Documentation for Draft Seismic-Hazard Maps for the State of Hawaii

F. Klein, A. Frankel, C. Mueller, R. Wesson, and P. Okubo
U.S. Geological Survey
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Introduction

We have recently completed draft seismic hazard maps for the state of Hawaii, for review and comment. We welcome any and all comments on these draft maps before March 25. The documentation and draft maps are also available on our Internet Web site at: http://geohazards.cr.usgs.gov/eq/. The maps will be revised in light of these comments and final maps will be produced in the beginning of April 1998. This documentation describes the methodology used to produce the new maps.

The first rigorous probabilistic seismic hazard map for the southeast part of the main island of Hawaii was prepared by Klein (1994). This was later expanded to the entire island and the area west to Molokai (Klein, 1997). The present study extends the hazard maps to the entire state and updates these earlier reports by using improved earthquake catalogs, better probability calculations, and a regionalized approach with different treatments appropriate for each source area and magnitude range.

The new maps are for peak horizontal ground acceleration (PGA) and spectral acceleration (SA) at 0.2 sec and 1.0 sec periods (5% of critical damping). We show two probability levels: 10% and 2% probabilities of exceedence (PE) in 50 years. These correspond to return times of about 500 and 2500 years, respectively. Our maps assume that earthquakes are Poissonian and that hazard is independent of time.

The draft maps are based on hazard calculations for a site spacing of 0.02 degrees in latitude and longitude. Hazard was calculated at about 88,000 sites, although, of course, only a small fraction are on land. Note that there is some jaggedness to the highest contours on some of the maps, which is due to the site spacing. We will try to correct this in the final maps. We may also want to mask out certain portions of the maps that are well away from the islands.

As with the USGS seismic hazard maps for the contiguous U.S. (Frankel et al., 1996), the maps are for a reference "firm-rock" site condition. This is defined as the NEHRP B-C boundary, which corresponds to an average shear-wave velocity of 760 m/sec in the top 30m. This is a typical western U.S. rock site. For Hawaii, these maps are meant for probabilistic ground motions at lava sites. The shear wave velocity in the near-surface for one lava site in Hawaii was measured at about 600m/sec (Thurber, pers.

comm., 1998), similar to the B-C boundary used here. The values in the maps should be adjusted upward for ash sites (by a factor of 2.0 for PGA).

The highest hazard in the maps is for the southeast coast of the island of Hawaii. The next highest area is the Kona coast of Hawaii. The hazard generally decreases to the northwest along the island chain. We find values of about 50%g at Hilo and 13%g at Honolulu for peak ground acceleration with 10%PE in 50 years.

We briefly summarize the methodology in the following sections. More details about the tectonics, the seismicity parameter calculations, catalogs, declustering, etc. are contained in the **Appendix.**

Methodology

There are five basic components of the hazard calculation (Figure 1): (1) area source zones for areas on the flanks of active volcanos on the main island, (2) area source zones for Kilauea caldera and narrow rift zones, (3) spatially-smoothed shallow seismicity for other areas of the main island, (4) spatially-smoothed deeper seismicity (d>20 km), and (5) a large area source zone extending from Maui to west of Kauai with the log of the seismicity rate (a-value) ramping down to the northwest. Each of these models is based on our level of knowledge of the processes which cause large earthquakes in that region. We address each one of these three components in the following sections. In all cases, the minimum magnitude considered in the hazard calculation is a moment magnitude of 5.0. This is standard practice in probabilistic seismic hazard assessments for the western U.S. The following discussion frequently refers to “a” and “b” values which correspond to the Gutenberg-Richter recurrence relation: log N= a- bM, where N is the number of earthquakes with magnitudes greater or equal to M.

1. Area source zones on flanks of active volcanoes (shallow seismicity, d<= 20 km)

For these areas, we used five source zones taken from Klein (1994). These source zones are shown in Figure 2 (SFL= south flank; KAO= Kaoiki; HLE=Hilea; KON= Kona, and HUA= Hualalai). The a-values were determined separately for each source zone. For the SFL, KAO, and HLE zones, a single b-value was determined from the total seismicity in these areas. The a-values were chosen to preserve the historic rate of magnitude 5 and larger events observed in each zone. The b-values were determined from the frequency-magnitude data for events of magnitude 5.0 and greater. The b-values for the KON and HUA zones were determined separately. Details on the a and b-value estimation are contained in the Appendix.

For M5.0-6.5, the hazard calculation assumed point sources at 10 km depth (except for the attenuation relations which have fictitious depths; see below). For M>6.5 in these zones, we used finite fault planes. These fault planes were sub-horizontal at a depth of about 9 km. We “floated” these rupture zones along the strike of each area zone, to estimate the hazard. The a-values of the individual zones of SFL, KAO, and HLE were used in the hazard calculation from M5.0 to M7.0.

For M7.0-8.2 we combined these three southern zones into one large source zone. We realize that the M=7.2 Kalapana earthquake was entirely within the south flank, but we divided the modeling of separate vs. joint zones at M=7.0 to simplify the assumptions. Large earthquakes such as Kalapana were included in the rate determinations for both the south flank and the three zones together. We agree with Wyss' (1988) proposal that the great Kau earthquake of 1868 ruptured the entire south flanks of Mauna Loa and Kilauea to account for the intensity distribution and to produce the total moment and 7.9 magnitude. Combining the three south island zones is tectonically very reasonable because most large earthquake focal mechanisms have S to SE directed slip vectors in each zone.

For the two Kona zones (KON and HUA), the maximum magnitude used was 7.0. These zones were treated as separate zones for the entire magnitude range (M5.0-7.0).

2. Area source zones for Kilauea caldera and rift zones (shallow seismicity)

Seismicity located in Kilauea caldera and the rift zones was also treated as area source zones (Figure 3). The maximum magnitude assigned to the hazard calculation from these zones was 6.5. We may want to lower this maximum magnitude for the final maps. In any case, these zones contribute little hazard to the maps.

3. Spatially-smoothed shallow seismicity

The area in and around the main island, not in the aforementioned area zones (1 and 2), was treated by calculating hazard from the spatially-smoothed seismicity in the modern catalog. This procedure was used extensively in the USGS maps for the contiguous U.S. (see Frankel, 1995; Frankel et al., 1996) and is an effective approach to seismic hazard analysis when the specific geologic structures causing large earthquakes are poorly known.

In this procedure, the number of events greater than some threshold magnitude is counted on a grid. This basically represents a maximum likelihood estimate of 10**a for each grid cell. These rates are then smoothed using a Gaussian smoothing operator with a half-width (correlation distance) of 10 km. Hazard is then calculated from summing the hazard from each grid cell over a range of magnitudes (see Frankel, 1995 for details of procedure).

We used different b-values for different regions when calculating the hazard from the smoothed seismicity, since there are significant regional differences in b-value. These b-value zones are shown in Figure 4.

For most areas, we used M3.0 and larger events since 1970 when determining the a-values. The minimum magnitudes, catalog periods, and b-values are listed in Table 1.

For the shallow spatially-smoothed seismicity, we used a maximum magnitude of 7.0 in the hazard calculation. We assumed point sources when estimating the hazard.

4. Spatially-smoothed deep seismicity (d > 20 km)

For earthquakes deeper than 20 km, we also calculated the hazard using the spatially-smoothed historic seismicity. Again, a smoothing distance of 10 km was applied. When calculating ground motions we assumed a depth of 30 km. Regionalized b-values were also used (see Figure 5). We assumed a maximum magnitude of 6.5 for the deeper events. Different attenuation relations were used for the deeper events (see below).

The threshold magnitude, completeness time, and b-value varied between zones. These are listed in Table 1.

5. Northwest area source zone with ramped a-value

The first impression of the seismicity northwest of Hawaii is that it diminishes with distance to the NW from Hawaii. The age of the islands increases and the rate of volcanism and subsidence decreases to the NW, thus a lessening of lithospheric stress is reasonable. We attempted to model the decreasing seismicity with a ramping a-value.

To characterize the seismicity from Hawaii to Oahu, we considered the box shown in Figure 6. The modern (1959-97) catalog from Hawaii to Oahu appears to be complete to about magnitude 4.0 (fig. 7). This frequency-magnitude distribution includes events in the region box in fig 6. Analysis of individual regions shows the completeness is about 4.0 near Oahu, 3.8 near Molokai, and 3.0 near Maui and in the Maui-Hawaii channel. b-values for each sub-region are similar and the regional value 0.8949 was used for the whole region.

The ramping seismicity was measured by counting the number of M 4.0 or larger earthquakes in 30 km bins along the 220 km wide box in fig. 6. We only used earthquakes north of 20 degrees latitude, which excludes most of the Hualalai and offshore earthquakes but leaves enough to demonstrate decay from Kohala and Hawaii. The count includes earthquakes of all depths because events near Maui and to the NW have poorly determined depths. Most depths are probably between 5 and 20 km.

The log of the number of M>=4.0 earthquakes per bin (fig. 8) is crudely fit by a least-squares line. For the 1959-97 catalog, the fit line corresponds to a = -0.968 - 0.00223*D where a is the log of the number of M>=0 earthquakes per square km per year, and D is the distance NW along the box. Earthquake location quality is fairly poor NW of Hawaii because low-gain stations at Barber's Point Oahu and Haleakela Maui were used on only a few of the larger earthquakes. The possible "excess" of M>=4.0 events near Oahu (compared to the adjacent point) may be a result of the earthquake location's failing to iterate away from Oahu as the first arriving station.

The ramping a-value predicts the total number of events in the box of fig. 6. If the a-value is integrated from D=0 out to Kauai, it predicts 46 vs. the observed 48M>=4.0 earthquakes.

The historic (1868-1997) earthquake rate must also be considered. Magnitude 6 and greater earthquakes occurred in 8/1870, 2/19/1871 (M6.8), 5/1877, 9/1881, 1/1885, 1/1938 and 6/1940, but no M>6 events are in the modern 1959-97 catalog. The historic 1868-1997 catalog is plotted with X symbols in fig. 7 normalized to the 1959-97 period of the modern distribution. Unfortunately, the number of historic earthquakes is too small and their location uncertainty too large to fit a ramping a-value distribution. We therefore use the ramping a-value distribution from the 1959-97 catalog adjusted upward by 0.4111 implied by the offset of distributions of fig. 7. This provides the best long-term earthquake rate estimate combined with a spatial occurrence reduced to a simple 1-dimensional fitted line. The resulting a-value is:

a = -0.557 -0.00223*D

where 10**a is the number of M>=0 earthquakes of all depths per square km per year, and D is the distance NW along the box of fig. 6.

The source zone used for the hazard calculation extended further to the west than that shown in Figure 6. It’s western boundary is just to the west of Niihau. On the hazard maps the northern and southern boundaries of this zone are clearly visible as areas of dense contours. The choice of the location of the north and south boundaries was somewhat arbitrary. We did not include earthquake sources more than 110 km from the island chain because they are far and the hazard they cause on land is small. In the final maps we may want to only show values closer to the islands. The maximum magnitude used for this zone was 7.0.

We particularly welcome comments about this source zone, including the seismicity rate determination.

Attenuation Relations

Events from M5.0 to 7.0. For PGA we used a combination of four attenuation relations: Boore et al. (1997), Sadigh et al. (1997), Campbell (1997), and Munson and Thurber (1997), each weighted equally. Munson and Thurber (1997) was the only relation that used Hawaii earthquakes in their empirical regression. For 0.2 sec spectral acceleartion (SA), we used Boore et al. (1997), Sadigh et al. (1997) and Munson and Thurber (1997), multiplied by 2.5 to convert PGA to 0.2 sec SA. Each was weighted equally. For 1.0 sec SA, we used Boore et al. (1997) and Sadigh et al. (1997). Thrust faulting was assumed for the relations which vary with fault type. We found very little difference in PGA hazard maps made with using the Boore et al., Sadigh et al., Campbell, and Munson and Thurber relations individually, for this magnitude range.

Events from M6.5 to M8.2 in the SFL, KAO, HLE, KON, and HLE zones. For PGA and 0.2 sec SA, we used Sadigh et al. (1997) and Munson and Thurber (1997), equally weighted. For 1.0 sec SA, we used only Sadigh et al. (1997). We decided not to use Boore et al. (1997) for this magnitude range for these zones, since it does not have the proper distance dependence past about 100 km. Since these zones have very high seismicity rates, they produce significant hazard even for sites greater than 100 km distance. Thus, applying the Boore et al relation would produce erroneously high ground motions at distances hundreds of kilometers from the main island.

Following Klein (1997), we modified the magnitude dependence of Munson and Thurber (1997) for magnitudes above 7.0, since the coefficient determined from their study is inconsistent with the magnitude dependence from other studies which used earthquake data above M7.0. From M7.0-7.7, we used a magnitude coefficient of 0.216. Above M7.7, we assumed no magnitude dependence.

For the deep events, we used attenuation relations by Youngs et al. (1997), which were derived from regressions of observations of intermediate-depth earthquakes in subduction zones. These attenuation relations have a term dependent on source depth (in addition to the measure of hypocentral distance). This is the only modern attenuation relation for rock sites that we are aware of for deeper earthquakes.

Table 1: Minimum magnitudes, b-values, and earliest date used to calculate a-values for Spatially-Smoothed Seismicity

Zone	Magmin	b-value	Date
Shallow zones			
hs1	4.1	1.21	1970
hs2	3.0	0.97	1970
hs3	3.0	1.23	1970
hs4	3.0	0.81	1970

hs5	3.0	1.13	1970
hs6	3.0	1.23	1970
hs7	3.0	1.36	1970
hs8	3.0	0.84	1959
Deep zones			
hd1	3.0	0.90	1970
hd2	3.6	2.03	1959
hd3	3.3	0.93	1959
hd4	4.2	1.71	1959
hd5	3.0	1.07	1970
hd6	3.0	0.91	1959

Figure Captions

1. Chart showing general methodology for producing Hawaii seismic hazard maps.

2. Area source zones used in this study for the flanks of active volcanos on the main island.

3. Area source zones for the Kilauea caldera and rift zones.

4. Zones used to characterize the b-values of shallow earthquakes. Spatially-smoothed seismicity was used to estimate hazard for these areas.

5. Zones used to characterize the b-values of deeper earthquakes (d > 20 km). Spatially smoothed seismicity was used to estimate hazard for these areas.

6. Map of the 1959-97 earthquakes located by the HVO network to determine the ramping a-value for the island chain. Earthquakes inside the box were counted into 30 km bins as a function of the distance D along the box.

7. Modern and historical FM distribution of earthquakes in the box of fig. B1. The ramping decrease of the a-value with distance D along the box was adjusted upward because of the higher rate of historical 1868-97 seismicity.

8. Numbers of 1959-97 M>=4.0 earthquakes counted into 30 km bins along the island chain from Kohala to Oahu. A least-square line fit to the points yields a ramping a-value which reduces the scattered seismicity along the chain to a smoothly declining hazard to the NW.

Appendix

Background Description

The seismic hazard in Hawaii is high, especially on the south side of Hawaii Island where the largest earthquakes have occurred (M7.0 and M7.9 in 1868, M7.2 in 1975) and where earthquake rates are high. Since 1868, approximately 29 M 6 or greater earthquakes have occurred on the big island and seven M 6 or larger events NW of Hawaii from the Maui area to Molokai. Many of the magnitudes and locations of these M6 earthquakes were derived by Wyss and Koyanagi (1992) from isoseismal maps. Their map of maximum intensities (up to XII in 1868) demonstrates the high potential hazard on the south side of the island.

The largest earthquakes occur under the mobile flanks of the active volcanoes Kilauea, Mauna Loa and Hualalai. The volcanoes grow by intrusions in the rift zones and caldera complex, and lava flows from caldera and rifts. The mobile flank adjacent to an active rift zone responds by storing this compressive stress and releasing it in seaward slip on its basal decollement plane near the buried seafloor surface. Under the south side of Hawaii, the surface is about 9 km deep at the coastline and dips about 4 degrees to the north. The seaward, unbuttressed flanks are seismically the most active and have demonstrated the largest earthquakes. Ultimately, seaward flanks can break away in a catastrophic event and produce the observed submarine landslides and debris flows. Landward flanks are much less active. In addition to the active flanks, the entire island chain produces earthquakes by flexure of the lithosphere and volcanic pile under the volcanic load. As the volcanic activity of a volcano lessens and the age increases of islands to the NW, seismicity decreases.

The first quantitative hazard map, with probabilistic peak accelerations (10% exceedance in 50 years) in excess of 1.0g, was published by Klein (1994) for the south side of Hawaii island. The present effort extensively updates this earlier report by using improved catalogs, better probability calculations, extending the map to the entire state, and using a regionalized approach with different treatments appropriate for each source area and magnitude range.

We assume the earthquakes are Poissonian and that the hazard is constant in time. Because flank earthquakes are driven by volcanic activity on adjacent rift zones through the mechanism of stress stored in the flank, this constancy assumption is not always true. Klein (1996) noted linkages between large Mauna Loa eruptions and large flank earthquakes, and that the lower Mauna Loa eruptive activity since 1951 may mean a temporarily lower hazard from Mauna Loa flank earthquakes. For each zone, we choose the earthquake catalog ending in 1997 that is the most complete in the largest earthquakes to best represent the hazard for the next decades. We consider both the longer historic catalog which may be complete to M5.9 since 1868 and the recent network catalog which may be complete to M2.7 since 1959. In areas such as the Hilea zone where activity before 1920 was higher than at present, the longer catalog includes hazard from large earthquakes but is diluted by the long 130 year length of the catalog.

The modeling of seismic sources is summarized in below:

1. FLANK ZONES CAPABLE OF RUPTURING IN LARGE ZONE-FILLING EARTHQUAKES
    a) 5.0<M<6.5 Point sources uniform in each zone.
    b) 6.5<M<7.0 Discrete sources in each zone. (ie. 1975, 1983)
    c) 7.0<M<8.2 Kaoiki, Hilea & south flank together (ie. 1868 M7.9)
    d) 6.5<M<7.5 Kona (ie. 1951 M6.9)

2. OTHER AREAS OF HAWAII ISLAND 5.0<M<7.0
    a) 0 < depth < 20, Kilauea caldera and rift zones,
    uniform seismicity, little hazard contribution.
    b) 0 < depth < 20, Smoothed seismicity with gridded a-values.
    c) 20 < depth < 70, Smoothed seismicity with gridded a-values.

3. ISLANDS NW OF HAWAII MODELED WITH SMOOTHLY DECREASING A-VALUE

DIVISION OF HAWAII INTO SOURCE AREAS

Figure A1 shows the Hawaiian source areas. The boundaries of the three Kilauea volcanic areas (fig. A1a) enclose the caldera and rifts with most earthquakes directly related to magma movement. The three active flank zones of fig. A1b were drawn to enclose seismic zones defined by the catalog of 1970-97 earthquakes. The SFL and KAO zones were also drawn to approximate the rupture (aftershock) zones of the 1975 and 1983 earthquakes. The two other flank zones (Kona and Hualalai, fig. A1c) were also drawn both to enclose contemporary seismic zones and approximate the rupture zones of the 1950 and 1929 earthquakes proposed by Wyss and Koyanagi (1992b). These zones are the west and unbuttressed flanks of the active Mauna Loa and Hualalai volcanoes.

The remaining source areas (figs. A1c and A1e) were chosen either to enclose concentrated areas of seismicity (ie. Loihi submarine volcano and the offshore Hualalai area), or areas of similar earthquake activity and seismic network coverage. The spatially-smoothed seismicity was used to calculate the hazard in these areas. The b-value was determined separately for each area.

EARTHQUAKE CATALOGS

The primary catalog used here was gathered by the Hawaii Volcano Observatory from a network of stations near Kilauea initially recorded on smoked paper drums in the late 1950's but recently with digital recording of an island-wide network in the 1980s and 90s. The 10/59-6/97 catalog was recently reprocessed with the Hypoinverse location program after cleaning up poor locations and assigning preferred magnitudes of different types to all possible events. The 59-97 catalog is complete to magnitude 2.7 for the onshore areas of Hawaii island. Hypocenter determination and completeness are poor NW of Hawaii although low gain stations on Maui and Oahu were often used with large events. The 59-97 catalog appears to be complete to M3.0 in the Maui area and M3.9 in the Molokai-Oahu area.

Most larger events have local Wood-Anderson magnitudes, or in some cases teleseismic surface wave magnitudes. No instrumental moment magnitudes are available, but the best available magnitudes are self consistently used for both rate determination and ground motion estimation. These catalog magnitudes were used by Munson and Thurber (1997) in their determination of a PGA attenuation relation.

The historical (pre 1959) earthquake catalog consists of two primary sources. Wyss and Koyanagi (1992a) compiled both epicenters and magnitudes (where possible) of 1868-1989 M>~6 earthquakes from intensity maps using calibration events and radii of isoseismals to estimate magnitudes. A few additional events in the Oahu-Maui area are drawn from Cox (198?). Additional events are being compiled by Tom Wright and Fred Klein from text entries in the Lyman diary, the Early Serial Publications and the Volcano Letter of HVO, and bulletins of the Honolulu station HON. Magnitudes are assigned to these historic events from amplitudes read from microfilms of the Milne (1904-1921) and Milne-Shaw (1921-1963) station in Honolulu, and from size classes assigned by HVO from readings on the Bosh-Omori instrument at HVO. Where no other magnitude information is available, magnitudes are assigned from maximum intensities using a relation determined from Hawaii earthquakes.

The catalog completeness magnitude for 1868-1903 is about 5.9 for most of the state. The 1904-31 part of the catalog is under development but this hazard study uses the larger events complete to M 5.2 near Hawaii island. The 1932-59 catalog is complete to M 4.5. This historic catalog is only used in areas where the earthquake rate was significantly higher than in the modern 1959-97 catalog, or where the rate of M>5 earthquakes needs a longer catalog for its determination. Because the location of most historic events is poorly known, their epicenters are never used directly. Earthquakes are assigned to a source zone (with reasonable confidence) and used only for tabulation in the frequency-magnitude distributions.

Aftershocks were removed from the catalog by a modified version of Reasenberg's (1985) declustering algorithm. Parameters were chosen so the algorithm removed aftershocks without removing unrelated earthquakes in different tectonic areas. The algorithm was modified to preserve the mainshock as it occurred without moving it to the centroid of the cluster and without assigning it the magnitude summed from the moments of all events in the cluster. The algorithm removed 9 years of aftershocks (and possible background events) of the M7.2 1975 Kalapana earthquake, and 8 months of aftershocks of the M6.6 1983 and M6.1 1989 events. Aftershocks of the M7.9 1868 earthquake were removed by hand because the algorithm was not suited for an incomplete catalog of poorly located historic events. The 1929 Hualalai sequence was complex with aspects of a swarm of similar magnitude but poorly located events before the M6.5 10/5/29 mainshock and its aftershocks. All aftershocks and half of the M 5 events from the swarm were removed from the catalog by hand. It should be noted that the present hazard calculation does not include the effects of several years of heightened activity following these large earthquakes.

Declustering was not done on Kilauea's volcanic areas or on the Loihi zone. When confronted with an earthquake swarm of many events of similar magnitude, Reasenberg's algorithm would break it into one or more clusters and either replace the swarm with its largest event (and thus underestimate the hazard) or with an unrealistically large event equal to the total moment of the swarm (and thus overestimate the hazard). Because there were many swarms during the decades of the catalog, the time independence of seismicity is violated by the bunching together of earthquakes into swarms but not by the occurrence of many swarms throughout the catalog.

DETERMINATION OF a AND b VALUES

Frequency-magnitude distributions plotted for each source zone of fig. A1 yield completeness magnitudes and a- and b-values. Fits to the distributions are done by picking a minimum magnitude and using the maximum likelihood method of Aki (1965) to determine a and b. Least-square fitting is used in some cases with just a few large earthquakes where maximum likelihood does not yield a good visual fit to the distribution. The a-values from the distributions are only used in the flank and volcanic zones where the a-value is assumed to be uniform.

An example of the distribution for a volcanic zone is that of Kilauea Caldera in fig. A2. b-values are high, the rate of larger earthquakes is low, and earthquakes larger than 5 or 5.5 have not been recorded. Distributions for earthquakes close to the magmatic system often curve and fall off steeply near a maximum magnitude around 4.0.

An important feature of the distributions in the flank zones is a break in slope between linear parts of the distribution near magnitude 5. Fig. A3 shows the bi-linear distribution for the combined three south island flank zones for 1959-97. Only the least-square line for higher magnitudes is used in the hazard calculation which is based on M>5.0 earthquakes. The historic distribution (X symbols) agrees with the modern distribution but is not as well determined. It seems unlikely that the slope break results from a change in magnitude type with increasing magnitude because the saturation of local magnitudes is near M~6 and because the teleseismic, isoseismal area (historic catalog), and local magnitudes generally agree where they overlap.

An interpretation of this change in slope of the distribution is that earthquakes are becoming "characteristic" in the sense that the source size is spanning the width of the flank zone above M5, ultimately filling the entire zone with a characteristic earthquake. Large, characteristic earthquakes falling above the line extrapolated from smaller magnitudes have been noted in other areas (eg. Schwartz and Coppersmith, 1984; Papadopulos et al, 1993). Another way to view the two slopes of the distribution is that the low magnitude part with b near 1.0 is produced by earthquakes of fractal dimension 2 and occur distributed throughout a plane. Events in the higher magnitude range with b near 0.5 are produced by earthquakes of fractal dimension 1 and occur distributed along a line of sources which feel the edge of the fault zone.

The break in slope is also visible for each zone individually (figs. A4-7). Unfortunately the break in slope of the distribution near M5 means the fit line for high magnitudes is difficult to determine because there are fewer earthquakes. For the three south island zones, we therefore assumed the b-value fit from the combined zones and determined the a-value from the number of M5 and larger earthquakes in each zone. For the south flank (fig. A4), this fit line gives a reasonable approximation to both the recent (1959-97) and historic (1904-97) distributions. The fit (with the assumed b-value) from the historic Kaoiki catalog (fig. A5) is good. The modern distributions for both the south flank and Kaoiki are a bit higher than the historic rates, probably because of the higher volcanic activity of Kilauea since the early 1950's. The high rates for the south flank are mostly from the recent 1970-97 period (even with Kalapana aftershock removal) because there were no magnitude 5 or larger south flank earthquakes between 1954 and 1972.

The rates of M>5 earthquakes in the other three flank zones are also not well determined. The historic distribution extends the modern distribution in Hilea (fig. A6). The fit line with the assumed b-value which is tied to the number of M>=5.5 events predicts the historic rate of M5's but does not fit the distribution of 6's or the 1868 M7.0 and M7.9 assigned to this zone. Magnitude 7's are better fit by the distribution for the entire south island. The lines fit to the Kona (fig. A7) and Hualalai (fig. A8) historic distributions are determined by a small number of earthquakes, but this is the best representation of the hazard that we have. The modern (1959-97) distributions do not include the historic M6 earthquakes and underestimate the hazard.

Two of the deep seismic zones exhibit distributions with a "knee" with a lower and larger magnitude branch (fig. A9). These upper-mantle earthquakes are not well understood except that they are driven by a combination of lithospheric flexure, near-vertical magma conduits and tractive stresses applied from the overlying volcanic pile (Klein et al. 1987; Klein 1987; Okubo). One explanation of the deficiency of large magnitude events in the DEP zone surrounding Kilauea's vertical magma conduit may be the difficulty of generating large rupture areas near this zone of large effective stresses. Three large deep earthquakes of magnitudes 6.0, 6.2 and 6.3 have occurred since 1950 and so we feel that extrapolating the upper branch of distributions like fig. 9 to the range of M6's is realistic. All a- and b-values used in the hazard calculations are summarized in table 2.

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FIGURE CAPTIONS

A1. Maps of catalog seismicity and individual source areas. The zones outlined in heavy lines are modeled as flank zones capable of large earthquakes. Region code names correspond to the data of table 2.

(a) Shallow Z<5 earthquakes and the three volcanic source areas of Kilauea Caldera (CAL), East Rift Zone (ERZ) and Kilauea Rift Zones (KRZ). Even though seismicity is assumed uniform within each zone, the zones are small and do not contribute much hazard because the maximum assumed magnitude is only 5.5.

(b) Intermediate depth seismicity 5<Z<20 and the three source zones on the south flanks of Kilauea and Mauna Loa. All earthquakes of depths 0<Z<20 were counted in the frequency-magnitude distributions for each zone, even though separate maps of both shallow and intermediate depth ranges are shown for clarity.

(c) Earthquakes of Z<20 for Hawaii island source zones. The Kona and Hualalai zones are modeled with uniform sources and are capable of producing large zone filling earthquakes.

(d and e) Deep Z>20 earthquakes and deep seismic areas. All deep seismicity is modeled with smoothed M>3 seismicity, but the areas are useful for defining regions of constant b-value and for catalog completeness determination. Earthquakes in the three areas to the north (Mauna Kea & Kohala), west (Kona) and south (Loihi) were found to be most complete for 1970-97 (fig. 1d), but all other areas are usefully complete for 1959-97 (figs. 1d & 1e).

(f) Earthquakes of all depths for the island chain 1959-97. The Alenuihaha Channel zone uses gridded a-values from smoothed seismicity and the island chain zone uses ramped a-values.

A2. Frequency magnitude (FM) distribution for Kilauea Caldera earthquakes 1970-97. Solid symbols are the cumulative distribution and open symbols are the counts of earthquakes in 0.1 magnitude units during the 27.5 years covered by the figure. The fit parameters are also given above the figure. See additional parameters in table 2.

A3. FM distribution of earthquakes for the 3 flank zones in south Hawaii taken together from 1959-97. Note the prominent high magnitude branch of earthquakes with a lower b-value and occurrence above the level extrapolated from lower magnitudes. x symbols are the historic (1868-97) catalog normalized to the 37.75 years covered by the modern distribution. Lines are the maximum likelihood fit to the 1959-97 M>=2.2 distribution, and the least-square fit to the 1868-97 5.1<M<7.9 distribution.

A4. Modern and historical FM distributions of earthquakes on Kilauea's south flank. The b-value for the high magnitude branch was assumed to be that of the joint south island zone, and the a-value determined by tying the line to the number of M>=5.2 1959-97 earthquakes.

A5. Modern and historical FM distributions of earthquakes in the Kaoiki seismic zone. See also captions for figs. A2-4.

A6. Modern and historical FM distributions of earthquakes in the Hilea seismic zone. See also captions for figs. A2-4.

A7. Historical FM distribution of earthquakes in the Kona zone on Mauna Loa's west flank. See also captions for figs. A2-4.

A8. Historical FM distribution of earthquakes in the Hualalai zone on Hualalai's SW flank. See also captions for figs. A2-4.

A9. Modern FM distribution of earthquakes in the deep (20<Z<70) seismic zone under Kilauea Caldera. Note the "knee" in the distribution. See also captions for figs. A2-4.