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The Tau Inversion method has been used to invert earthquake travel times from the Hawaiian Ridge to determine velocity structure with limits. The inversion gives a velocity model showing a rapid increase in velocity from 5.9km/sec to 7.2 km/sec between 4-km and 7.5-km depth, a monotonic increase to 7.5km/sec near 11km, and Moho velocity of 8.0 kn-sec at 15-km depth. Three prominent travel time delays, indicating hetergeneous velocity structure, are shown to correspond to the major volcanoes on Hawaii: Kilauea, Mauna Loa and Mauna Kea. Also, from the Moho depth determined by Tau Inversion, we infer that previous

VELOCITY STRUCTURE OF THE SOUTHEASTERN HAWAIIAN RIDGE DETERMINED BY TAU INVERSION

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Abstract. The Tau Inversion method has been used to invert earthquake travel times from the Hawaiian Ridge to determine velocity structure with limits. The inversion gives a velocity model showing a rapid increase in velocity from 5.9 km/sec to 7.2 km/sec between 4-km and 7.5 -km depth, a monotonic increase to 7.5 km/sec near 11 km, and Moho velocity of 8.0 km/sec at 15 -km depth. Three prominent travel time delays, indicating heterogeneous velocity structure, are shown to correspond to the major volcanoes on Hawaii: Kilauea, Mauna Loa and Mauna Kea. Also, from the Moho depth determined by Tau Inversion, we infer that previous estimates of crustal flexure for the Hawaiian Ridge, based on deeper Moho depths (> 15 km), are too large. The Tau method is shown to be useful in delineating heterogeneous velocity structure and determining limits on velocity depth models from local earthquake travel time data.

Introduction

The method and results of the Tau Inversion method were applied to Hawaiian Ridge earthquake travel time data to determine a velocity-depth function and its limits for the Hawaiian Ridge. The Hawaiian Ridge is instrumented by seismograph stations (Fig. 1) of the Hawaii Volcano Observatory (HVO), Honolulu Tsunami Observatory (HTO) and Hawaii Institute of Geophysics (HIG). Using these seismometer arrays and Hawaiian earthquakes (Estill and Odegard, 1978), we obtained travel time sampling of the crust and upper mantle.

Previous studies of the velocity structure of the island of Hawaii by Eaton (1962), Ryall and Bennett (1968), Hill (1969), Ward and Gregersen (1973) and Ellsworth and Koyanagi (1977) are summarized in Figure 2. Important findings of this previous work applicable to Tau Inversion results are: (1) higher P-wave velocities along volcano summit and rift zones than in the shield areas due to the presence of denser igneous intrusives and greater velocity variation in the crust than in the mantle under Hawaii (Hill, 1969), and (2) no large P-wave low velocity zones caused by reservoirs of magma in the upper mantle, but either an extensive magma conduit system or narrow magma pathways at depth (> 40 km) (Ellsworth and Koyanagi, 1977). Older offshore refraction profiles along the Hawaiian Ridge, discussed by Furumoto _et al_. (1973), indicate mantle depths between 12 km and 20 km for the major islands of the Hawaiian chain and some evidence for systematic increase of Moho depth with island age.

Data Analysis

Travel times to seismograph stations were determined from 65 earthquakes occurring along the Hawaiian Ridge during the period July 20, 1976 to March 30, 1977. These events were relocated by use of arrival times at seismographs located along the Hawaiian Ridge (Estill and Odegard, 1978). Travel times were corrected to sea level using an assumed velocity of 5.5 km/sec. The assumed velocity may bias surface velocity determinations but will not significantly affect deeper determinations. The travel times, shown in Figure 3, are plotted versus distance with a reducing velocity of 7.0 km/sec. Travel times with distances out to 120 km are Hawaii Island and near-shore events, whereas greater distances are travel times to Maui and Oahu seismographs stations from events on Hawaii. In order to determine velocity-depth limits from this data, the Tau method (Bessonova et al. 1974) was used for inversion.

The Tau inversion process went through three steps. First, Tau versus distance data were plotted using the intercept time and a set of assumed ray parameters. The limits on the maximum Tau were determined for each ray parameter and gave Tau as a function of the ray parameter. A plot of Tau versus distance for a specific ray parameter is shown in Figure 4. Because of the scatter, this data was filtered by means of a center-weighted moving average filter as shown in Figure 5. The large peaks at 43 and 65 km and the less distinct peak at 85 km correspond to distances for events with ray paths that passed beneath three major volcanoes of the island of Hawaii: Kilauea, Mauna Loa and Mauna Kea. Since Tau is the intercept time for a given distance and ray parameter, these peaks indicate that there is a time delay caused by the structure beneath the three volcanoes.

The second part of the Tau method involves construction of an envelope of the Tau versus ray parameter values found in the first part. The extent of scatter in the data was considered and the time delays associated with the three volcanoes were eliminated. The third operation in the Tau process is integration of the Tau integrals to determine limits of the velocity depth function.

The computer program used to invert the data first calculates an average model by means of Herglotz-Wiechert inversions and the Tau-ray parameter envelope. The limits are then calculated for various averaging intervals, as shown in Figure 6, essentially contouring the limits. All models consistent with the travel time data are contained within the limit contours closest to the average model.

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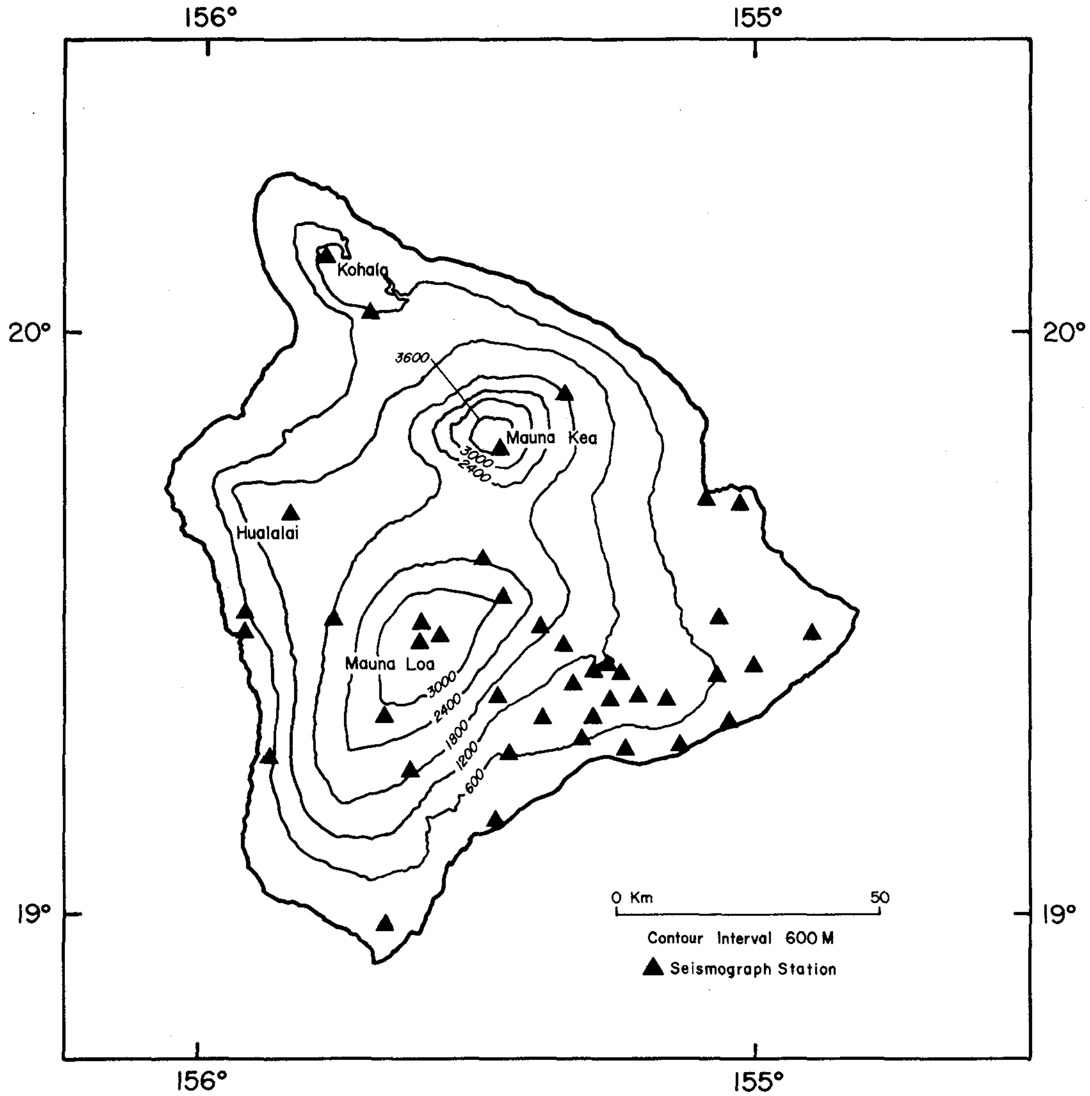

Fig. 1. Hawaii island seismograph array.

Discussion and Conclusions

Three large delay times are noted for epicentral regions corresponding to three major volcanoes on Hawaii: Kilauea, Mauna Loa and Mauna Kea. Because they are so large, the delays must be caused in part by errors in hypocenters and topography corrections. Furthermore the size of the three time delays should not be taken as direct evidence of magma or partial melt at shallow depths, but as partly due to lower velocity shield volcanics lying above higher velocity igneous intrusions. Ellsworth and Koyanagi (1977) and Hill (1969) also note that the mean crustal P-wave velocities within summit and rift areas of Kilauea are substantially higher than shield area velocities, because of possible differences in structure. Applying the techniques described in this paper to a more detailed P- and S-wave study could help to determine limits on contrasting crustal velocities for shield and rift areas as a possible explanation of the observed time delays.

Velocity depth model and extremal limits resulting from the Tau inversion procedure are shown in Figure 6. Physically, the average

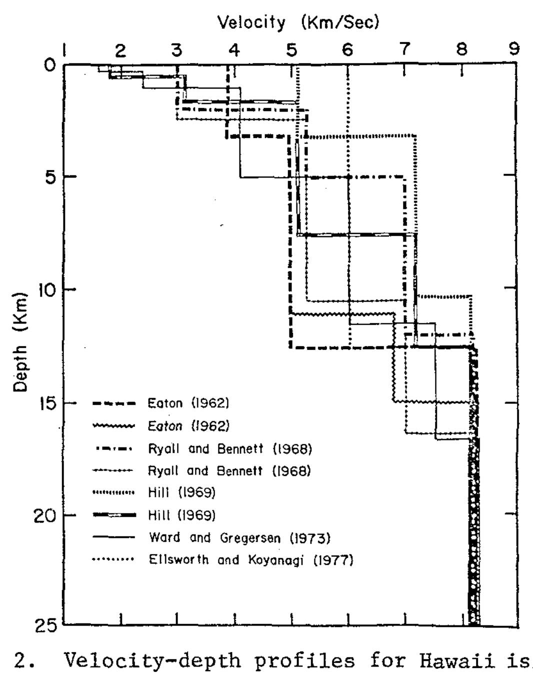

Fig. 2. Velocity-depth profiles for Hawaii island.

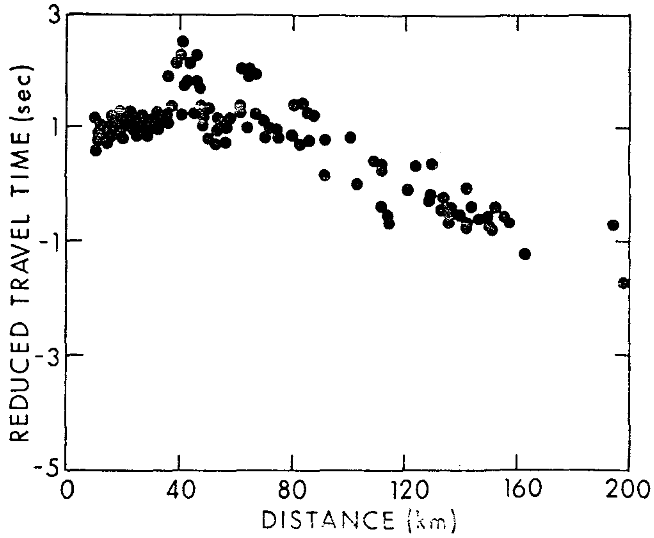

Fig. 3. Plot of reduced travel time data used for inversion.

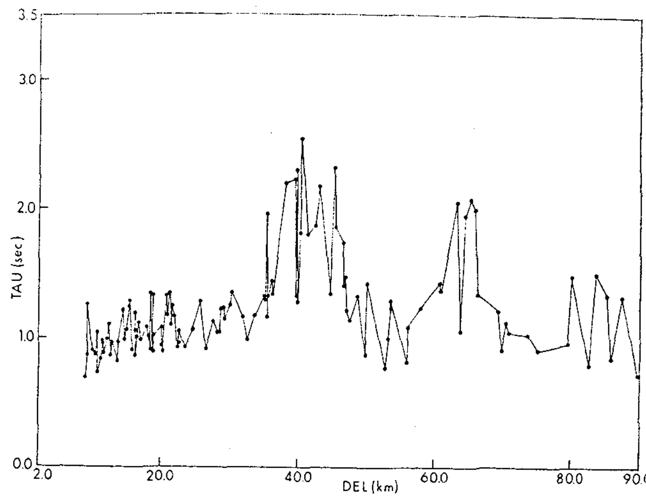

Fig. 5. Filtered Tau versus distance plot using center weighted moving average filter.

velocity-depth model for the Hawaiian Ridge shows the assumed velocity of 5.5 km/sec near the surface, a change in velocity from 5.9 km/sec between 4 km and 7.5 km and then a gradual increase to 7.5 km/sec at 11-km depth. Between 11 km and 12.5 km the velocity increases rapidly to 7.9 km/sec. Moho velocity of 8.0 km/sec is reached between 12.5-and 15-km depth, and the velocity is essentially constant at 8.1 km/sec below 15 km.

The velocity depth function determined by the Tau Inversion procedure agrees in its major features with the more recent Hawaiian crustal refraction studies shown in Figure 2. The models with significant lower velocities at depth fall outside the limits of the Tau model, indicating possible effects from the areas that caused the Tau delays shown in Figure 5. Further, the average Moho depth of 12.5 to 15 km from the Tau model is significantly less than the depths of greater than 18 km given by Furumoto et al. (1968) for some sections of the Hawaiian Ridge. Thus there is no apparent thickening of layer 3 and the amount of lithospheric flexural deflection should be considerably less than that assumed by Walcott (1970) and Watts and Cochran (1974). The Tau model is in closer agreement with the 2 to 3 km deflection inferred by Woollard (1970) and Suyenaga (1978) using the layer 2- layer 3 boundary.

The Tau method has been shown to be useful as a inversion technique for determining velocity-depth limits on travel time data. Also, the Tau-distance-ray parameter diagrams are useful in delineating heterogeneous structures. Further work should determine a more detailed P-wave and S-wave velocity structure for Hawaii.

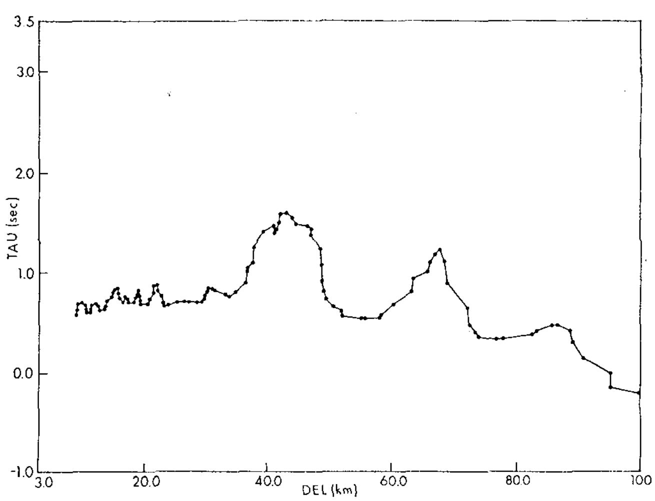

Fig. 4. Tau versus distance plot for a ray parameter of 920.

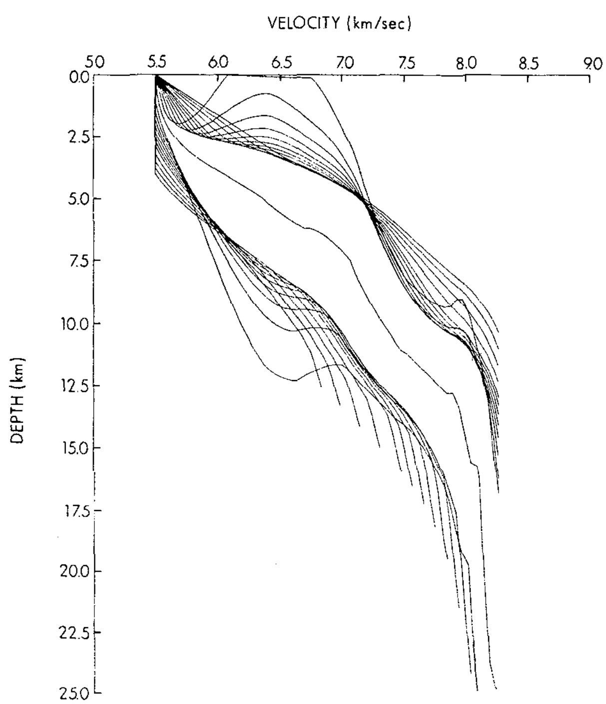

Fig. 6. Velocity-depth function for Hawaiian Ridge showing extremal bounds and contour plot of limits around average model.

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