Seismicity of the Koae fault zone and lower Southwest Rift zone, Hawaii

Stacey D. Robertson
Department of Geosciences, Trinity University, 715 Stadium Drive #45, San Antonio, TX 78212-7200
Faculty sponsor: Glenn Kroeger, Trinity University

INTRODUCTION

Kilauea, an active volcano located on the island of Hawaii, has two large rift zones, the southwest rift zone (SWRZ) and east rift zone (ERZ). Both rifts have been seismically active in the past, but the ERZ has been the more active of the two in recent years. Because the north flank of Kilauea is buttressed by massive Mauna Loa, the widening of the rift zone is directed toward the ocean to the south. Thus the volcano grows both by addition of lava flows and by large-scale ground deformation. The area of the volcano which most frequently moves to accommodate the expanding ERZ is referred to as the south flank. It is bounded to the west by the SWRZ, to the east by the ERZ, and to the north by the Koae faults. Movement of the south flank is documented by Swanson, Duffield, and Fiske (1976), whose geodetic evidence suggested that forceful injection of magma into the rift zones has uplifted the south flank of Kilauea and caused it to move several meters seaward during the 20th century, whereas the north flank has experienced almost no movement.

The Koae fault zone is a long, sinuous fault zone located south of Kilauea's summit caldera. It trends east-northeast and extends twelve kilometers between the SWRZ and ERZ of Kilauea, generating the zone of detachment for the volcano's south flank. Movement of the south flank to the southeast is almost exactly perpendicular to the trend of the ERZ and Koae fault system, indicating that these faults provide a major plane of separation (Swanson, Duffield, and Fiske, 1976). The Koae fault system structure consists of steep (70°-90° at the surface), northerly dipping, en echelon, listric normal faults which have vertical offsets up to 20 m and an average dilation component of 25 m which increases to the east.

The sliding of the south flank, termed "volcanic spreading" by Borgia (1994) is accompanied by many earthquakes of widely ranging magnitudes. Shallow earthquakes reflect local stress which is most likely induced by magma pressure, whereas the deeper portions of the volcano are influenced by more regional stresses. The volcanic spreading thus results in upper flanks which experience extensional stress and lower slopes which are affected by confining pressure. As Kilauea undergoes this process, its upper flanks and summit region are stretched apart while its basal contact with the oceanic crust forms a decollement under regional compression (Borgia, 1994).

In this project I studied in detail the distribution of faulting mechanisms within the south flank in an effort to determine faulting patterns and confirm the existence of a decollement. Previous studies have examined the more active ERZ, but very little attention has been focused on the SWRZ. I therefore chose to examine 11,899 earthquakes located in the region of the Koae faults and the lower portion of the SWRZ (Figures 1 and 2).

DATA PROCESSING

Arrival time data for earthquakes, contained in archive (ARC) files, was obtained from the Hawaiian Volcano Observatory (HVO) for the years 1968 to 1975 for the Koae faults and the lower SWRZ. Event foci were located using the USGS program HYPOINVERSE (Klein 1989) and a laterally homogeneous crustal model which contains two homogeneous layers of linearly increasing velocity with depth. The output of HYPOINVERSE is a summary (SUM) file of event origin times, locations, and magnitudes. I surveyed the resulting SUM file for interesting swarms to study. I used a FORTRAN program, SELECT, to separate the data into smaller summary files based on the dates and magnitudes of events. I then generated many different types of plots to search for interesting trends within or between the two rift zones. These plots included examinations of depth, epicenter distribution, frequency of events, and cumulative percentages of events. Next I used EXTRACT, another FORTRAN program, to generate ARC files containing only events of interest, which could in turn be used to run FPFIT and FPPLOT (Reasenburg and Oppenheimer, 1985). FPFIT uses P-wave polarity picks in ARC files to search for best fit double-couple focal mechanisms, and the program's output includes five parameters which can be used to determine the quality of the solution. FPFIT's algorithm includes a grid search and may find multiple solutions for any one event. FPPLOT and FPPAGE were used to plot the nodal planes and P and T axes of the various faulting events. I ran GRADE, a program written by Paul Okubo, on the output files generated by FPFIT, and this classified each earthquake mechanism as decollement, normal, reverse, or strike-slip faulting.

Upon return to Trinity, I had to reconstruct all necessary software to run on a Sun SPARC workstation which used a UNIX operating system rather than the VMS system used in Hawaii. We therefore had to rebuild SELECT, EXTRACT, HYPOINVERSE, FPFIT, and FPPLOT. We then used SELECT and EXTRACT to separate the data into smaller summary files, and we wrote a "C" program which formatted these files as tab-delineated ASCII text so they could be read into Excel or KaleidaGraph spread sheets. When running the reconstructed FPFIT at Trinity, I used a finer grid search than the one previously used in Hawaii. After analyzing several sets of data and plotting histograms of different faulting mechanisms, we determined that GRADE should be rewritten to classify faulting mechanisms in a more accurate way. The program used by HVO simply assigned every faulting plane with a dip greater than 80 degrees to a strike-slip mechanism and every faulting plane with a dip less than 20 degrees to a decollement mechanism. It classified fault planes between 20 and 80 degrees as normal or reverse, based upon the rake of fault motion. We rewrote GRADE to classify faulting motions in more detail. Fault planes dipping less than 20 degrees were still classified as decollement events, but those with a dip of 70 to 90 degrees were classified as either normal, reverse, or strike-slip based upon their rake. Faults with a dip of 45 to 70 degrees were also classified as reverse, normal, or strike-slip, but a strong lateral motion component was required for these shallower planes to be classified as strike-slip. Finally, fault planes dipping between 20 and 45 degrees were classified as either normal, reverse, or oblique. We believe that our new version of GRADE provides a more accurate portrayal of the faulting mechanisms, and I therefore reprocessed all of the data studied in Hawaii with this new program. I compared the results of GRADE with focal mechanisms generated by FPFIT (Figure 3) and found that the mechanisms agreed. FPFIT often generated multiple solutions for single faulting events, and GRADE selected the solution with the smallest possible error in terms of strike, dip, and rake.

After processing the faulting events of 1968 to 1975 with the new version of GRADE, I again plotted multiple histograms of the data. In order to decrease processing time of the data, I examined only earthquakes with a magnitude greater than or equal to 2.0. I also eliminated events which were located at depths greater than 12 km because there was virtually no seismicity between 12 km and 25 km depth and events located beneath 25 km are assumed to have misfit depths. The resulting histograms are shown in Figure 4, and a trend is clearly visible. Strike-slip mechanism events are most prevalent near the surface, at depths of less than or equal to 1 km. In contrast, decollement events are focused at 8 - 11 km depth. Reverse and normal mechanisms are distributed more evenly than strike-slip or decollement, but they seem to be focused at a depth of 3 - 4 km.

I generated maps of earthquake swarms using The Generic Mapping Tools Package (GMT) but have thus far been unable to determine any variations in mechanism type with map location. An example plot including a fault of each mechanism type is shown in Figure 2.

CONCLUSIONS

The examination of focal mechanisms on the western portion of Kilauea's south flank indicates the existence of several zones of seismicity with depth. The surface seismicity (less than 1 km depth) is primarily strike-slip faulting, and it is likely caused by extensional forces as the rift zones dilate at varying rates. Normal and reverse faults are concentrated at approximately 4 km depth, and these are probably caused by extension of the south flank and by magmatic intrusions into the rift zone. The deepest earthquakes, located at 8 - 11 km depth, are predominantly decollement events. This suggests that the basal decollement is located at approximately 11 km depth and the shallower decollement events are generated by imbricate thrusts from the larger fault.

A previous study performed by Denlinger and Okubo (1995) on a larger, eastern portion of the south flank identified seismicity due to dike injection at 2 to 4 km, seismicity due to reverse faulting at 7 to 10 km, and the base of seismicity at 10 to 12 km. These depths agree with the results found at the Koae faults and lower SWRZ in terms of strike-slip and decollement mechanisms, but the reverse mechanisms in the western data seem to have a shallower average depth. This difference in reverse mechanisms could be due to variations in fault depths and intrusion depths between the east and the west, largely due to the fact that the ERZ is much more active than the SWRZ. We therefore conclude that several different forces cause faulting on the south flank of Kilauea. Large scale compressive forces cause the south flank to slip southeast along a deep decollement, whereas smaller extensional forces caused by rifting and magmatic intrusions generate normal, reverse, and strike-slip faulting near the volcano's surface.

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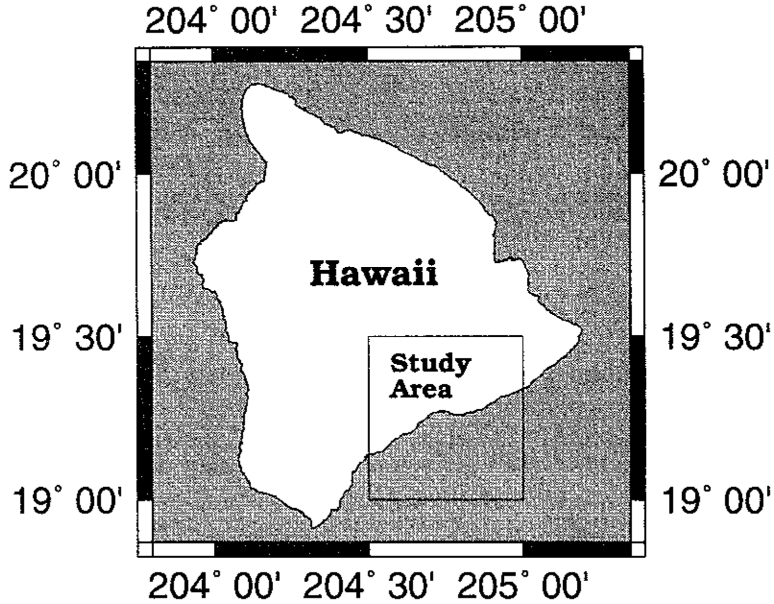

Figure 1. The island of Hawaii and location of study area on the south flank of Kilauea volcano.

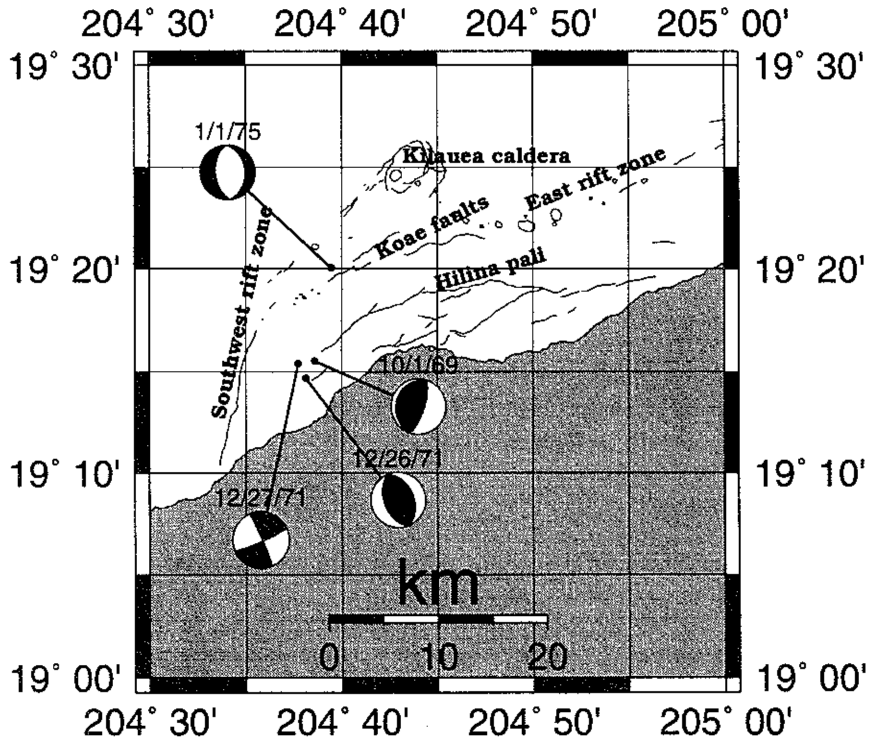

Figure 2. South flank of Kilauea with faults and four focal mechanism plots. The 1/1/75 event was normal with a magnitude of 2.1; the 12/26/71 event was reverse with a magnitude of 2.2; the 10/1/69 event was decollement with a magnitude of 2.1; the 12/27/71 event was strike-slip with a magnitude of 2.4.

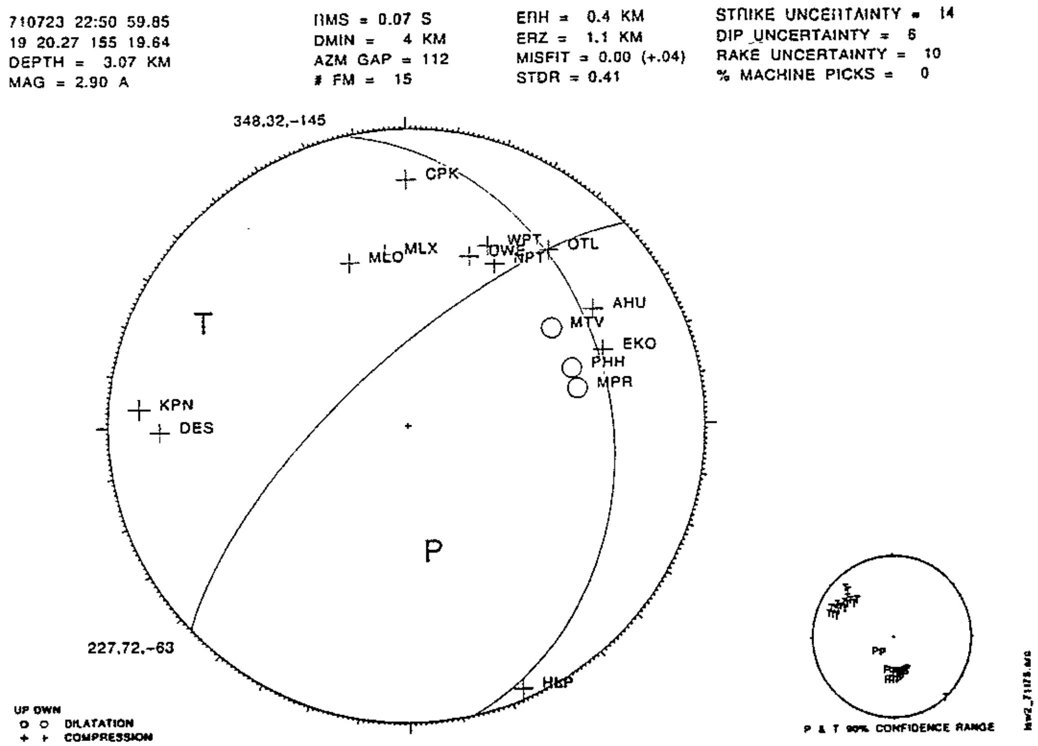

Figure 3. FPPLOT diagram of a normal faulting mechanism event from 7/23/71, with compressional and dilational axes labeled as T and P, respectively.

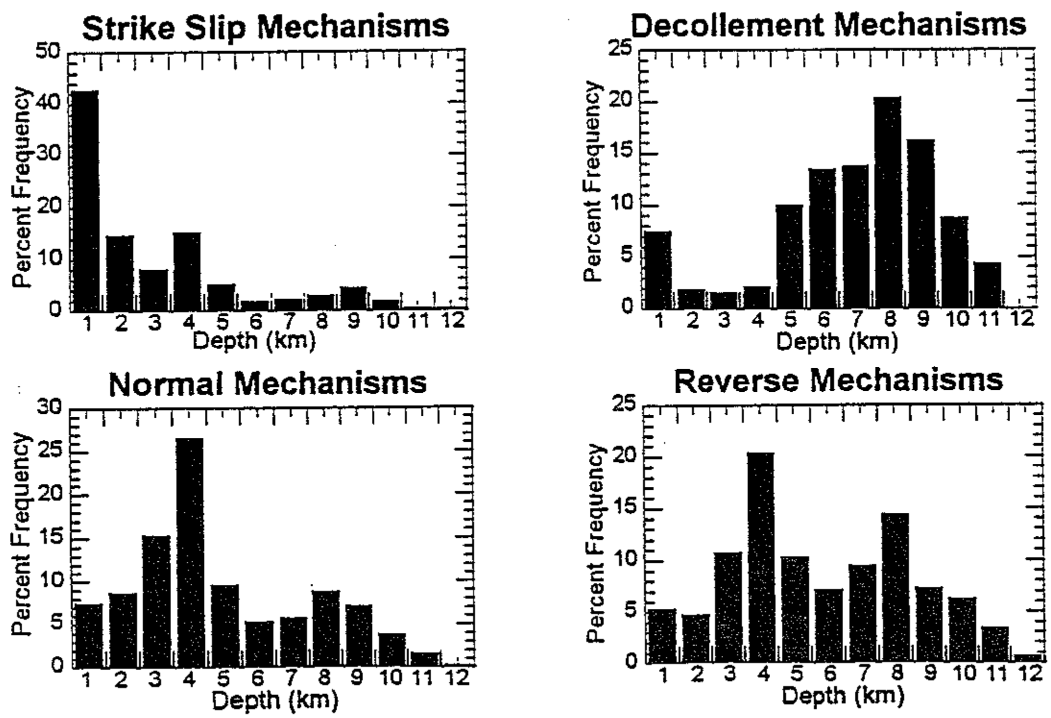

Figure 4. Histograms of percent frequency of mechanism type vs. depth to earthquake focus (for all earthquakes with magnitude greater than or equal to 2.0).