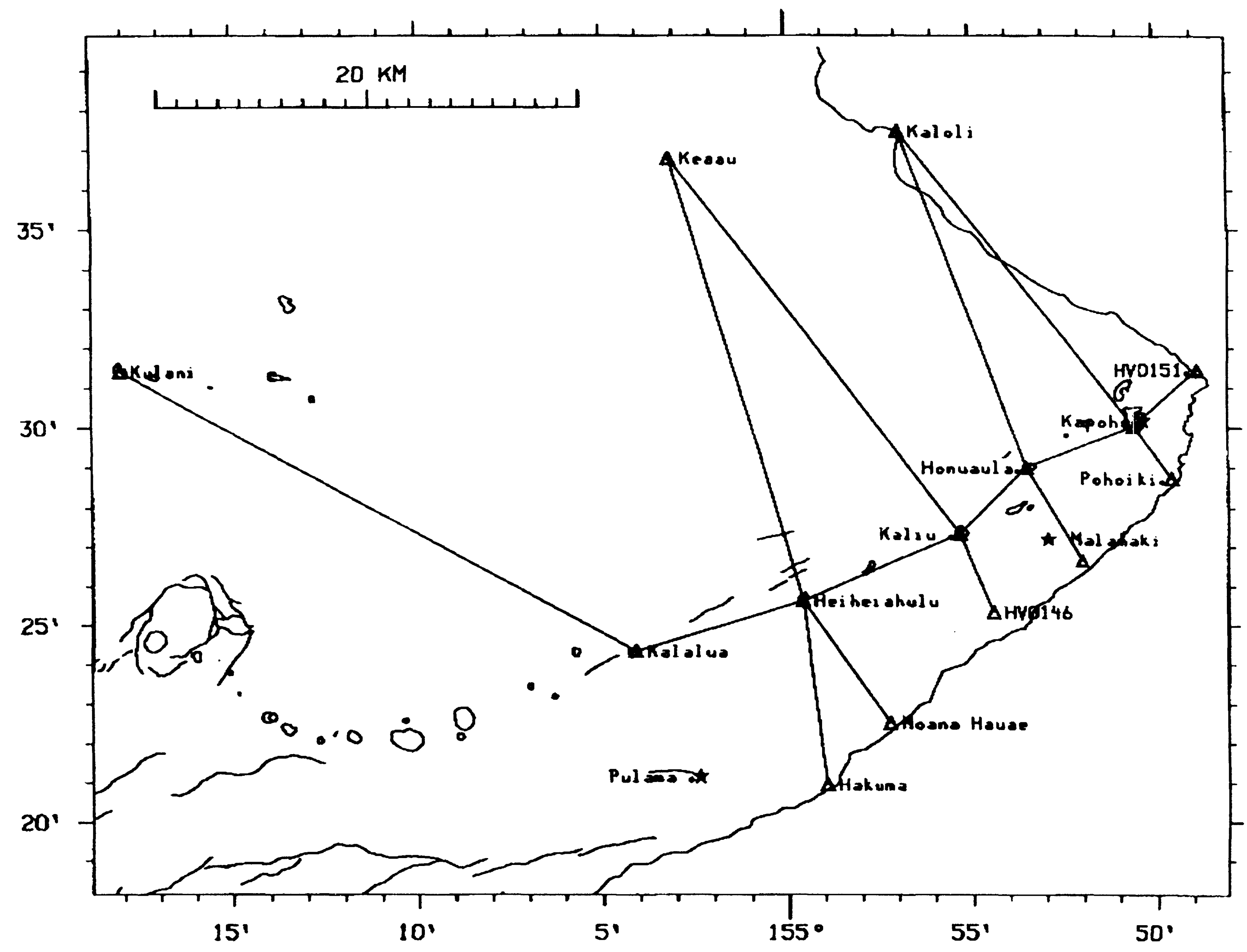

20 KM
Kaloli
Keaau
Kulani
HVO151
Kapoho
Honuaula
Pohoiki
Kaliu
Malamaki
Heiheiahulu
HVO146
Kalalua
Moana Hauae
Pulama
Hakuma
35'
30'
25'
20'
15'
10'
5'
155°
55'
50'

FIG. 7

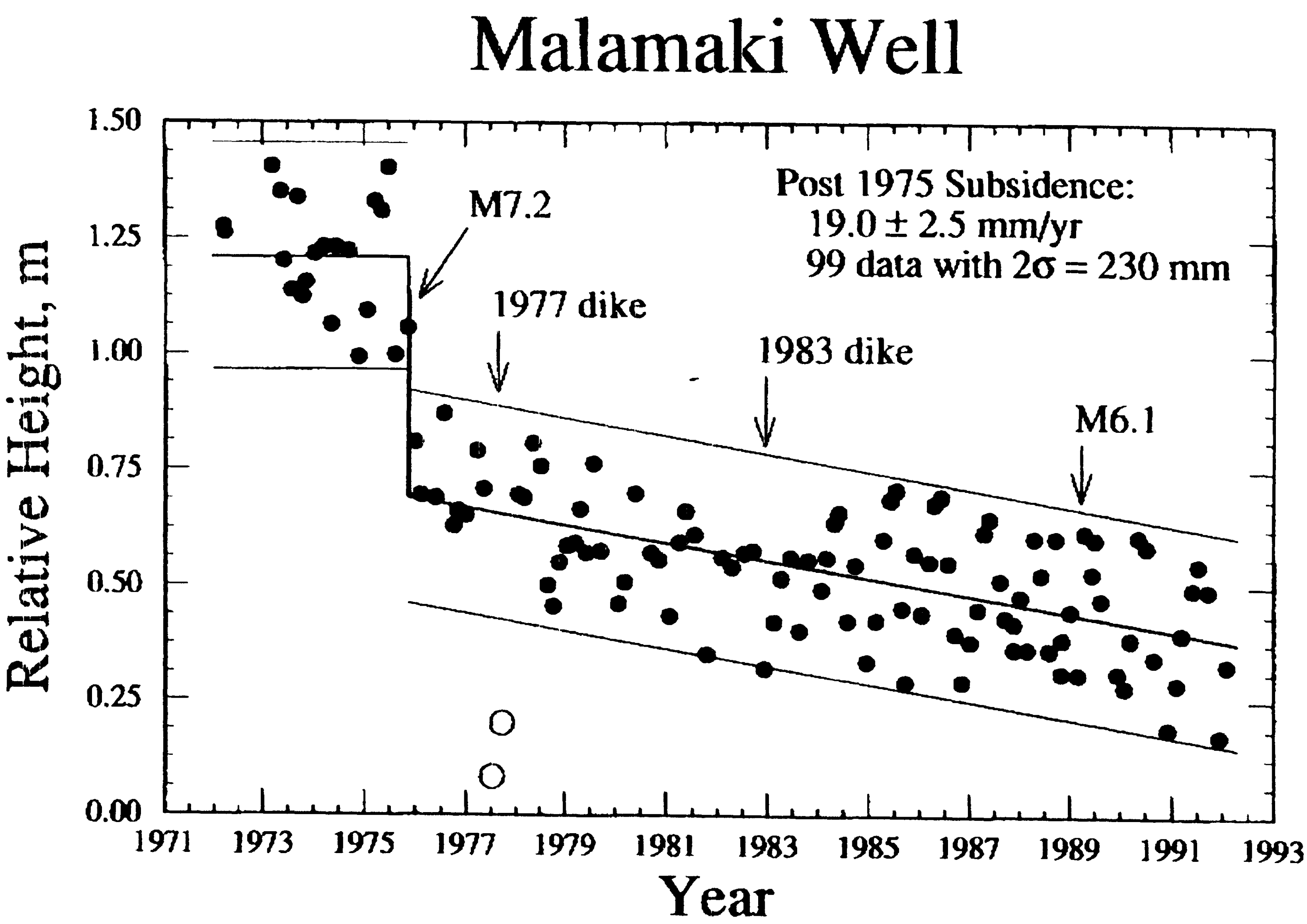

Malamaki Well
Relative Height, m
1.50
1.25
1.00
0.75
0.50
0.25
0.00
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
Year
M7.2
1977 dike
1983 dike
M6.1
Post 1975 Subsidence:
19.0 ± 2.5 mm/yr
99 data with 2σ = 230 mm

FIG. 8A

Kapoho Well

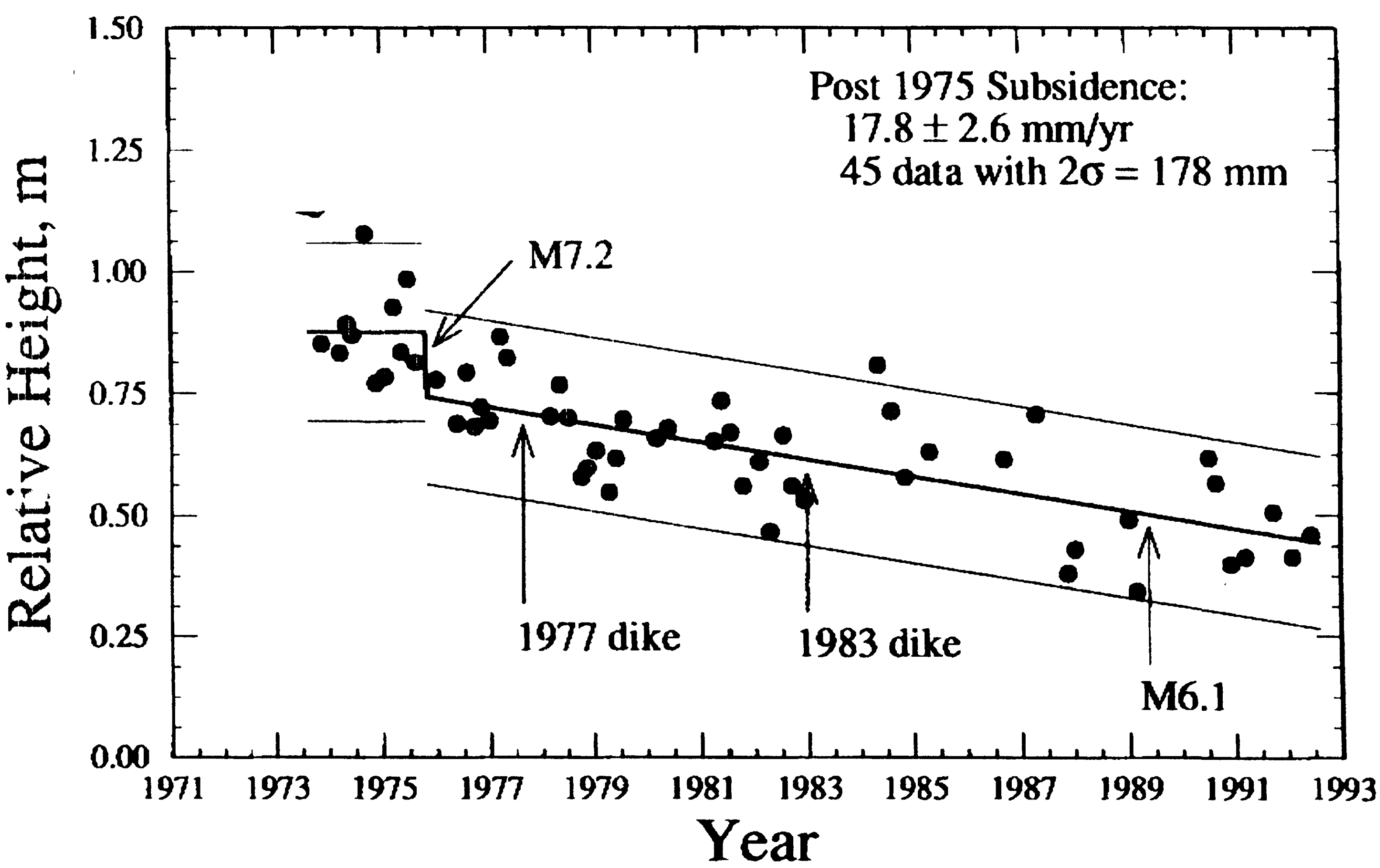


FIG. 8B

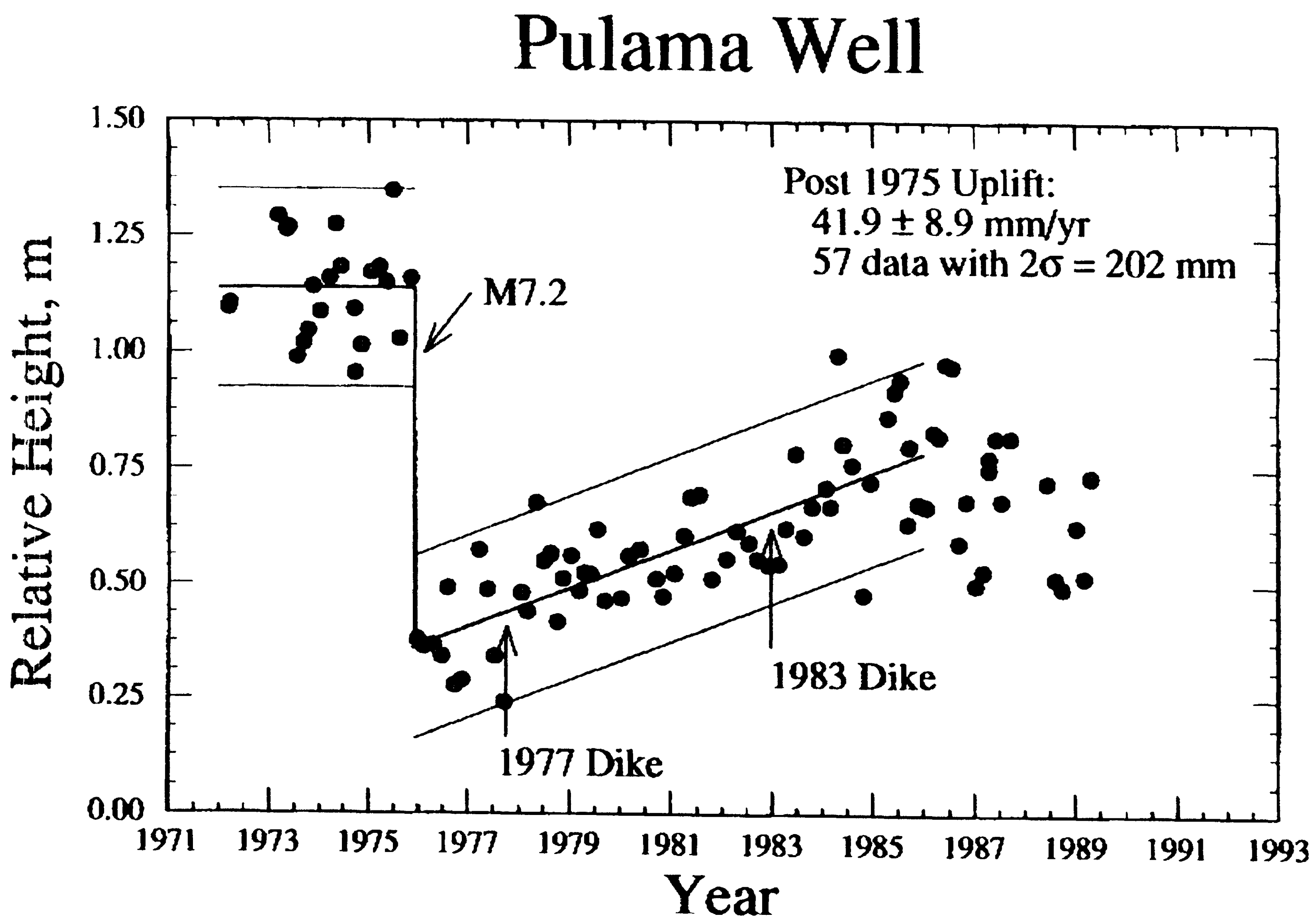

Pulama Well
Post 1975 Uplift:
41.9 ± 8.9 mm/yr
57 data with 2σ = 202 mm
M7.2
1977 Dike
1983 Dike
Relative Height, m
Year
1.50
1.25
1.00
0.75
0.50
0.25
0.00
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993

FIG. 8C

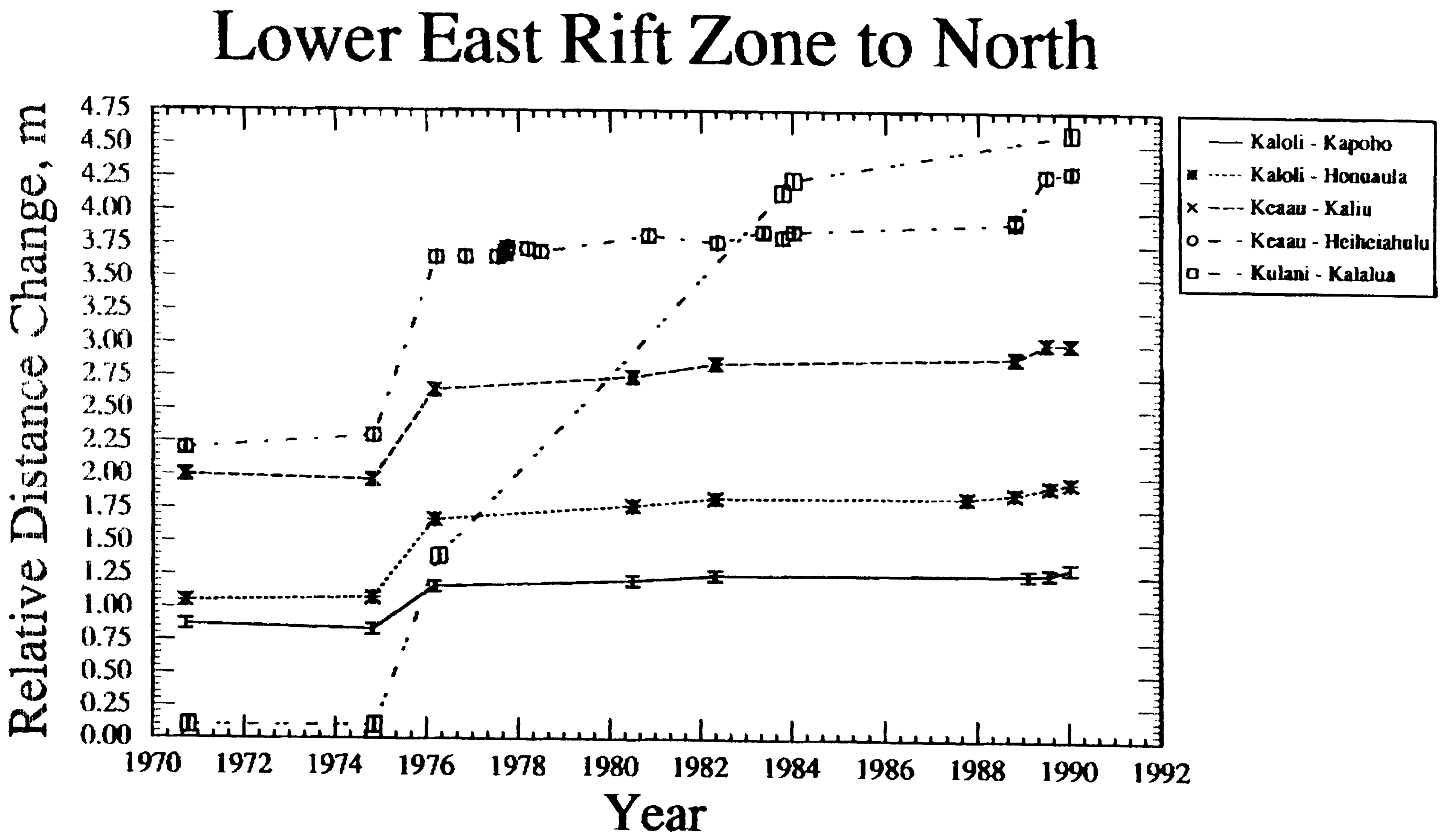

Lower East Rift Zone to North
Relative Distance Change, m
4.75
4.50
4.25
4.00
3.75
3.50
3.25
3.00
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
Year
Kaloli - Kapoho
Kaloli - Honuaula
Keaau - Kaliu
Keaau - Heiheiahulu
Kulani - Kalalua

FIG. 9A

Lower East Rift Zone to South

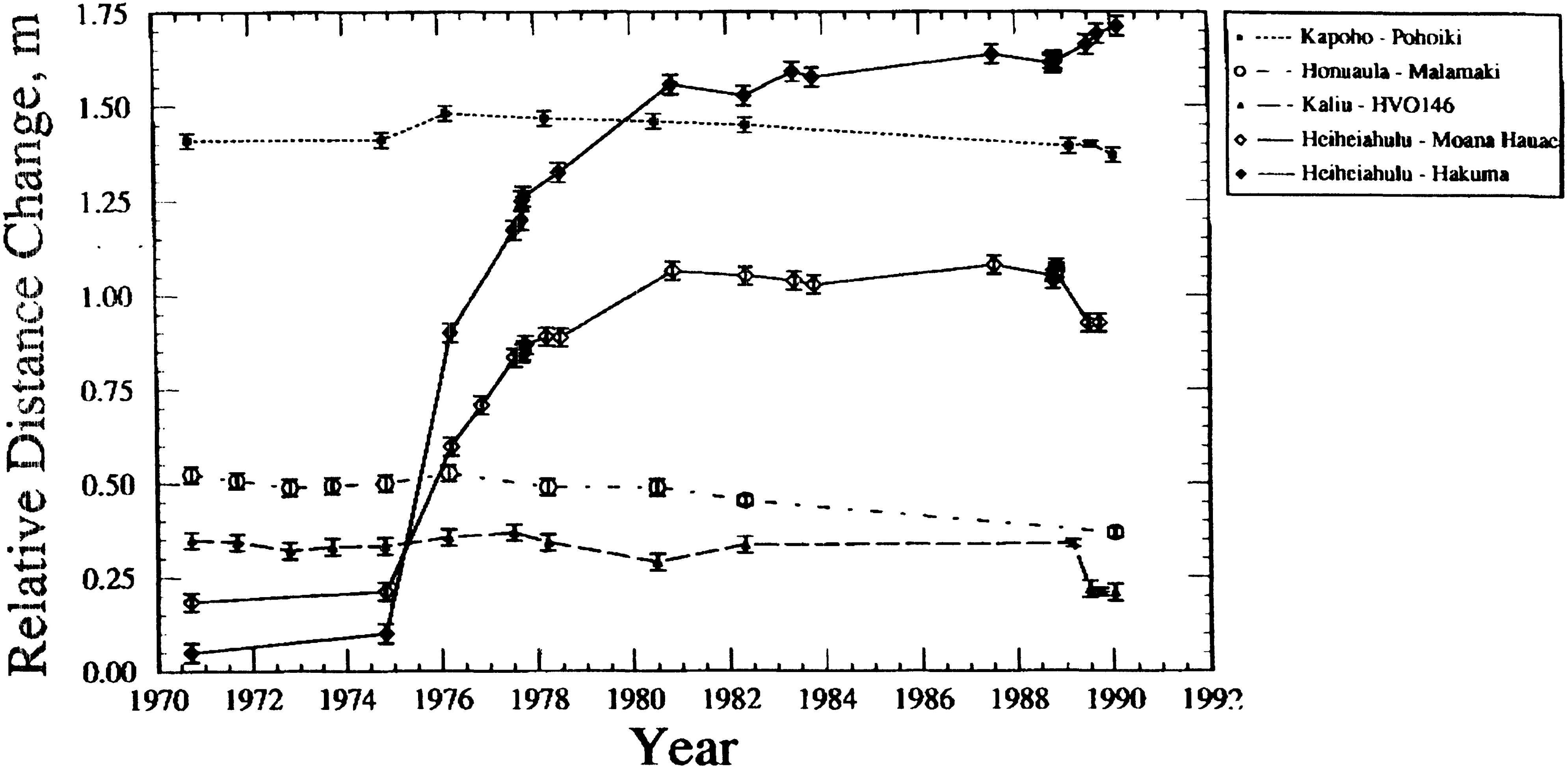


FIG. 9B

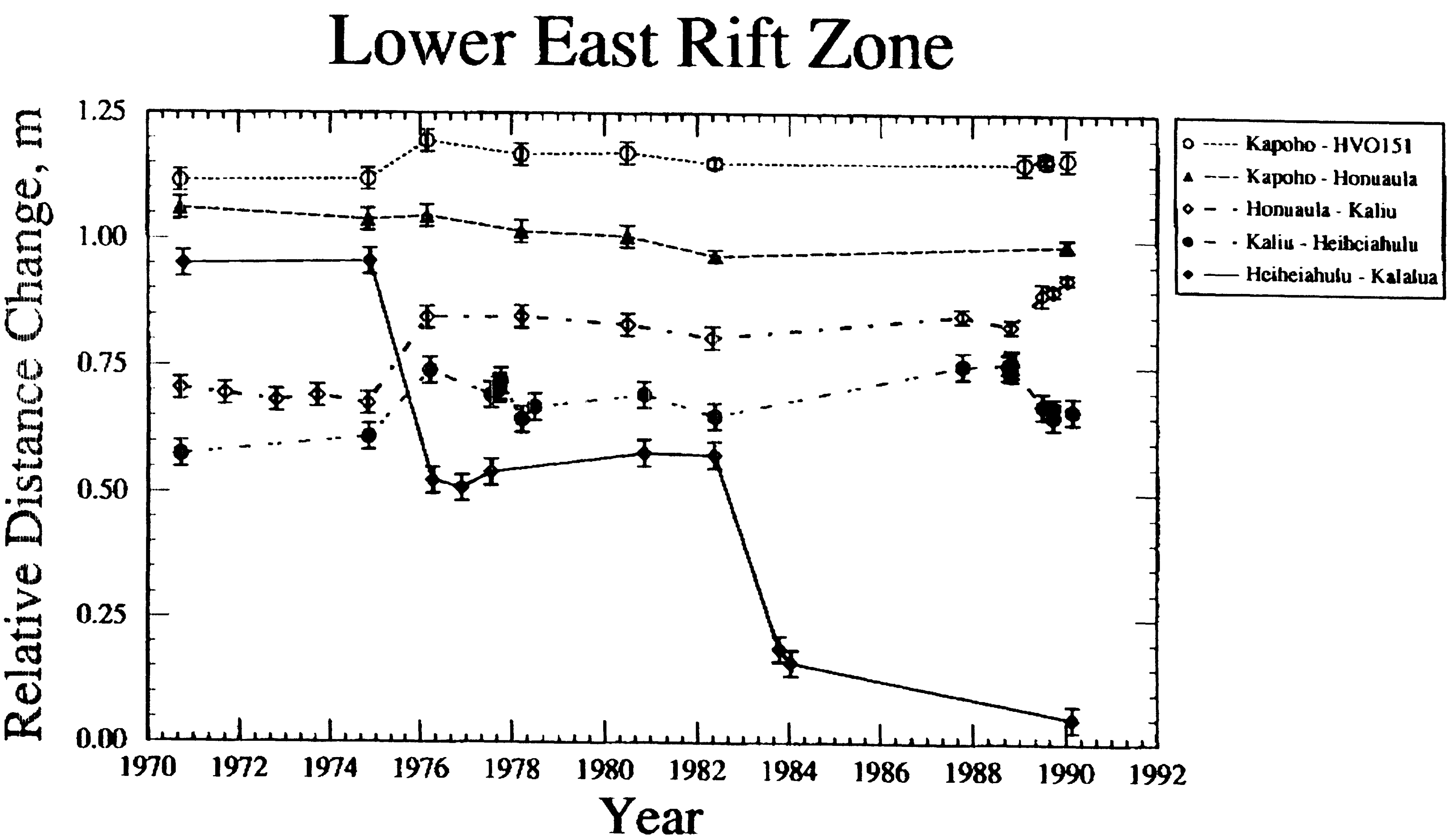

Lower East Rift Zone
Relative Distance Change, m
0.00
0.25
0.50
0.75
1.00
1.25
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
Year
Kapoho - HVO151
Kapoho - Honuaula
Honuaula - Kaliu
Kaliu - Heibciahulu
Heiheiahulu - Kalalua

FIG. 9C

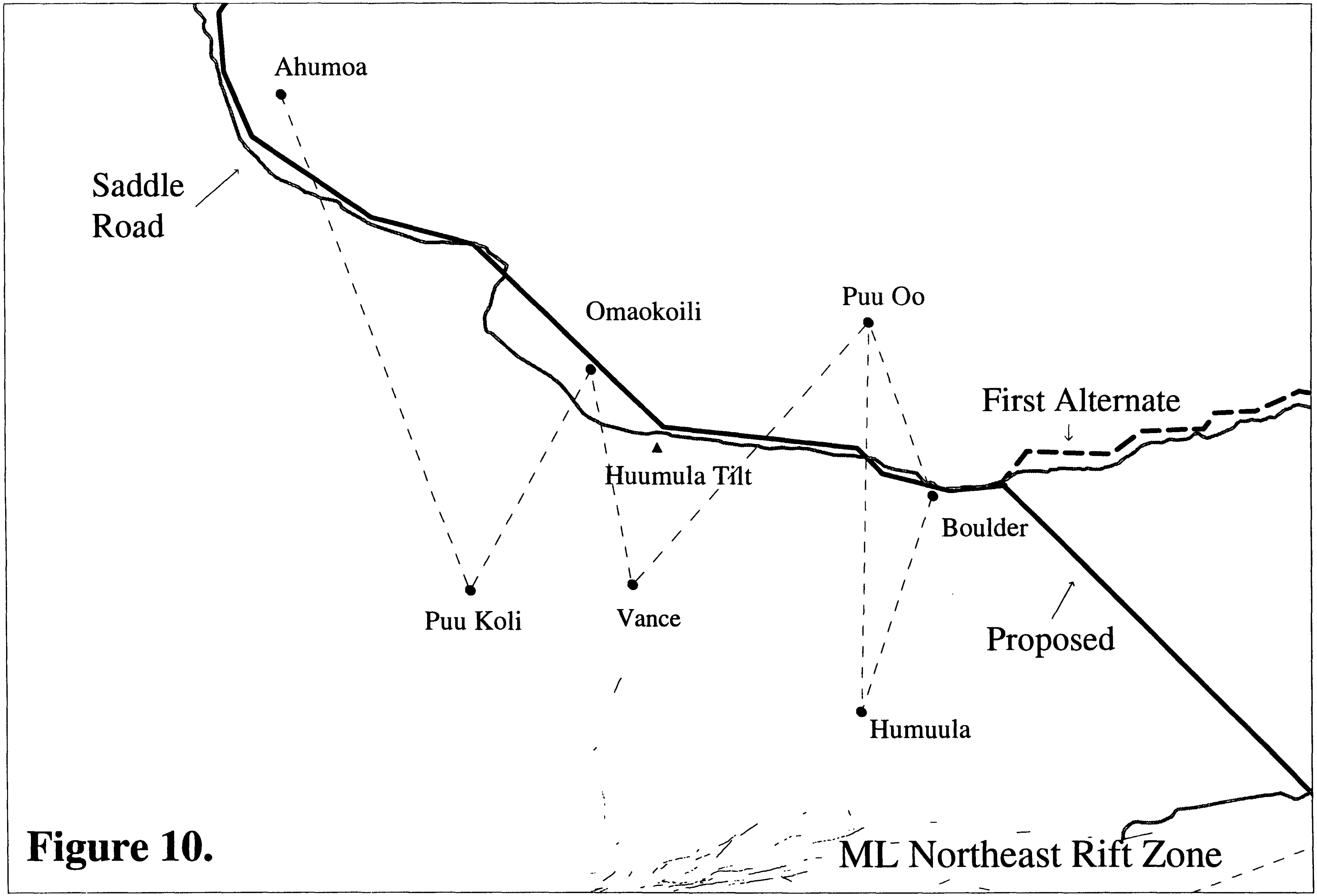

Ahumoa
Saddle Road
Omaokoili
Puu Oo
First Alternate
Huumula Tilt
Boulder
Puu Koli
Vance
Proposed
Humuula
ML Northeast Rift Zone

Figure 10.

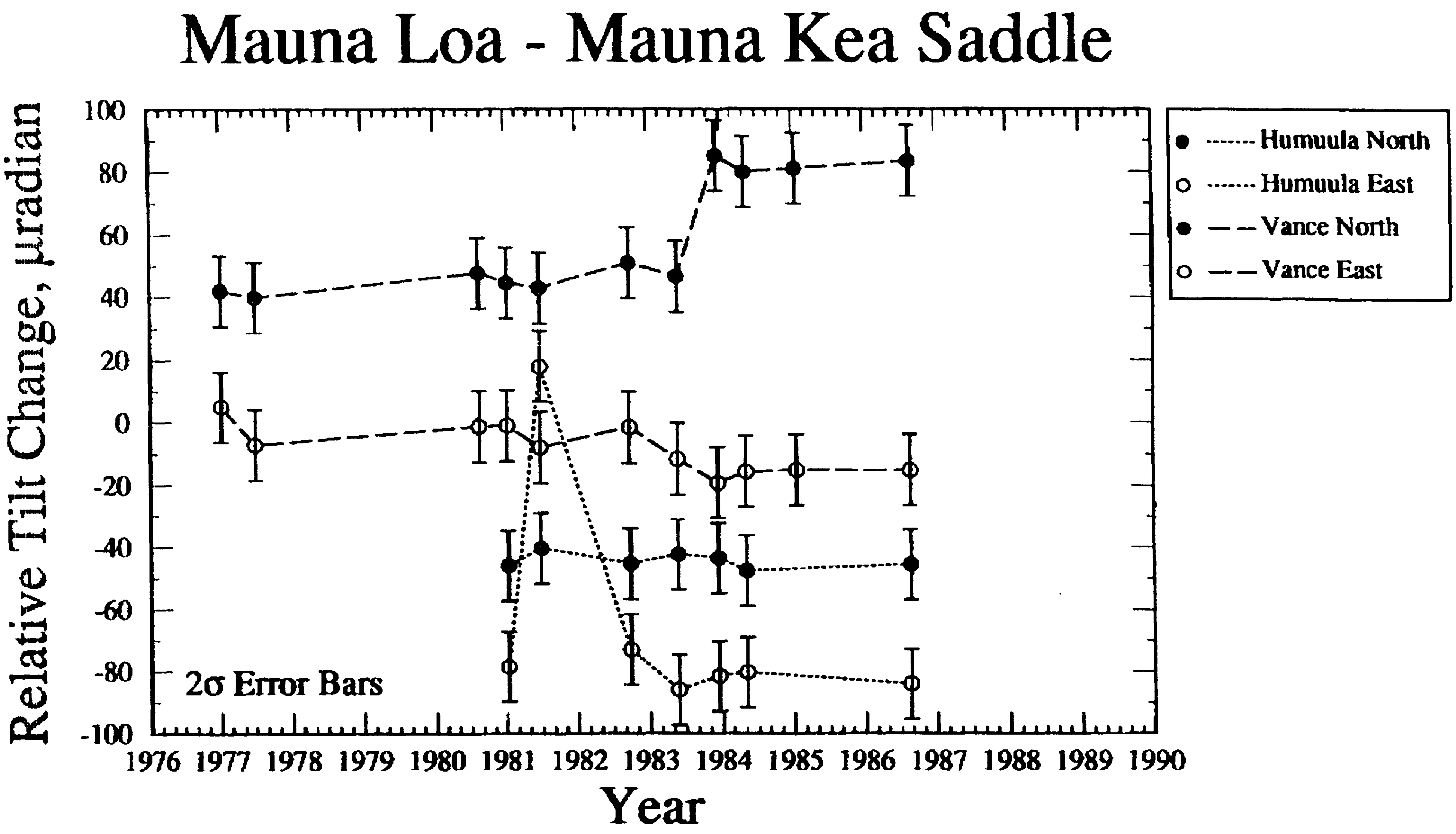

Mauna Loa - Mauna Kea Saddle
Relative Tilt Change, µradian
100
80
60
40
20
0
-20
-40
-60
-80
-100
1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990
Year
2σ Error Bars
Humuula North
Humuula East
Vance North
Vance East

Fig. 11

Mauna Loa - Mauna Kea Saddle

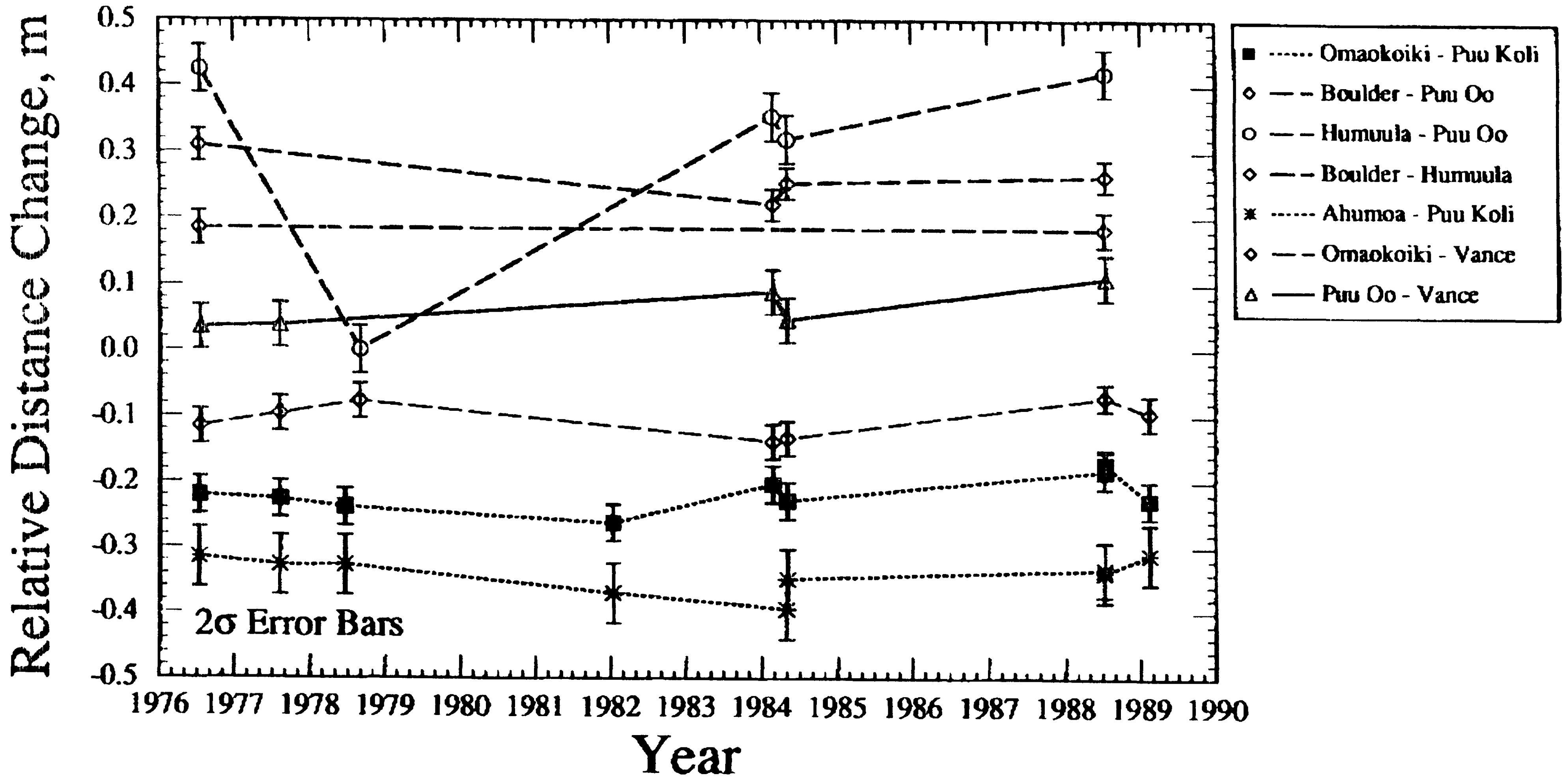


FIG. 12