University of Nevada

Reno

Seismic Hazard within the Greater San Francisco Bay Region: A Reevaluation after the Loma Prieta Earthquake

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by

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Abstract

Prior to the 1989 Loma Prieta earthquake, seismic hazard maps were constructed for California (Wesnousky, 1986). I reconstructed the hazard maps of Wesnousky (1986) for the San Francisco Bay region to examine the effects of 1) the crustal stress release associated with the Loma Prieta earthquake and 2) new evidence of slip rates and paleoearthquake histories for Bay area faults. The new maps indicate a high probability that heavily populated areas in the San Francisco Bay region will experience strong ground motions of ≥ 0.1g on hard rock sites during the next 50 years. The reconstructed maps are of limited utility because they consider only relatively low levels of ground motion on hard rock sites. Therefore, I constructed another set of maps that show higher levels of strong ground motion (≥ 0.4 cm/sec and ≥ 0.5g) and combine the relationships of strong ground motion for hard rock sites with amplifications due to local site geology (Borcherdt et al., 1991). A consequence is that the largest predicted levels of ground motion commonly do not lie directly adjacent to mapped fault zones but rather in regions of weakly consolidated Quaternary alluvium along the margins of the San Francisco Bay.

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Introduction

Prior to the Loma Prieta earthquake, the probability of strong ground motions due to earthquakes in the southern San Francisco Bay region was considered to be high, in apparent accord with the occurrence of the Loma Prieta earthquake (Wesnousky, 1986; Figure 1). The high probability was in part due to then current geologic and geodetic estimates that the average accumulation of slip along the San Andreas was 12 mm/yr (Wesnousky, 1986) and last ruptured in 1906, producing coseismic surface offsets ranging from 0.5 to 1.5 m along the Loma Prieta section of the fault (Lindh, 1983; Sykes and Nishenko, 1984; Scholz, 1985). In that regard, at the time figure 1 was constructed, the amount of slip accumulated along the Loma Prieta section of the San Andreas was estimated to equal about 1 meter ([1986 - 1906] x 12 mm/yr), comparable to the fault slip that occurred in 1906. Hence, that section of the fault was viewed to be in the later stages of the strain accumulation cycle and, in turn, the seismic hazard within the vicinity was considered to be high (Wesnousky, 1986).

In accord with the concept of elastic rebound, the seismic hazard, or probability of strong ground shaking due to an earthquake on a specific fault, excluding probable aftershocks, is generally considered lowest during the period immediately following a major earthquake - the time when accumulated strain is minimal. The Loma Prieta earthquake represents such a major earthquake. As a result, to first order, we might expect the regional seismic hazard within the San Francisco Bay area to be significantly altered in comparison to the years immediately prior to the

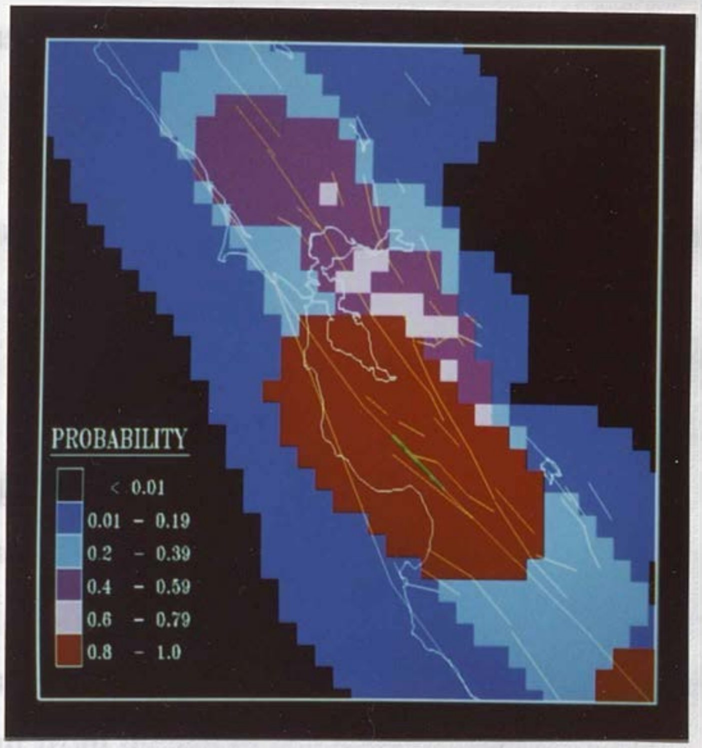


Figure 1. Contour map constructed prior to the Loma Prieta event (Figure 3b in Wesnousky (1986)) that shows the estimated probability for the 50 years subsequent to 1986 that Quaternary faults mapped in the San Francisco Bay region would produce peak horizontal ground accelerations $\geq 0.1g$.

October 17 event. Similarly, a number of seismological, geological, and geodetic studies of the San Andreas and other Bay Area faults have brought new data to bear on the slip rates and paleoearthquake histories of faults within the San Francisco Bay region. In this paper, I reconstruct the hazard maps of Wesnousky (1986) to examine the effects of 1) the crustal stress release associated with the Loma Prieta earthquake and 2) new evidence of slip rates and paleoearthquake histories for Bay Area faults.

The map of Wesnousky (1986) (Figure 1) was calculated for estimates of strong ground motion at hard rock sites. That strong ground motions can be modified by local site conditions is well known (Lawson, 1908; Gilbert, 1909; Borcherdt, 1975; Su, 1992). Most recently, Borcherdt and others (1991) have reported an empirical correlation between strong ground motion and specific geologic units in the Bay Area (Table 1). I incorporate these empirical relationships with an existing geologic map (Borcherdt, 1975) for a part of the San Francisco Bay Region to illustrate the increased resolution and, hence, utility of hazard maps which result from including site amplification effects.

Construction of the Hazard Maps

Knowledge regarding the slip rates and the past history of earthquakes along each fault in the Bay Area formed the foundation for construction of hazard maps in Wesnousky (1986). The exact methodology has been detailed in Wesnousky (1983) and Wesnousky (1986) and is briefly reviewed in Appendix A. As well, the slip rates and earthquake histories of each fault were outlined in Wesnousky (1986). Therefore, I limit my review of data to those fault zones where paleoseismic studies have been made or earthquakes have occurred since 1986. I also note that Holocene observations are more likely reflective of the current long-term activity than are estimates made from offsets of older rocks and therefore, my discussion is limited to studies of Holocene rocks. The San Andreas, Hayward, and Calaveras fault systems which are the major fault systems of the region will be the focus of discussion. Figure 2 shows the faults considered in this study. Data and references bearing on the slip rates of all faults used in the calculations are summarized in Appendix B.

Fault Slip Rates

Geological estimates of the San Andreas fault slip rate to the north of San Juan Bautista range from about ≥ 7.5 to 28 mm/yr. Hall (1984) interpreted a displaced channel on the San Francisco Peninsula at the north end of Crystal Springs Reservoir to suggest a minimum late Holocene fault slip rate of ≥12 mm/yr. However, in a recent reexamination of that site, additional radiocarbon dates on multiple new samples showed that the original 1130 ± 160 yrs B. P. radiocarbon age on which the 12 mm/yr slip rate was based is incorrect (Tim Hall, personal communication). The new data suggest a minimum slip rate of ≥ 7.5 mm/yr. Farther north, near Olema, Niemi and Hall (1992) determined a minimum slip rate of 24 ± 3 mm/yr for the San Andreas north of the junction with the San Gregorio fault from an offset buried channel dated at 1800 ± 78 yrs B. P. The channel date is the weighted average of six tree-ring-calibrated radiocarbon dates with a 2-sigma range. Near Point Arena, Prentice (1989) interpreted

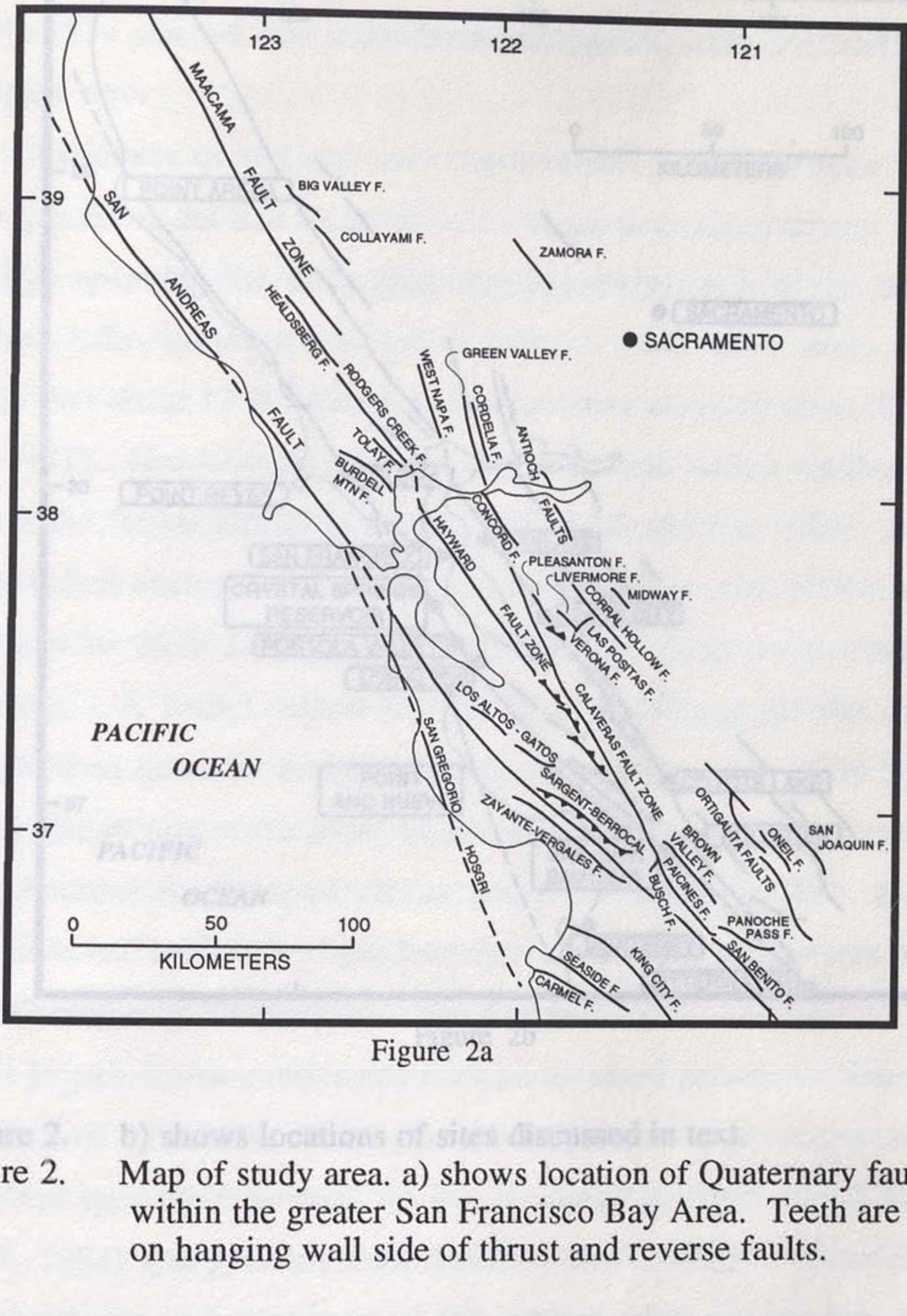


Figure 2a

Figure 2. Map of study area. a) shows location of Quaternary faults within the greater San Francisco Bay Area. Teeth are placed on hanging wall side of thrust and reverse faults.

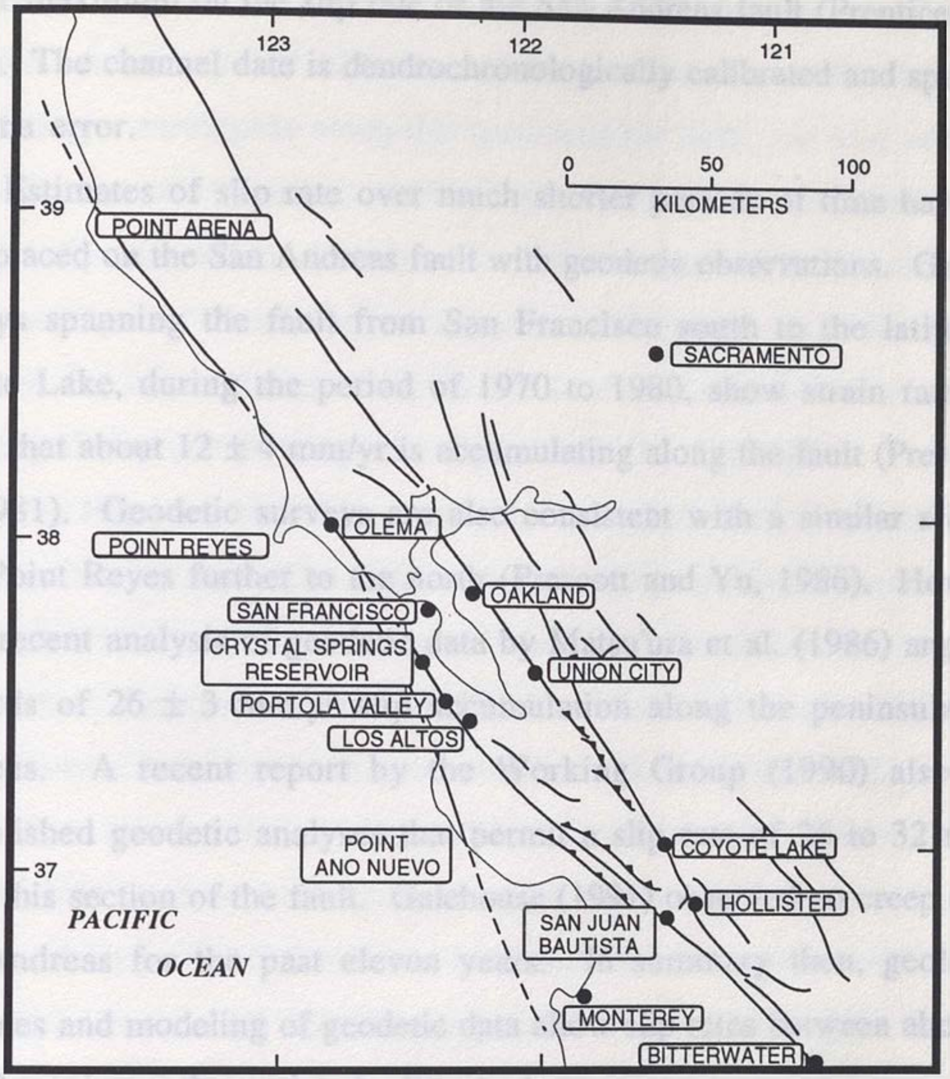


Figure 2b

Figure 2. b) shows locations of sites discussed in text.

a buried Holocene offset channel (2356 - 2709 yrs B. P.) to place a 25 ± 3 mm/yr maximum on the slip rate of the San Andreas fault (Prentice et al., 1991). The channel date is dendrochronologically calibrated and spans the 2-sigma error.

Estimates of slip rate over much shorter periods of time have also been placed on the San Andreas fault with geodetic observations. Geodetic surveys spanning the fault from San Francisco south to the latitude of Coyote Lake, during the period of 1970 to 1980, show strain rates that imply that about 12 ± 4 mm/yr is accumulating along the fault (Prescott et al., 1981). Geodetic surveys are also consistent with a similar slip rate near Point Reyes further to the north (Prescott and Yu, 1986). However, more recent analysis of geodetic data by Matsu'ura et al. (1986) argue for upwards of 26 ± 3 mm/yr slip accumulation along the peninsular San Andreas. A recent report by the Working Group (1990) also cites unpublished geodetic analyses that permit a slip rate of 26 to 32 mm/yr along this section of the fault. Galehouse (1991) observed no creep on the San Andreas for the past eleven years. In summary then, geological estimates and modeling of geodetic data allow slip rates between about 7.5 and 32 mm/yr on the peninsular San Andreas.

Figure 1 was constructed with an assumed peninsular San Andreas slip rate of 12 mm/yr. The assumption appeared to be supported by the apparent agreement between the late Holocene geologic rate of 12 mm/yr (Hall, 1984) and geodetic data (Prescott et al., 1981). Although recent developments and reanalysis of the geologic data do not rule out a 12 mm/yr rate, there now exists no firm basis for using 12 mm/yr as a preferred slip rate. I note here that (1) the Loma Prieta earthquake produced 1.6 m of lateral coseismic slip (Lisowski, 1990) and (2) it had been 83 years since the 1906 earthquake ruptured this segment of the San Andreas. Assuming that all the lateral slip accrued since 1906, the time of the last major earthquake along this section of the fault, one may estimate a strike-slip rate of 19 mm/yr. A 19 mm/yr slip rate is also the median value for the slip rate values I reviewed. I thus assume the peninsular San Andreas slips at 19 mm/yr, an increase of 7 mm/yr over the slip rate assumed for construction of figure 1. It should also be noted that the Working Group (1990) adopted a slip rate of 19 ± 3 mm/yr.

The Hayward and Calaveras faults are subparallel to and lie east of the San Andreas fault. The Calaveras fault splays northeastward from the San Andreas fault 30 km southeast of Hollister. Ten kilometers southwest of Hollister, Perkins and Sims (1988) determined a 9 mm/yr slip rate on the Calaveras fault from radio-carbon dates (14,425 ± 215 CAL yrs B. P.) of an offset alluvial terrace riser. They interpret this as a minimum value because it is south of the latitude at which slip is transferred from the San Andreas fault to the Calaveras system and further suggest the Calaveras fault slips between 15 and 20 mm/yr northwest of Hollister. Geodolite measurements of Savage et al. (1979) are consistent with 17 ± 2 mm/yr of right-lateral slip across the section of the Calaveras fault located south of the Hayward fault. Prescott et al. (1981) further interpreted that the 17 ± 2 mm/yr is divided between the Hayward and Calaveras faults to the north.

Recent trenching studies along the Hayward fault near Union City by Lienkaemper and Borchardt (1991) have yielded an estimate of the minimum geologic slip rate of 8 ± 0.6 mm/yr for the past 8,260 ± 90 years. This age is calibrated and has a one sigma range. They also note that the average historic creep has been approximately 5 mm/yr. Measurements by Galehouse (1991) confirm a creep rate between 4 and 5 mm/yr on the Hayward fault for the past eleven years. Based on synthesis of historic creep rates, geodetic data, historical seismicity, and long term geologic slip rates, Lienkaemper and others (1991) have proposed a deep slip rate of 9 mm/yr for the Hayward fault with a locked zone between 3 and 10 km. Prescott and Lisowski (1982) determined strain rates from both small (1-2) and large (10-30 km) aperture geodetic networks that straddle the Hayward fault. They concluded that no more than 4 mm/yr of slip is presently accumulating as elastic strain in rocks adjacent to the fault, whereas the total rate of displacement measured geodetically is about 8 mm/yr (Prescott et al., 1981). However, since that time, the strength of that conclusion has been questioned by the author (Prescott, pers. comm.). Hence, the relation between surface creep and crustal stress accumulation is not well understood for the Hayward fault. Wesnousky (1986) assumed that a 4 mm/yr slip rate is characteristic of the strain accumulation rate on the Hayward fault based on the analysis of Prescott and Lisowski (1982). Because it is not clear whether or not significant crustal strain is being released by aseismic creep, I follow Lienkaemper et al. (1991) and assume the slip is 9 mm/yr.

The Rodgers Creek-Healdsberg and Maacama fault zones are right-step northward extensions of the Hayward fault zone. Budding and others (1990) interpreted offset buried channel deposits along the Rodgers Creek fault to indicate a minimum slip rate equal to 2.1 to 5.8 mm/yr for the past 1,200 years. More recently, new radiocarbon dates (dendrochronologically calibrated one-sigma range) from the same site, suggest slip rates are higher; between 6.4 and 10.4 mm/yr for the past 750 years (Schwartz et al., 1992). Galehouse (1991) found no evidence of creep on the Rodgers Creek and West Napa faults until late in 1990 when both began showing some evidence of movement. For construction of the Hazard map, each is assumed to slip at the same rate as the Hayward fault (9 mm/yr).

The Calaveras Fault also appears to have a complex relationship between surface creep and strain accumulation. Although it is generally assumed the Calaveras is creeping, there have been four and possibly five moderate earthquakes historically (Wesnousky, 1986). Galehouse (1991) observed a creep rate of 10 mm/yr in the Hollister area but found no creep at the northwest end of the fault. I follow Wesnousky (1986) and assign a slip rate of 7 mm/yr. The Concord and Green Valley faults are the right-step continuation of the Calaveras fault (Page, 1982), and each is assumed to slip at the same rate as the Calaveras fault. There are no geologic slip rates for these two faults but Galehouse (1991) found creep rates of 3-4 mm/yr on the Concord fault and 5-7 mm/yr on the Green Valley fault.

Wesnousky (1986) reviewed the meager data on the San Gregorio-Hosgri fault. I use the same interpretation here because no new data are available. Finally, it should be noted that the sum of slip rates across the major faults in the study area is consistent with 38 ± 3 mm/yr measured geodetically across the San Andreas-Calaveras fault system in the Hollister area (Matsu'ura and others, 1986).

Fault Behavior and Recurrence Intervals

Information regarding fault slip rate provides a measure of the strain accumulation rate along a fault. It is the paleoseismological and historical record of earthquakes and the distribution of coseismic slip observed in those earthquakes that provide some basis for hypotheses regarding the future behavior of faults. I follow Wesnousky (1986) and estimate the size of future events from fault length and repeat times of ruptures.

The San Andreas fault in Figure 3a is divided into 4 segments which are labeled A, B, C, and D. The basis of the divisions is the historical record of earthquakes and the distribution of slip that occurred during the largest of those earthquakes. More specifically, the San Francisco 1906 earthquake produced surface ruptures along a 420-km-long section of the San Andreas that strikes northward from San Juan Bautista (Lawson, 1908; Thatcher, 1975; Prentice and Schwartz, 1991). Lawson (1908) reported coseismic surface offsets averaged 2.5-5.0 m between Los Altos and Point Arena in 1906, but measurements south of Los Altos were significantly less; between 0.5 and 1.5 meters. Reexamination of geodetic data bracketing the 1906 earthquake confirm a decrease in the 1906 slip function to the south of Crystal Springs Reservoir, but do not reflect the factor of two difference indicated by surface offsets (Thatcher and Lisowski, 1987). A new study of the surface expression of the San Andreas fault in the southern Santa Cruz mountains (Prentice and Schwartz, 1991) suggests that the surface displacements reported by Lawson (Lawson, 1908) in this area were not coseismic surface faulting of the San Andreas, but were shaking induced slope failures and fractures. Therefore, none of the reported measurements of surface offset are

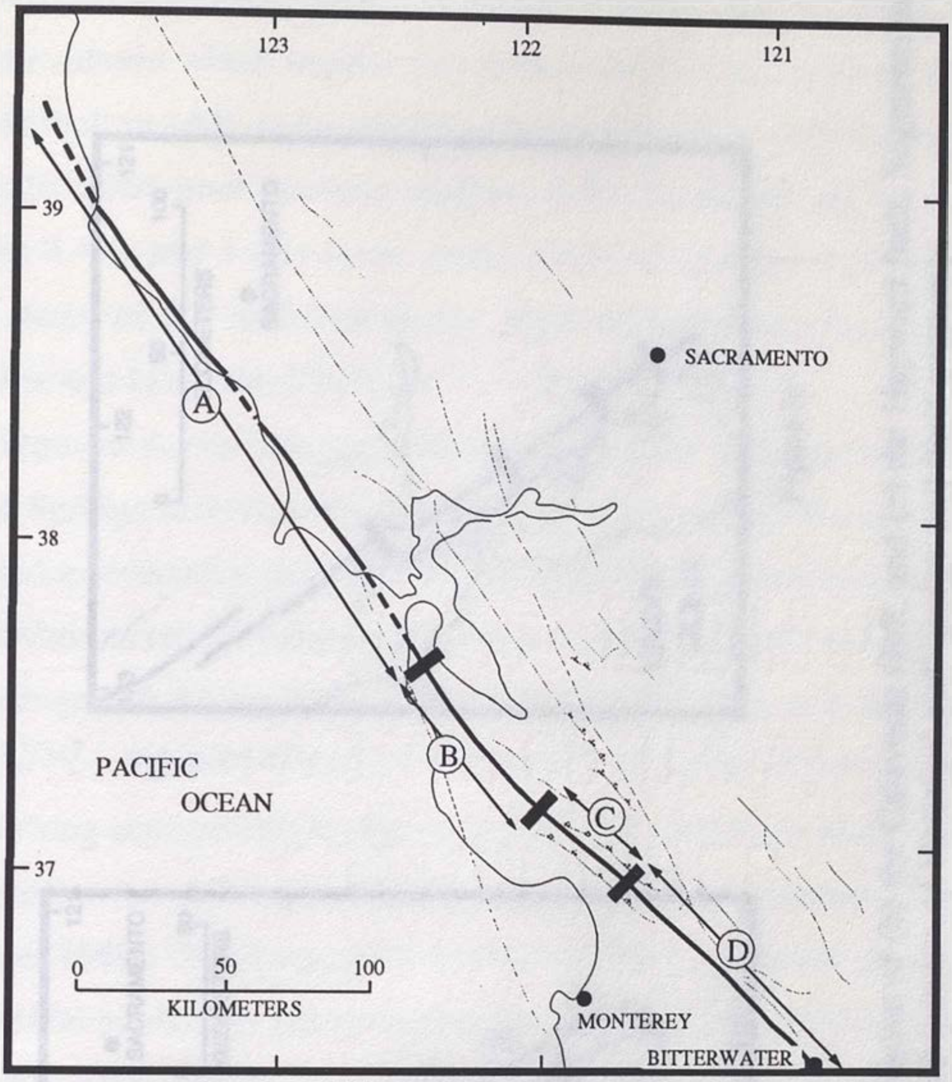


Figure 3a

Figure 3. Map showing segmentation of (a) the San Andreas fault.

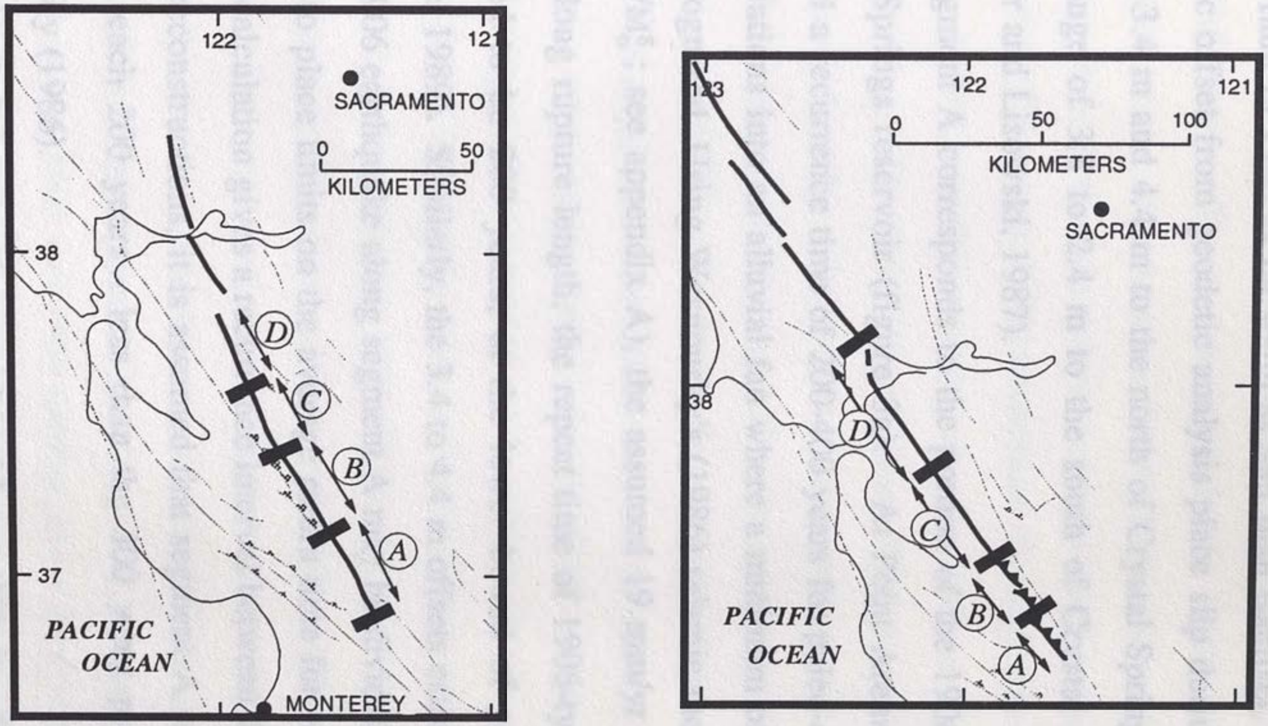


Figure 3b

Figure 3c

Figure 3. Map showing segmentation of (b) the Calaveras fault, and (c) the Hayward fault. Segments are based on the extent and location of historical earthquakes and fault geometry.

reliable as indicators of the fault offset in the Santa Cruz mountains in 1906 (Prentice and Schwartz, 1991). However, Prentice and Schwartz (1991) present evidence which implies that surface rupture did occur on the San Andreas fault in 1906 as far south as San Juan Bautista. Best estimates of coseismic offset from geodetic analysis place slip during the 1906 event between 3.4 m and 4.4 m to the north of Crystal Springs reservoir and a lesser range of 3.8 to 2.4 m to the south of Crystal Springs reservoir (Thatcher and Lisowski, 1987).

Segment A corresponds to the portion of the 1906 rupture north of Crystal Springs reservoir (figure 3a). At Point Arena, Prentice (1989) estimated a recurrence time of 200-400 years for paleo-earthquakes based on excavations into an alluvial fan where a minimum of five earthquakes were recognized. Using Wesnousky's (1986) seismic moment relationship ($T = M_o^e/\dot{M}_o^g$; see appendix A), the assumed 19 mm/yr slip rate, and the 420-km-long rupture length, the repeat time of 1906-type earthquakes is calculated to be 200 years; at the lower bound of geologic estimates (Prentice, 1989). Similarly, the 3.4 to 4.4 m offsets estimated geodetically for the 1906 earthquake along segment A may be divided by the 19 mm/yr slip rate to place limits on the average return time for rupture of segment A. This calculation gives a recurrence interval between 179 and 232 years. For my reconstructions, it is assumed that segment A is characterized by M_W=7.8 each 200 years - less than the 300 years previously used by Wesnousky (1986).

Historical documents provide evidence that, in addition to the most recent Loma Prieta earthquake, a major earthquake also ruptured the San Andreas fault in 1838 (Louderback, 1947). Based on interpreted intensities at Monterey and San Francisco, Louderback suggested that the fault rupture extended from near San Francisco to San Juan Bautista. In 1865 a moderate sized earthquake (estimated magnitude 6.3, Toppozada et al., 1981) occurred in the south bay. Because of the uncertainty concerning it's location (McNutt and Toppozada, 1990; Tuttle, 1990), I do not include it in the analysis of the San Andreas fault. I also do not include the 1890 earthquake which is thought to have ruptured the San Andreas north of San Juan Bautista (Ellsworth, 1991) because of it's small size ($M_I = 6.0$).

The 1989 Loma Prieta earthquake was not accompanied by primary surface faulting. Geodetic observations of the Loma Prieta earthquake have been fit best by a fault model characterized by oblique slip on a buried 37-km-long plane dipping 70^o to the southwest and striking N44^oW (Lisowski et al., 1990). Slip during the event was limited to between 5 km and 17.5 km depth and characterized by 1.6 m and 1.2 m of right-lateral and reverse slip, respectively. Analysis of seismicity prior to the earthquake suggests that the San Andreas fault has a vertical dip, whereas the Loma Prieta earthquake occurred on a dipping plane that showed no prior seismic activity (Olson, 1990; Dietz and Ellsworth, 1990). A recent geomorphic study (Prentice and Schwartz, 1991) of the San Andreas fault in the Santa Cruz mountains shows the fault to be a simple through-going typical strike-slip fault which was probably defined by a simple rupture scarp in 1906. Segall and Lisowski (1990) compared geodetic data spanning both the 1906 and 1989 earthquakes and concluded that the 1989 fault model could not explain the 1906 displacements. Thus, although the 1989 earthquake occurred along the San Andreas fault zone, the seismicity and geodetic data and a reevaluation of the geologic data have been used to suggest that the Loma Prieta and 1906 earthquakes did not rupture along the same fault plane. However, in view of the close proximity of the Loma Prieta rupture plane to the vertical plane of the San Andreas, it cannot be ruled out that shear stress along the San Andreas was significantly reduced by the Loma Prieta earthquake.

The behavior of the San Andreas fault between San Francisco and San Juan Bautista is very complicated. Large earthquakes, such as the 1906 earthquake, nucleate northwest of this area and rupture through it, but this section of the fault also generates large earthquakes whose rupture zones are confined to it (such as the 1989 Loma Prieta earthquake). The seismicity pattern is sparse and clustered (Hill and others, 1991). Gaps, such as the one filled by the Loma Prieta earthquake and it's aftershocks, occur between the clusters. Just north of the Loma Prieta rupture zone, in the Portola Valley area, a prominent gap currently exists (Olson, 1990). I divide this section of the San Andreas fault into segments based on the length and location of the Loma Prieta rupture zone and coseismic slip during the 1906 earthquake. Segment B corresponds to the 53-km-long section of the San Andreas fault that lies between the northern terminus of the Loma Prieta rupture zone and Crystal Springs reservoir where there was a relative drop in coseismic offset during the 1906 earthquake (Figure 3a) and segment C is the approximately 37-km-long rupture length of the 1989 Loma Prieta earthquake. The Portola Valley gap lies within segment B.

Because of the complexity associated with historical earthquakes along segments B and C, estimating future recurrence intervals for moderate to large earthquakes are not straightforward. Segment B ruptured in 1838 and 1906. If it is assumed that the minimum coseismic slip that occurred on segment B in 1906 (2.5 m) accrued in the 68 years subsequent to 1838, a slip rate of 37 mm/yr is implied. This is greater than available geologic and geodetic estimates I have reviewed. In that regard, 68 years is likely a minimum estimate of the average return time. Interpretation of geodetic measurements places best estimates of coseismic offset along segment B between about 2.5 and 3.5 meters (Thatcher and Lisowski, 1987) in 1906. At the assumed slip rate of 19 mm/yr, it would take between 131 and 184 years to accumulate 2.5 m and 3.5 m, respectively. In my assignment of recurrence intervals for segment B, I assume 68 years is a minimum repeat time, 184 years is a maximum repeat time, and 131 years is the average repeat time for earthquakes. Segment C ruptured in 1906 and 1989 and likely ruptured in 1838. I use the 83 year time interval between the 1906 and 1989 earthquakes as a recurrence interval for segment C.

The extent of historical earthquake ruptures and the location of the mapped discontinuities in fault strike were used by Wesnousky (1986) to divide the Calaveras fault zone into four segments (Figure 3b), each assumed capable of producing moderate sized earthquakes. The same interpretation is used here in the reconstruction of the hazard map because no new data on slip rate or recurrence have been reported since 1986.

The Hayward fault zone splays off the Calaveras fault at a point south of San Francisco Bay, striking northwestward a distance of about 120 km. Segmentation of the fault (figure 3c) is similar to that put forth in Wesnousky (1986). Segments A and B include the Silver Creek-Coyote Creek and Evergreen fault systems, respectively (Aydin, 1982), show predominantly reverse-type motion (e.g. Bryant, 1982; Page, 1982), and are 18 to 25-km-long. The 36-km-long segment of the fault that ruptured in a magnitude 6.8 (Toppozada et al., 1981) earthquake on October 21, 1868 (Lawson, 1908) is labeled C in Figure 3c. A recurrence interval between 250 - 400 years is inferred for this segment of the Hayward fault from offset, tilt, and liquefaction of late Holocene pond and fluvial deposits at the north end of Tule Pond, Fremont (near Union City) (Williams, 1991). An event similar to the 1868 event may have also ruptured the Hayward fault in 1836 (Louderback, 1947). Although data for it's location is vague Louderback (1947) presents evidence for surface rupture in the Oakland area. It has most recently been suggested (Working Group, 1990) that the event ruptured segment D and, as such, is assumed in reconstruction of the hazard map.

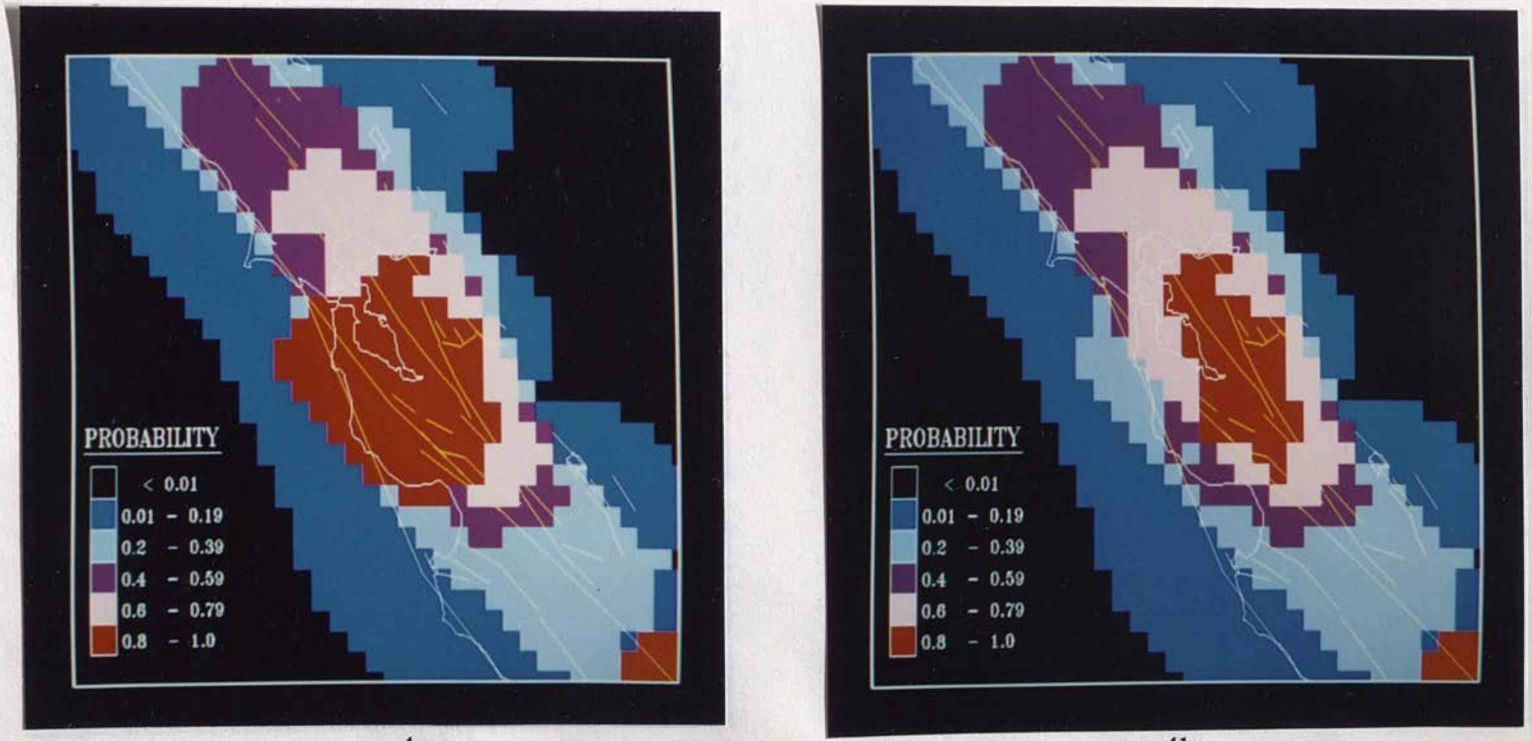
The Rodgers Creek-Healdsberg fault has no historical record of rupture. However, geologic evidence (Budding et al., 1991) indicate a maximum recurrence of $M_W = 7$ earthquakes between 248 and 679 years (Budding et al., 1991). A more recent examination of another site along the fault provides evidence for three paleoearthquakes during the last 1000 years (Schwartz et al., 1992). The one sigma range dendrochronologically corrected ages indicate a recurrence interval between 170 and 490 years.

Discussion

Hazard Maps for Strong Ground Motion on Hard Rock Sites

Reconstructed maps showing the probability of peak strong ground accelerations of ≥ 0.1g for hard rock sites during the 50 years subsequent to the 1989 Loma Prieta earthquake are shown in Figure 4. At the time of Wesnousky's (1986) investigation, a simple model of fault behavior was allowed by the relatively few data for the recurrence behavior of this section of the fault. New data imply a more complicated behavior and various viable scenarios exist to predict the future rupture behavior of the Peninsular San Andreas fault. Minimum (68 years) and maximum (184 years) estimates for the return time of Segment B on the San Andreas fault are reflected in figure 4a and 4b, respectively. For both figures 4a and 4b, it is assumed that the Loma Prieta earthquake released all the strain accumulated on segment C since 1906. However, given arguments exist that this may not be true, I also show in figures 4c and 4d the likelihood of strong ground motions assuming segment C on the San Andreas fault last rupture in 1906 and not 1989. Figures 4c and 4d are constructed similarly to figures 4a and 4b, respectively, with the exception that the former figures (Figures 4c and 4d) assume accumulated strain was not released in 1989.

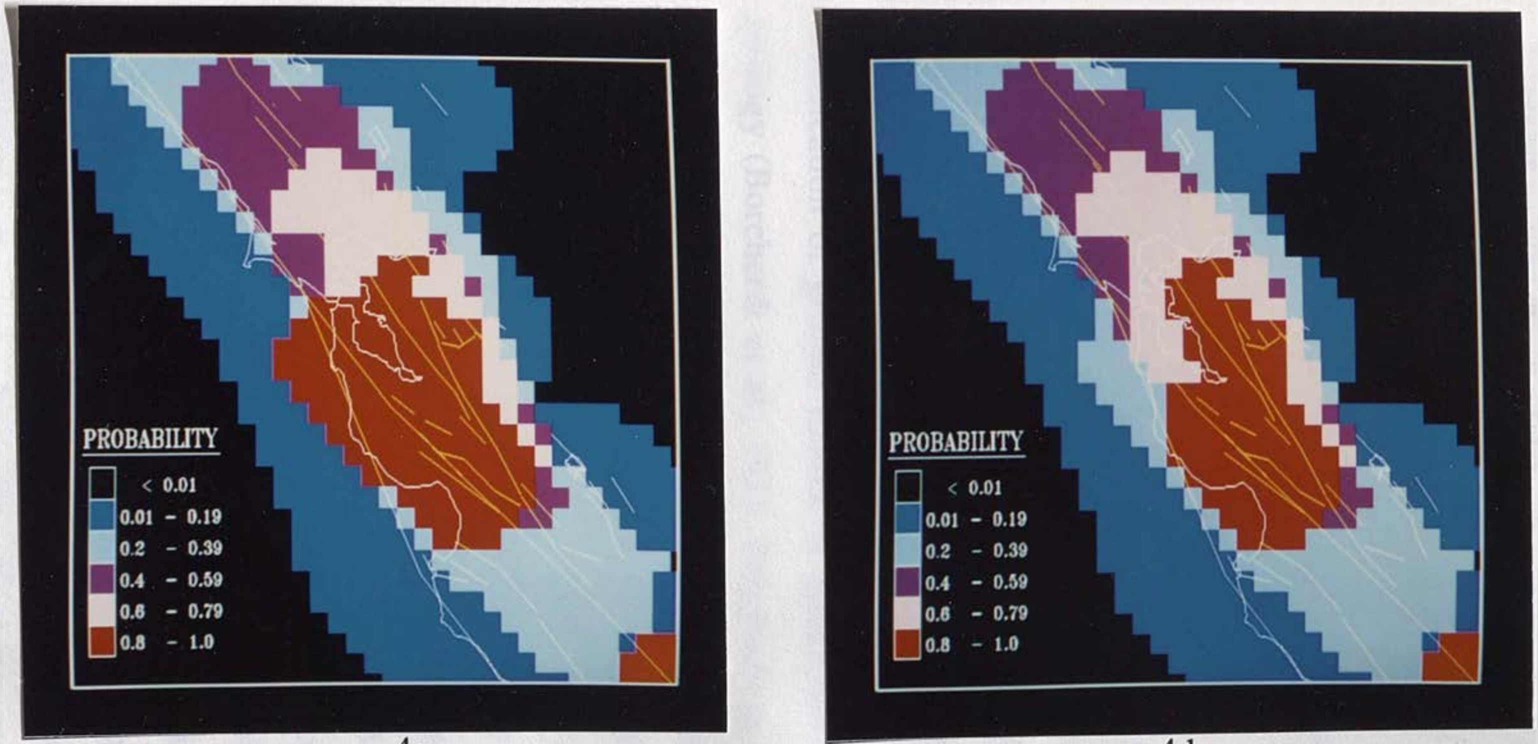
End point hypotheses for segments B and C of the San Andreas fault are shown in figure 4 to illustrate the range of spatial distributions of strong ground motion within the San Francisco Bay region. The difference in the probability of strong ground motion between figure 4a and 4b shows that the uncertainties in our knowledge of the future behavior of segment B of the San Andreas fault has a large impact on the predicted strong ground motions within the region. Nonetheless, in all cases, the probability is approximately 50% or better that the heavily populated areas of the region will experience strong ground motions of 0.1g or more during the next 50 years. While this probability is lower than predicted before the Loma



4a

4b

Figure 4. Maps showing estimated probability that Quaternary faults in the San Francisco Bay region will produce peak horizontal ground accelerations ≥ 0.1g for hard rock sites during the 50 years subsequent to 1989 Loma Prieta event. a) assumes the 68 year minimum repeat time for the Peninsula segment of the San Andreas fault (see text) and that the Loma Prieta event released all the crustal strain accumulated since 1906. b) assumes the 184 year maximum repeat time for the Peninsula segment of the San Andreas fault (see text) and that the Loma Prieta event released all the crustal strain accumulated since 1906.



4c

4d

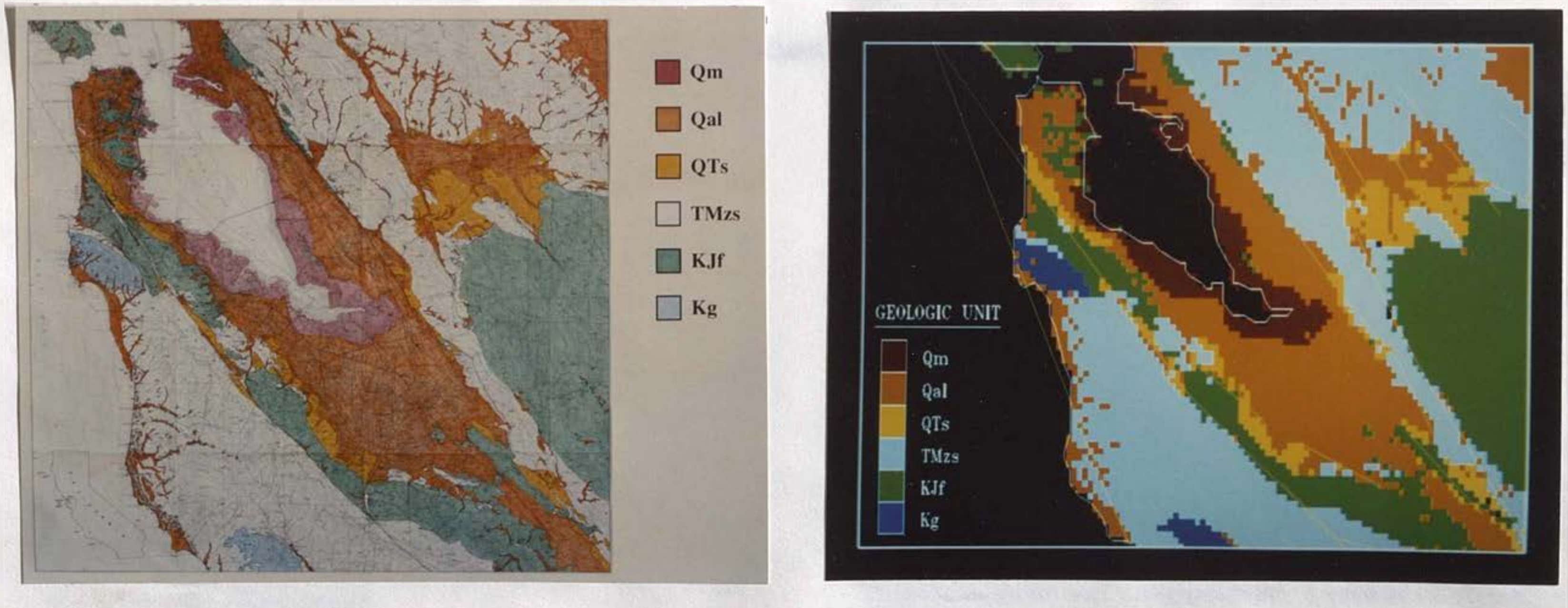
Figure 4. c) assumes the 68 year minimum repeat time for the Peninsula segment of the San Andreas fault (see text) and that the Loma Prieta event did not release the crustal strain accumulated since 1906. d) assumes the 184 year maximum repeat time for the Peninsula segment of the San Andreas fault (see text) and that the Loma Prieta event did not release the crustal strain accumulated since 1906.

Prieta earthquake, it is still quite a bit higher than was expected. New slip rate studies of the Hayward and Rodgers Creek faults have resulted in calculating an increased likelihood of strong ground motions in the East Bay with respect to Wesnousky's 1986 map. The hazard in the East Bay and northward remains high regardless of the rupture scenario for the San Andreas fault.

Hazard Maps Including Effects of Local Soil Site Conditions

An inadequacy of the maps in figure 4 is that they assume all sites are hard rock sites, but studies show that horizontal ground motion at the surface of a soil site can be substantially larger than that in the bedrock below (Borcherdt, 1975). Studies of site amplification show that modification of ground motion is systematically related to the surficial geology (Borcherdt et al., 1975; Borcherdt et al., 1991; Su et al., 1992); younger loosely consolidated sediment having the highest amplification. Su and others (1992) used a recursive stochastic inverse method to determine the site amplification from coda waves in central California. They classified the numerous geologic formations into five geologic units by age. Within each unit the mean site amplification was associated with the median geologic age. Their results correlate well with strong motions during the Loma Prieta earthquake outside the epicentral region (50 km), but do not agree with observations within 50 km of the epicenter. They attribute this disagreement to non-linear behavior of the sediment. Borcherdt and others (1975) analyzed horizontal ground motions from nuclear explosions in Nevada to determine the average amplification of geologic units in the southern San Francisco Bay area. They classified six geologic units based on seismic response to low strain data. The amplification values were further refined by Borcherdt and others (1991) based on average shear wave velocities (Fumal, 1991) to a depth of 30 m and strong ground motions which occurred during the Loma Prieta earthquake (Borcherdt et al., 1991). Borcherdt and Glassmoyer (1992) found amplifications due to site geology during the Loma Prieta earthquake not statistically different from the values predicted by Borcherdt and others (1991). A geologic map with six units differentiated by physical properties and geologic characteristics was compiled by Borcherdt and others (1975) (Figure 5a). I digitized this map (Figure 5b) and used the amplification values from Borcherdt and others (1991) to incorporate local site effects into the hazard maps. Descriptions and amplification values for the six generalized geologic units are listed in table 1.

Although the correlations between site amplification and geologic unit were determined for measurements of velocity response, for illustrative purposes, I also use the same amplification values to construct a map showing the probability of acceleration. In figure 6a, I show the probability of ground velocities ≥ 40 cm/sec for the area around San Francisco Bay during the next 50 years and, for the same period of time, I show the probability of occurrence of accelerations ≥ 0.5g in figure 6b. Notice that this level of acceleration is 5 times the level of strong ground motion shown for the hard rock sites. In both maps, I assume that the Loma Prieta earthquake released the strain accumulated since 1906 along segment C of the San Andreas fault and that the average recurrence interval for segment B of the San Andreas is 131 years, which is the



5a 5b

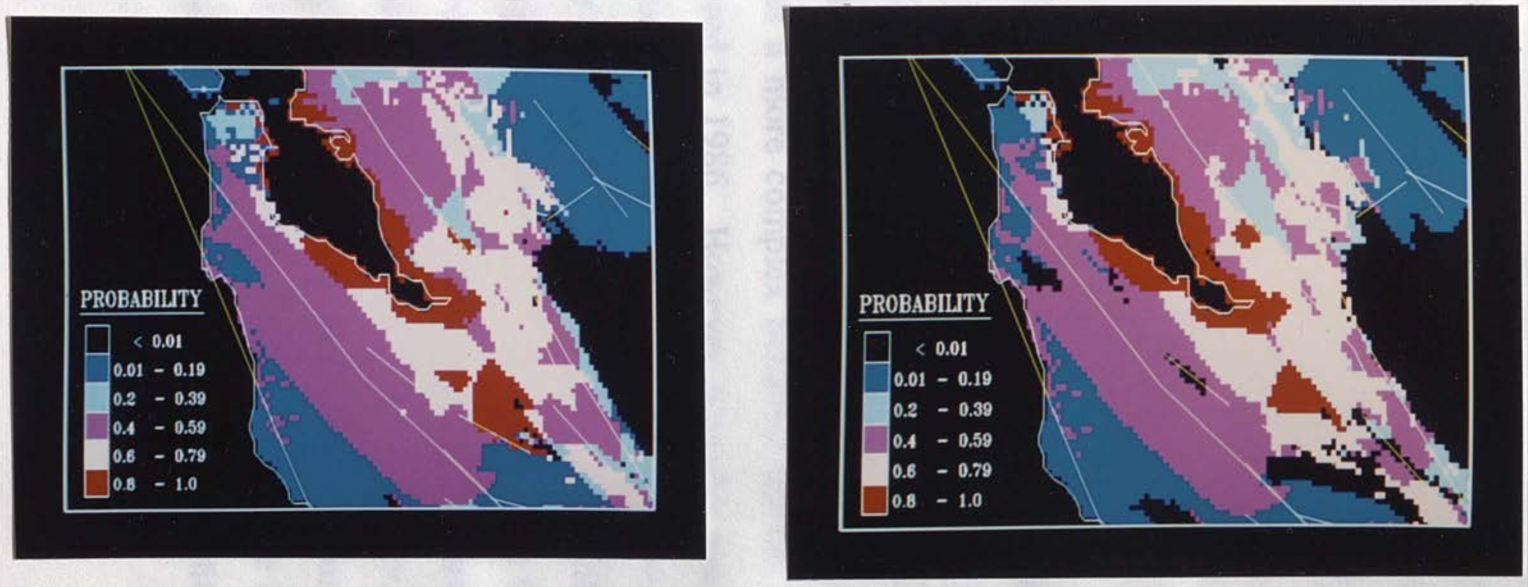
Figure 5. a) Geologic map of the southern San Francisco Bay area from Borcherdt and others (1975)
b) Digitized map of soil sites taken from the geologic map compiled by Borcherdt and others (1975). Descriptions of the geologic units are listed in table 1.

Table 1. Soil Site Conditions (modified from Borcherdt and others, 1975)

Geological unit	Symbol	Amplification	Description
estuarine Bay Mud Artificial fill (Holocene)	Qm	5.70	Unconsolidated water-saturated mud. Consists of mud deposited in San Francisco Bay, artificial fill overlying bay mud, and estuarine mud at the mouths of coastal streams.
Alluvium (Quaternary)	Qal	2.50	Unconsolidated to weakly consolidated silt, sand, and gravel. Consists of late Pleistocene and Holocene alluvium. Includes minor deposits of late Pleistocene and Holocene beach and dune sand, and marine terrace deposits.
Sedimentary rocks (Quaternary and Tertiary)	QTs	1.70	Weakly to moderately consolodated and indurated mudstone, sandstone, and conglomerate. Consists of the Santa Clara Formation along the southwestern margins of the bay basin, and the Irvington and Livermore Gravels (Rogers, 1966; Jenkins, 1943) along the northeastern margin of the bay basin.
Sedimentary rocks (Tertiary and Mesozoic)	TMzs	1.40	Moderately to highly consolidated and indurated chert, shale, sandstone and conglomerate. Consists of all bedrock units except Franciscan Complex and plutonic rocks. Predominantly Mesozoic marine shale and sandstone northeast of the Hayward fault, and Tertiary marine sandstone, shale, chert and minor amounts of volcanic rocks in the upland areas throughout the southern bay region. Underlies parts of younger sedimentary units.
Franciscan Complex (Cretaceous)	KJf	1.00	Mostly well-indurated sandstone and shale but includes subordinate amounts of greenstone, chert, limestone, conglomerate, and metamorphic rocks of blueschist facies. Generally highly deformed and locally intensively sheared with hard blocks of various lithologies in a matrix of clay materials. Constitutes the basement complex northeast of the San Andreas fault and in the small area southwest of the fault between the Pilarcitos fault and the San Andreas fault.

Table 1. Soil Site Conditions (continue)

Geological unit	Symbol	Amplification	Description
Granitic rocks (Cretaceous)	Kg	0.63	Consists of Montara Quartz Diorite (Curtis and others, 1958) and Ben Lomond (Baldwin, 1967) Quartz Diorite. Generally jointed and deeply weathered. Constitutes the basement complex southwest of the San Andreas fault except for the small area notheast of the Pilarcitos fault.



6a

6b

Figure 6. Map showing estimated probability that Quaternary faults in the San Francisco Bay region will produce peak horizontal ground a) velocities ≥ 40 cm/sec and b) accelerations ≥ 0.5g during the 50 years subsequent to 1989 Loma Prieta event. These maps include amplification due to soil site effects. Geologic conditions at the site are taken from the geologic map of the southern San Francisco Bay area compiled by Borcherdt and others (1975).

average value for that segment of the fault. It is clear that the maps (figure 6) are strongly modified by incorporation of site effects. For example, the highest levels of probability track closely with the distribution of Bay mud. High probabilities are also associated with areas of Quaternary alluvium.

Conclusion

To summarize, in the East Bay, fault slip rates and paleoearthquake studies are interpreted to indicate an increased level of hazard with respect to that recognized in 1986. This high level of hazard is insensitive to different rupture scenarios of the San Andreas fault. New evidence indicates a more complex behavior for the San Andreas fault than was considered in 1986. However, plausible interpretations of fault behavior show that the probability remains high that strong ground motions of 0.1g or more will occur on hard rock within heavily populated areas during the next 50 years. This result was unexpected at the beginning of this study. I expected a very low probability in the area around the Loma Prieta segment of the San Andreas fault. Finally, incorporation of local site geology increased the level of strong ground motion and dramatically changed it's distribution. It is clear that the largest advances to be made will result from incorporation of site amplification effects due to local geologic conditions.

APPENDIX A

Methodology

The hazard maps are based on a combined data set encompassing instrumental, historical, and geological observations. The methodology used to construct the maps have been described in detail (Wesnousky, 1986; Wesnousky, 1983). It is based on a simple model of mechanical fault behavior whereby the average repeat times of earthquakes on faults or fault segments are approximated to equal

$$T = \frac{M_o^e}{\dot{M}_o^g} \qquad (1A)$$

where the seismic moment M_o^e of the expected event is determined from paleoseismic evidence, historical seismicity, or an empirical fault length versus seismic moment relationship (Wesnousky, 1986) (Figure 1A). The geologically or geodetically determined moment rate $\dot{M}_o^g$ is a function of fault slip rate or more specifically, $\dot{M}_o^g = \mu uwl$, where μ = rigidity (3×10^{11} dyn/cm^2), u = slip rate, w = width (15 km), and l = length of the fault or fault segment considered. Each fault or fault segment is assumed to rupture along the entire segment in one large event. I do not take into account small earthquakes. For faults that have some slip due to creep at depth, I use a slip rate equal to the total estimated slip rate minus the creep rate.

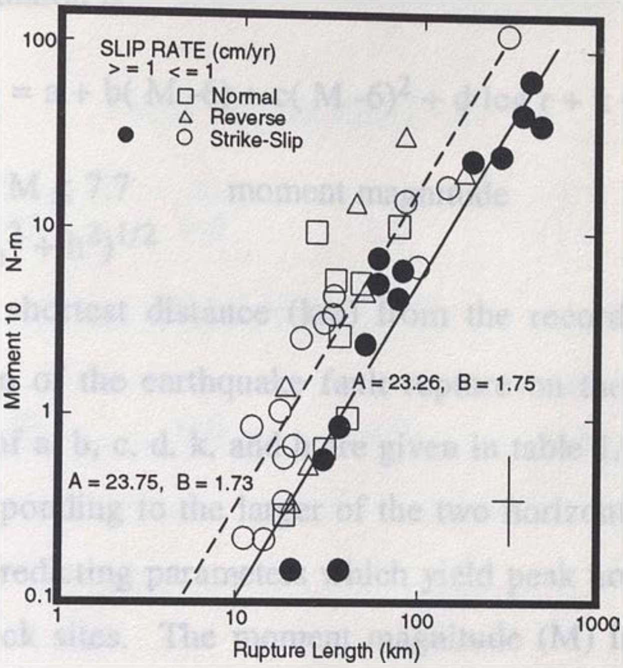


Figure 1A. Seismic moment M_o versus rupture length l. Solid symbols indicate earthquakes on major plate boundary faults generally characterized to have slip rates of 1 cm/yr or greater. Earthquakes on faults with lesser slip rates are shown by open symbols. Lines form $\log M_o = A + B \log l$ are fit through the solid and open symbols, respectively. Squares, triangles, and circles correspond to normal, reverse, and strike-slip type earthquakes, respectively. The vertical and horizontal bars of the cross in lower right corner of plot correspond to a factor of 3 in M_o and 50% in l, respectively. Taken from Wesnousky (1986).

Strong Ground Motion

Levels of strong ground motion at a gridwork of sites are calculated using the strong ground motion relationship of Joyner and Boore (1988). The predictive equation is

$$\log\ y = a + b(M - 6) + c(M - 6)^2 + d \log r + k r \qquad (2A)$$

for $5.0 \leq M \leq 7.7$ moment magnitude
and $r = (r_o{}^2 + h^2)^{1/2}$

where r_o is the shortest distance (km) from the recording site to the vertical projection of the earthquake fault rupture on the surface of the earth and values of a, b, c, d, k, and h are given in table 1A for predicting parameters corresponding to the larger of the two horizontal components. I use values for predicting parameters which yield peak horizontal ground acceleration at rock sites. The moment magnitude (M) is related to the seismic moment M_o^e through the equation $M = 2/3 (\log M_o^e - 16.1)$ (Hanks and Kanamori, 1979). As mentioned above, the seismic moment for each expected event is determined from paleoseismic evidence, historical seismicity, or an empirical fault length versus seismic moment relationship (Wesnousky, 1986). Although the Joyner and Boore (1988) attenuation equation underestimated the strong ground motion during the Loma Prieta earthquake (Boore et al., 1989), for comparative purposes with Wesnousky (1986), I use the Joyner and Boore relationships (1988) . Therefore, my predicted strong ground motions may be somewhat underestimated.

For maps which include the effects of local site conditions, a two tier method is used to generate the Strong ground motions.

Table 1A. Parameters in the predictive equations of Joyner and Boore (1988) for the larger of two horizontal components.

PEAK ACCELERATION

a	b	c	h	d	k
0.49	0.23	0.0	8.0	-1.0	-0.0027

PEAK VELOCITY

a	b	c	h	d	k
2.17	0.49	0.0	4.0	-1.0	-0.0026

First, I estimate the level of strong ground motion for a hard rock site at each grid point. For these calculations, I use values for predicting parameters corresponding to the larger of the two horizontal components (Table 1A). Then I multiply the level of hard rock strong ground motion by a local site amplification factor. To determine the local site amplification factor, I digitized the geologic map compiled by Borcherdt and others (1975) and assigned an amplification value to each geologic unit (Borcherdt and others, 1991). The final estimated level of strong ground motion is a combination of the strong ground motion due to source size and source to site distance and the local site amplification that is related to geologic materials at the site. I do not include amplifications due to basin geometry, directivity of the rupture, or critical reflections from boundaries such as the Moho.

Probability

The probability of occurrence of a given ground motion is a function of the frequency of occurrence of the specified ground motion and the time period for which one is concerned. More concisely, the probability that the occurrence time R of a certain level of strong ground motion will occur during the period of time from t_1 to t_2, conditional to t_1 years having elapsed since the last occurrence of similar ground shaking, is generally expressed as

$$P(t_1 \leq R \leq t_2 | R > t_1) = \frac{\int_{t_1}^{t_2} f_T(t)\, dt}{\int_{t_1}^{\infty} f_T(t)\, dt} \qquad (3A)$$

where $f_T(t)$ is an assumed probability density function. To calculate $f_T(t)$, I separate the data set (Quaternary faults) into two disjoint sets - a time independent set and a time dependent set.

For faults where I have no information regarding the past history of earthquakes, the occurrence of specific levels of strong ground motion at a site is described as a Poisson process and, hence, $f_T(t)$ is appropriately defined by the exponential function $\lambda e^{-\lambda t}$, where λ is the frequency of occurrence of the level of ground motion specified. With empirical relationships between seismic moment, source to site distance, and strong ground motions, equation 1A and data describing the length and average slip rate of faults in the San Francisco Bay area, the average expected frequency of occurrence of seismic shaking may be computed at a gridwork of sites for a range of different levels. The value λ, for a given level of strong ground motion at site location j, is defined by the relation

$$\lambda_j = \sum_{i=1}^{N} \frac{1}{T_j} \qquad (4A)$$

where T_i are the average repeat times of the N faults that are capable of producing a specific level of ground motion at site location j. Thus, for the time independent case, repeated use of equations (4A) and (3A) for a given level of strong motion at a gridwork of sites provides the initial base map. Additionally, where appropriate data were available, the time-dependency of seismic hazard was incorporated by taking into account the occurrence times of historical earthquakes.

Toward that end, I define the expected date T_e of rupture on a fault to equal $T_{last} + T$, where T_{last} is the date of the last earthquake rupture and T is the estimated time necessary to accumulate strain equal to that released in the previous earthquake. It is also assumed that the actual recurrence times distribute normally about values of T and hence estimates of T_e may be described with the normal probability density function

$$f_T(t) = \frac{1}{\sigma\sqrt{2\pi}}\, e^{-(t-T)^2/2\sigma^2} \tag{5A}$$

where the standard deviation σ is assigned to represent the confidence given to a predicted value of T_e. More recently studies (Working Group, 1988; Working Group, 1990) have suggested the use of lognormal or Weibull distributions because they eliminate the physically unrealistic possibility of an earthquake occurring before time equals 0, which is allowed by equation 5A. Nonetheless, for comparative purposes with Wesnousky (1986), I maintain use of equation 5A in this analysis. A value of 0.33 is assumed for σ; based on Sykes and Nishenko's (1984) study of the reccurrence behavior of three fault segments in California. Substitution of $f_T(t)$ in equation 3A results in an estimate of the probability that the rupture time T_e of a fault will occur during the next $\Delta t = t_2 - t_1$ years conditional to t_1 years having elapsed since

T_{last}. This method reflects the concept that the likelihood of an earthquake on a specific fault or fault segment is minimal immediately following T_{last} and increases as a function of time. The time-dependent and time-independent probabilities are combined using established statistical methods. The hazard maps thus incorporate both conditional time-independent probability estimates for faults where I have no information about fault rupture histories and conditional time-dependent estimates of probability for faults in the Bay area that either ruptured historically or have had prehistoric ruptures that have been dated from Quaternary geologic studies.

APPENDIX B

Quaternary Faults

Fault	Location[1]		S[2]	L[3]	M[4]	C[5]	Slip Rate[6] (mm/yr)			T[7]	D[8]	A[9]	Reference[10]
	lat	long					Mn	Mx	Pr				
Antioch A	38.1	121.8		10	6.3	C							Jennings (1975)
Antioch B	38.0	121.8		19	6.6	C							Jennings (1975)
Big Valley	39.0	122.9	rl	16	6.5	B				2675	h	q	Wesnousky (1986) Hearn et al. (1976) Clarke et al. (1984)
Browns Valley *	36.9	121.3		29	6.8	C							Jennings (1975)
Burdell Mountain	38.1	122.6		21	6.6	C							Jennings (1975)
Calaveras A (Coyote Lake)	37.0	121.5	rl	28	5.7	A			17.0	82+	h	h	Wesnousky (1986) Prescott et al. (1981) Savage et al. (1979)
Calaveras B (Morgan Hill)	37.3	121.7	rl	28	6.3	A	7.0	17.0		150+	h	h	See segment A
Calaveras C	37.5	121.8	rl	31	6.3	A			7.0	150+		h	Wesnousky (1986)
Calaveras D	37.7	122.0	rl	23	6.3	A			7.0	150+	h	h	Wesnousky (1986)
Carmel*	36.6	121.9		28	6.8	C							Jennings (1975)
Collayami	38.9	122.8	rl	18	6.6	B		1.0	0.1		h	q	Hearn et al. (1976)c
Concord	38.0	122.0	rl	24	6.7	A			7.0	183			Wesnousky (1986) Harsh and Burford (1982)
Cordelia	38.3	122.1		22	6.7	C							Herd and Helley (1977)
Corral Hollow *	37.7	121.6		17	6.5	C							Jennings (1975)
Green Valley	38.2	122.1		35	6.9	A			7.0	242			Wesnousky (1986) Herd and Helly (1977) Frizzell and Brown (1976)

Quaternary Faults (continue)

Fault	Location[1] lat	Location[1] long	S[2]	L[3]	M[4]	C[5]	Slip Rate[6] Mn (mm/yr)	Slip Rate[6] Mx (mm/yr)	Slip Rate[6] Pr (mm/yr)	T[7]	D[8]	A[9]	Reference[10]
Greenville	37.7	121.7	rv	28	6.8	B	0.1	0.7		3585	h	h	Wright et al. (1982)
Hayward A (Coyote and Silver Creek faults)	37.2	121.7	ll	18	6.6	A			9.0	118	h	h	see text Wesnousky (1986)
Hayward B (Evergreen fault)	37.4	121.8	rl	32	6.9	A			9.0	149	h	h	see text Wesnousky (1986)
Hayward C	37.6	122.0	rl	32	6.9	A	6.0	9.0	9.0	189	h	h	see text Working Group (1990) Lienkaemper et al. (1991) Prescott el al. (1981) Prescott and Lisowski (1982) Lawson (1908)
Hayward D	37.9	122.3	rl	49	7.0	A			9.0	240	h	h	see segment C
Healdsburg	38.6	122.8	rl	32	6.8	A			9.0	178			see text Wesnousky (1986) Jennings (1975)
King City	36.0	121.6		57	7.1	C							Jennings (1975)
Las Positas	37.6	121.7	ln	10	6.3	B	0.04	1.6		873	t	q	Carpenter and Clark (1982)c Herd and Brabb (1980)
Livermore	37.7	121.8		18	6.2	C							Jennings (1975)
Los Altos *	37.3	122.1		14	6.4	C							Jennings (1975)
Los Gatos *	37.2	121.9		15	6.5	C							Jennings (1975)

Quaternary Faults (continue)

Fault	Location[1]		S[2]	L[3]	M[4]	C[5]	Slip Rate[6]			T[7]	D[8]	A[9]	Reference[10]
	lat	long					Mn	Mx	Pr				
							(mm/yr)						
Maacama	39.1	123.1		151	7.6	A			9.0	541			Wesnousky (1986) Pampeyan et al. (1981) Herd (1978) Herd and Helley (1977)
Midway	37.7	121.6	r	11	6.3	B	0.1	0.5		2651			Shedlock et al. (1980)c
Oneil	36.9	121.0	r	18	6.5	A	0.3	1.8		984			Lettis (1982)c
Ortigalita A	37.1	121.2	?	25	6.7	C	0.01	0.04		10000+	v	q	Anderson et al. (1982) Clark et al. (1984)
Ortigalita B	37.0	121.1	?	18	6.6	C	0.01	0.04		10000+	v	q	see segment A
Ortigalita C	36.9	121.0	?	18	6.6	C	0.01	0.04		10000+	v	q	see segment A
Ortigalita D	36.7	120.9	?	21	6.6	C	0.01	0.04		10000+	v	q	see segment A
Paicines	36.8	121.3	rl	36	6.9	A	5.0	13.0	1.0	1727		h	Wesnousky (1986) Harsh and Pavoni (1978) Ellsworth (1975) Savage et al. (1973) Lisowski and Prescott (1981)
Panoche Pass *	36.6	121.1		22	6.6	C							Jennings (1975)
Pleasonton	37.7	121.9		9	6.2	C							Jennings (1975)
Rinconada	35.8	120.9	rl	136	7.6	A	2.4	12.0	2.4	1883	h	p	Durham (1965)b Hart (1976)b
Rodgers Creek	38.3	122.6		51	7.0	A	2.1	10.0	9.0	248			Budding et al. (1991) Schwartz et al. (1992)
San Andreas A (Shelter Cove to Crystal Springs)	38.5	122.8	rl	420	7.8	AA	7.5	30.0	19.0	200+	h	h	see text Prentice (1989) Matu'ura et al. (1986) Hall (1984) Prescott and Yu (1986)

Quaternary Faults (continue)

Fault	Location[1] lat	Location[1] long	S[2]	L[3]	M[4]	C[5]	Slip Rate[6] Mn (mm/yr)	Slip Rate[6] Mx (mm/yr)	Slip Rate[6] Pr (mm/yr)	T[7]	D[8]	A[9]	Reference[10]
San Andreas B (Crystal Springs to Los Gatos)	37.4	121.1	rl	53	6.8	AA	7.5	30.0	19.0	131+	h	h	see text Thatcher (1987) Matu'ura et al. (1986) Hall (1984) Prescott et al. (1981)
San Andreas C (Los Gatos to Hecker Pass)	37.1	121.9	rl	37	6.6	AA	7.5	30.0	19.0	83+	h	h	see text Thatcher (1987) Matu'ura et al. (1986) Prescott et al. (1981)
San Andreas D (Hecker Pass to Bitterwater)	36.6	121.2	rl	86	7.0	AA	7.5	39.0	5.0	262	h	h	Wesnousky (1986) Burford and Harsh (1980) Clark et al. (1984)
San Benito	36.6	121.1	rl	24	6.7	A	5.0	13.0	1.0	1291			see Paicines fault
San Gregorio - Hosgri	37.1	122.3	rl	190	7.7	A	7.0	19.0	7.0	824	h	q	Weber and Cotton (1981)c Weber and Lajoie (1980)c Clark et al. (1984)
San Joaquin	36.9	120.8	?	21	6.6	A	0.2	2.0		1083	v	q	Lettis (1982)c
Sargent-Berrocal	37.0	121.7	rr	51	7.1	A		4.0	1.0	2225		h	Savage et al. (1979) Hay et al. (1980)
Seaside*	36.5	121.7		23	6.7	C							Jennings (1975)
Tolay	38.2	122.5		14	6.5	C							Jennings (1975)
Vaca	38.3	122.0	rl	7	6.1	A	0.3	4.0		260	h	q	Kneupfer (1977)c
Verona	37.6	121.8	r	8	6.2	B	0.02	0.1	0.1	9735	t	q	Herd and Brabb (1980)c
West Napa	38.3	122.3		17	6.5	C							Herd and Helley (1977)

Quaternary Faults (continue)

Fault	Location^1		S^2	L^3	M^4	C^5	Slip Rate^6 (mm/yr)			T^7	D^8	A^9	Reference^{10}
	lat	long					Mn	Mx	Pr				
Zamora	38.8	121.9	n	21	6.6	A	0.2	0.5	0.3	4631	v	q	Harwood et al. (1981)c Harwood and Helley (1982)c
Zayante-Vergales	37.0	121.8	rr	50	7.1	B	0.1	1.3		3140	t	q	Coppersmith (1979)c Dupre (1975)c

Key

1 - Location of fault. Coordinates mark approximate midpoint of fault or fault segment.

2 - Fault type (eg. reverse (r), normal (n), right-lateral (rl), left-lateral (ll), right-reverse (lr), right-vertical (rv), left-vertical (rv), right-normal (m), left-normal (ln).

3 - Fault length (kilometers)

4 - Moment-magnitude M_w of earthquake expected for rupture of entire fault length, estimated with slip-rate dependent emperical relations between seismic moment M_o and fault length Wesnousky (1986) in figure 1A, and assuming the emperical relation $\log M_o = 1.5M_w + 16.1$ (Hanks and Kanamori, 1979).

5 - Slip rate class : AA ≥ 10 mm/yr, A ≥ 1 mm/yr, B ≥ 0.1 mm/yr, C ≥ 0.01 mm/yr. Fault assumed to be class C when no slip rate data are available and assigned a slip rate equal to0.01 mm/yr for hazard map development.

6 - The minimum (Mn) and maximum (Mx) values of slip rate reported by referenced investigators. The preferred (Pr) value of rate, when listed, is used for estimating T. Otherwise, T is estimated with either the minimum, or average of the minimum and maximum reported rates, depending on which limits are placed on the respective faults.

7 - Repeat time of rupture for each fault estimated with equation 1, unless marked by $^+$. Repeat times estimated to be greater than 10000 years are not listed.

8 - The reported slip rate is determined from predominantly horizontal (h), vertical (v), dip-slip (d), or the total (t) component of displacement.

9 - Youngest feature used to determine slip rate and/or repeat time along entire fault zone; Holocene (h), Pleistocene (q), Pliocene (p), or Miocene (m). Range of slip rates may reflect rates determined from older offsets as well.

10 - References regarding location, slip rate, and repeat time of each fault. A subscript a, b, or c following the reference indicates that values of slip rate are those reported by a) Anderson (1979), b) Bird and Rosenstock (1984), and c) Clark et al. (1984), respectively.

* - Fault name assumed without reference to earlier studies.

\+ - Based on historical information, trenching studies, or other geological inferences, rather than equation 1. Cases discussed in the text.

APPENDIX C

The programs used to calculate the strong ground motion array were written by Steve Wesnousky in 1985 and modified by myself in 1991. They are not be presented here. The program which follows generates maps from the strong ground motion array, a fault input file, and a boundary file. The plotting program, plothaz, is written in standard fortran 77 with calls to the GK-2000 plotting package library. All maps presented in this Thesis were plotted on a Sun workstation.

```
      PROGRAM plothaz
*
*    this is the main program which drives subroutines to plot
*    the following types of seismic hazard data.
*      '1| QUATERNARY FAULTS PRODUCING GROUND ACCELERATION'
*      ' 2| EXPECTED RETURN TIME OF LARGE EARTHQUAKES'
*      ' 3| PROBABILITY OF A LARGE EARTHQUAKE'
*      ' 4| PEAK HORIZONTAL GROUND ACCELERATION'
*      ' 5| PEAK HORIZONTAL GROUND VELOCITY'
*      ' 6| soil site map')
*    The strong motion data is generated by steve's seismic
*    hazard programs.
*
      character*20 FNAME, plotitle, HLseg(2)
      character*1 ans
      logical highlight, showtitle
      logical hazplot, bold
      common /fltplt/ hazplot, bold
      logical BW
      common /screen/ BW
      logical crop
      common /testframe/ crop
      logical checkshift
      common /check/ checkshift
*
      integer numfile, segcolor, HLcolor(2)
      INTEGER wkid, plot
      common /sun/ wkid
      common /pltype/ plot
      real xoffset, yoffset, Txoffset, Tyoffset
      common /movexy/ xoffset, yoffset, Txoffset, Tyoffset
*
      integer numtemp
      real coord, temp
      dimension coord(12), temp(10000)
      common /plotline/ numtemp, temp
*
      integer wtype, errind, nawk
      integer connid, errlun, ilun, olun
      Data errlun, ilun, olun /6,0,0/
      data wkid /1/
*
*
*     **{begin main program}**
*
      crop = .false.
      call hazin
      if (plot .EQ. 99) goto 99020
*
      write(*,*) 'do you want to crop the plot? (Y)'
      read(*,100) ans
      if (ans .EQ. 'Y') then
        crop = .true.
        call getbounds
      endif
      xoffset = 4.0
      yoffset = 12.0
```

```
      write(*,1) xoffset, yoffset
    1 format(' xoffset = ',F3.1,'   yoffset = ',F4.1/
     +'do you want to move the probability label? (Y)')
      read(*,100) ans
      if (ans .EQ. 'Y') then
        write(*,*) 'xoffset, yoffset'
        read(*,*) xoffset, yoffset
      endif
      showtitle = .false.
      write(*,*) 'do you want to print a title? (Y)'
      read(*,100) ans
      if (ans .EQ. 'Y') then
        showtitle = .true.
        write(*,*) 'what is the title of the plot?'
        read(*,*) plotitle
        write(*,*) 'xoffset, yoffset'
        read(*,*) Txoffset, Tyoffset
      endif
      BW = .false.
      write(*,*) 'do you want B&W (Y) or color (default)?'
      read(*,100) ans
      if (ans .EQ. 'Y') BW = .true.
*
   10 write(*,*)' FAULT INPUT FILENAME : '
      READ(*,*) FNAME
      OPEN (unit=3, file=FNAME, err=10, status='old',
     +       access='sequential', form='formatted')
*     ** skip strong motion relationship **
      do 20, i=1,9
          read(3,*)
   20 continue
*
      highlight= .false.
      i=0
   25 write(*,26)
   26 format('Do you want to highlight a fault segment? (Y)'
     +        /'maximum 2 segment')
      read(*,100) ans
      if (ans.EQ.'Y') then
        highlight = .true.
        i=i+1
        maxseg=i
   30   write(*,*) ' FAULT segment INPUT FILENAME : '
        READ(*,*) HLseg(i)
        OPEN (unit=4, file=HLseg(i), err=30, status='old',
     +       access='sequential', form='formatted')
        close(4)
        write(*,31)
   31   format('color of segment'/ 'yellow = 12'/'green = 14')
        read(*,*) HLcolor(i)
        goto 25
      endif
      bold = .false.
*
      write(*,*) 'Do you want the crosshairs? (Y)'
      read(*,100) ans
      if (ans .EQ. 'Y') then
```

```
        checkshift = .true.
        call getlatlong
      else
        checkshift = .false.
      endif
*
*
*     ***{BORDER INPUT FILE}**
      OPEN (unit=2, file='border.i', err=99010, status='old',
     + access='sequential', form='formatted')
      m =1
   40 read(2,110,end=60) (coord(j), j=1,12)
      do 50, i=1,12
        temp(m) = coord(i)
        m = m+1
   50   continue
      goto 40
   60 continue
      temp(m) = 99.0
      temp(m+1) = 0.0
      numtemp = m
      close(2)
*
  100 format (A1)
  110 format (F6.2,F7.2,F6.2,F7.2,F6.2,F7.2,
     +        F6.2,F7.2,F6.2,F7.2,F6.2,F7.2)
*
**********************************************************
*
      connid = olun * 256 + ilun
      call gopks (errlun,-1)
      call gqewk (1,errind,nawk,wtype)
      if (errind .NE. 0) goto 99000
      call gopwk (wkid,connid,wtype)
      call gpause (wkid)
*
      call gacwk (wkid)
*
      call screencolor
      if (hazplot) then
*     ** hazard map **
      call plothaz
        call hazcode
        call hazlabel
      else
*     ** fault map **
        call faultcode
        call faultlabel
      endif
      numfile = 3
      segcolor = 8
      call faultseg(numfile,segcolor)
      close(3)
      call statebound
      if (highlight) then
        bold = .true.
        numfile = 4
```

```
        do 210, i=1,maxseg
          OPEN (unit=4, file=HLseg(i), err=210, status='old',
     +            access='sequential', form='formatted')
        segcolor = HLcolor(i)
        call faultseg(numfile,segcolor)
        close(4)
  210   continue
      endif
      call frame
      if (showtitle) call prtitle(plotitle)
      call gpause (wkid)
      call gdawk (wkid)
*
      call gclwk (wkid)
      call gclks
*
**************************************************************
*
      write(*,*) 'do you want to print the color array? (Y)'
      read(*,100) ans
      if (ans .EQ. 'Y') call prtarray
*
      stop
99000 write(*,*) 'error openning work station'
      write(*,*) errind
      call gclks
      stop
*
99010 write(*,*) 'can not find border.i'
      close(2)
      close(3)
99020 write(*,*) 'plot type EQ 99'
      stop
      end
*
*****************************************************************
*****************************************************************
*
      subroutine hazin
*
*  this subroutine reads and formats hazard data from steve's hazard
*  program.  It fills the array CALflt with integer color codes
*  for the hazard map.
*
      character*20 FNAME
      character*1 ans
      logical soilsite
      logical hazplot, bold
      common /fltplt/ hazplot, bold
      INTEGER plot, CALflt(1000,1000)
      common /pltype/ plot
      common /global/ CALflt
      real soil(1000,1000)
      common /site/ soilsite, soil
      real xscale, yscale, northB, southB, westB, eastB
      common /coord/ xscale, yscale, northB, southB, westB, eastB
      real xcenter, ycenter, xshift, yshift
```

```
      common /centerline/ xcenter, ycenter, xshift, yshift
      integer xmax, ymax, cellat, cellong, cellpoints
      common /cellscale/ xmax, ymax, cellat, cellong, cellpoints
      real proportion, latmult, longmult
      common /ratio/ proportion
      data latmult, longmult /10.5,8.5/
*
      WRITE (*,20)
   20 FORMAT('ENTER INTEGER 1,2,3,4, OR 5, RESPECTIVLY FOR MAPS OF'/
     +  ' 1| QUATERNARY FAULTS PRODUCING GROUND ACCELERATION'/
     +  ' 2| EXPECTED RETURN TIME OF LARGE EARTHQUAKES'/
     +  ' 3| PROBABILITY OF A LARGE EARTHQUAKE'/
     +  ' 4| PEAK HORIZONTAL GROUND ACCELERATION'/
     +  ' 5| PEAK HORIZONTAL GROUND VELOCITY'/
     +  ' 6| soil amplification map'/
     +  ' 7| Quaternary fault map')
      read(*,*) plot
      if (plot.EQ.7) then
        hazplot = .false.
      call getbounds
      else
        hazplot = .true.
   10   write(*,*) ' INPUT FILENAME : '
        READ(*,*) FNAME
        OPEN (unit=1, file=FNAME, err=10, status='old',
     +        access='sequential', form='formatted')
        read(1,100) xmax, ymax, cellpoints, northB, southB,
     +             westB, eastB, proportion
      endif
*
*    **{set scale}**
      yYscale = latmult * (northB - southB)
      yXscale = longmult * (westB - eastB)
      test = proportion * xmax
      if (test .GT. ymax) then
        yscale = yYscale
      else
        yscale = yXscale
      endif
      write(*,22) yYscale, yXscale, yscale
   22 format(/'scale 1 is ',F6.2,'scale 2 is ',F6.2/
     +            'recommended scale is ',F6.2)
      write(*,*) 'do you want to change the recommended scale? (Y)'
      read(*,120) ans
      if (ans .EQ. 'Y') then
        write(*,*) 'enter scale factor'
        read(*,*) yscale
      endif
      xscale = yscale / proportion
*
*    **{set array shift}**
      xshift = 0.
      yshift = 0.
      xcenter = (westB - eastB)/(0.2 * (xmax - 1))
      ycenter = (northB - southB)/(0.2 * (ymax - 1))
*
*    **{list parameters}**
```

```
      write(*,110) northB, southB, westB, eastB,
     +              cellpoints, proportion, plot
      write(*,*) 'type Y to continue'
      read(*,*) ans
      if(ans .NE. 'Y') goto 99010
      if (plot.EQ.7) return
*
      do 35, m=1, xmax
      do 30, n=1, ymax
        CALflt(m,n) = 0
   30   continue
   35 continue
      soilsite = .false.
*
*    **{input data}**
      if (plot .EQ. 1) then
        call column
        call plot1in
      else
        if (plot .EQ. 2) then
          call column
          call plot2in
        else
          if (plot .EQ. 3) then
            call column
            call plot3in
          else
            if (plot .EQ. 4) then
              call plot4in
            else
              if (plot .EQ. 5) then
                call plot5in
              else
*             ** plot EQ 6 **
                call plot6in
              endif
            endif
          endif
        endif
      endif
      close(1)
*
  100 format (2(I5),1x,I4,2(1x,F6.3),2(1x,F7.3),1x,F5.3)
  110 format (/2(1x,F5.2),2(1x,F6.2),1x,I4,1x,F4.2,1x,I2)
  120 format (A1)
*
      return
99010 write(*,*) 'program stopped by operator'
      plot = 99
      close(1)
      return
      end
*
*********************************************************
*
      subroutine getbounds
*
```

```
*   this subroutine reads the boundaries for a Quaternary
*   fault map.
*
      logical crop
      common /testframe/ crop
      integer xmax, ymax, cellat, cellong, cellpoints
      common /cellscale/ xmax, ymax, cellat, cellong, cellpoints
      real proportion
      common /ratio/ proportion
      real xscale, yscale, northB, southB, westB, eastB
      common /coord/ xscale, yscale, northB, southB, westB, eastB
      real tempnorthB, tempsouthB, tempwestB, tempeastB
      common /cropB/ tempnorthB, tempsouthB, tempwestB, tempeastB
*
      WRITE(*,*)'ENTER WEST AND EAST BOUNDING COORDINATES'
      READ (*,*) tempwestB, tempeastB
      write(*,*)'ENTER SOUTH AND NORTH BOUNDING COORDINATES'
      READ (*,*) tempsouthB, tempnorthB
      WRITE(*,*) 'enter number of gridpoints per degree'
      READ (*,*) numptdeg
      if (.NOT.crop) then
        write(*,*) 'ratio between lat and long?'
        read(*,*) proportion
        westB = tempwestB
        eastB = tempeastB
        northB = tempnorthB
        southB = tempsouthB
      endif
      NXXX = ((westB - eastB) * numptdeg) + 1
      NYYY = ((northB - southB) * numptdeg) + 1
      cellpoints = numptdeg
      WRITE(*,2060) westB, eastB, southB, northB, cellpoints
 2060 FORMAT('west boundary is ',F7.2,'   east boundary is ',F7.2/
     +    'south boundary is ',F7.2,'   north boundary is ',F7.2/
     +      'number of points per degree is ',I6/)
      return
      end
*
**************************************************************
*
      subroutine getlatlong
*
*   this subroutine reads the latitude and longitude for
*   placement of the crosshairs.
*
      integer xmax, ymax, cellat, cellong, cellpoints
      common /cellscale/ xmax, ymax, cellat, cellong, cellpoints
      real lathair, longhair
      common /haircoord/ lathair, longhair
      real xscale, yscale, northB, southB, westB, eastB
      common /coord/ xscale, yscale, northB, southB, westB, eastB
*
*
      write(*,*) 'What is the latitude of the crosshair'
      read(*,*) lathair
      write(*,*) 'What is the longitude of the crosshair'
      read(*,*) longhair
```

```
*
      cellat = ((lathair - southB) * cellpoints) + 1
      cellong = ((WestB - longhair) * cellpoints) + 1
*
      return
      end
*
*********************************************************
*
      subroutine column
*
*   this subroutine chooses the proper column to be read based
*   on the strong ground motion level chosen by the user.
*
      INTEGER icol
      common /index/ icol
      real ACC
      real level1, level2, level3, level4, level5, level6, level7
      real level8, level9, level10, level11, level12, level13
      data level1, level2, level3, level4 /0.065,0.075,0.085,0.095/
      data level5, level6, level7 /0.15,0.25,0.35/
      data level8, level9, level10 /0.45,0.55,0.65/
      data level11, level12, level13 /0.75,0.85,0.95/
*
      write(*,*) 'enter peak horizontal ground motion'
      read(*,*) ACC
      if(ACC .LT. level1) then
       icol=1
      else
       if (ACC .LT. level2) then
         icol=2
       else
        if (ACC .LT. level3) then
          icol=3
        else
         if (ACC .LT. level4) then
           icol=4
         else
          if (ACC .LT. level5) then
            icol=5
           else
           if (ACC .LT. level6) then
             icol=6
           else
            if (ACC .LT. level7) then
              icol=7
            else
             if (ACC .LT. level8) then
               icol=8
             else
              if (ACC .LT. level9) then
                icol=9
               else
               if (ACC .LT. level10) then
                 icol=10
               else
```

```
                if (ACC .LT. level11) then
                  icol=11
                else
                 if (ACC .LT. level12) then
                   icol=12
                 else
                  if (ACC .LT. level13) then
                    icol=13
                  else
                    icol=14
                  endif
                 endif
                endif
               endif
              endif
             endif
            endif
           endif
          endif
         endif
        endif
       endif
      endif
      write(*,100) icol
  100 format(2x,'I= ',I2)
*
      return
      end
*
*********************************************************
*
      subroutine plot1in
*
*
      INTEGER CALflt, icol
      DIMENSION CALflt(1000,1000)
      common /global/ CALflt
      common /index/ icol
      integer fault
      dimension fault(14)
      integer maxhaz, devastate
      data maxhaz, devastate /16,17/
*
   10 read(1,100,end=20) n, m, (fault(j), j=1,14)
      if (fault(icol).GT.maxhaz) fault(icol) = devastate
      if ((fault(icol).EQ.0).OR.(fault(icol).EQ.1)) then
        CALflt(m,n) = fault(icol)
      else
        if ((fault(icol).GT.1).AND.(fault(icol).LT. 5)) then
          CALflt(m,n) = 1
        else
          if ((fault(icol).GT.4).AND.(fault(icol).LT.9)) then
            CALflt(m,n) = 2
          else
            if ((fault(icol).GT.8).AND.(fault(icol).LT.13)) then
              CALflt(m,n) = 3
            else
```

```
              if ((fault(icol).GT.12).AND.(fault(icol).LT.17)) then
                CALflt(m,n) = 4
              else
                CALflt(m,n) = 5
              endif
            endif
          endif
        endif
      endif
      goto 10
   20 continue
*
  100 format(2I3,14I3)
*
      return
      end
*
**********************************************************
*
      subroutine plot2in
*
*
      INTEGER CALflt, icol
      DIMENSION CALflt(1000,1000)
      common /global/ CALflt
      common /index/ icol
      real repeatT, returnT
      DIMENSION repeatT(14)
*
   10 read(1,100,end=20) n, m, (repeatT(j), j=1,14)
        returnT = 1/repeatT(icol)
        if (returnT .GT. 1000) then
          CALflt(m,n) = 0
        else
          if (returnT .GE. 500) then
            CALflt(m,n) = 1
          else
            if (returnT .GE. 250) then
              CALflt(m,n) = 2
            else
              if (returnT .GE. 100) then
                CALflt(m,n) = 3
              else
                if (returnT .GE. 50) then
                  CALflt(m,n) = 4
                else
*               **{returnT LT 50}**
                  CALflt(m,n) = 5
                endif
              endif
            endif
          endif
        endif
        goto 10
   20 continue
*
  100 format(2I3,14F6.5)
```

```
*
      return
      end
*
************************************************************
*
      subroutine plot3in
*
*
      INTEGER CALflt(1000,1000), icol
      common /global/ CALflt
      common /index/ icol
      real prob
      dimension prob(14)
*
*
   10 read(1,100,end=20) n, m, (prob(j), j=1,14)
      if (prob(icol) .LT. 0.01) then
        CALflt(m,n) = 0
      else
        if (prob(icol) .LT. 0.2) then
          CALflt(m,n) = 1
        else
          if (prob(icol) .LT. 0.4) then
            CALflt(m,n) = 2
          else
            if (prob(icol) .LT. 0.6) then
              CALflt(m,n) = 3
            else
              if (prob(icol) .LT. 0.8) then
                CALflt(m,n) = 4
              else
                CALflt(m,n) = 5
              endif
            endif
          endif
        endif
      endif
      goto 10
   20 continue
*
  100 format(2I3,14F6.4)
*
      return
      end
*
************************************************************
*
      subroutine plot4in
*
*
      INTEGER CALflt(1000,1000)
      common /global/ CALflt
      real grmotion
      DIMENSION grmotion(20)
*
*         ** plot acceleration **
```

```
       m = 1
       n = 1
   10  read(1,100,end=30) (grmotion(j), j=1,20)
         do 20, i=1,20
           if (grmotion(i) .LT. 0.05) then
             CALflt(m,n) = 0
           else
             if (grmotion(i) .LT. 0.1) then
               CALflt(m,n) = 1
             else
               if (grmotion(i) .LT. 0.2) then
                 CALflt(m,n) = 2
               else
                 if (grmotion(i) .LT. 0.3) then
                   CALflt(m,n) = 3
                 else
                   if (grmotion(i) .LT. 0.5) then
                     CALflt(m,n) = 4
                   else
*                  **{grmotion GT .50}**
                     CALflt(m,n) = 5
                   endif
                 endif
               endif
             endif
           endif
         if (m .EQ. 111) then
           if (n .EQ. 101) goto 30
           m = 1
           n = n + 1
         else
           m = m + 1
         endif
   20  continue
         goto 10
   30  continue
*
  100 format(20F4.2)
*
      return
      end
*
*********************************************************
*
      subroutine plot5in
*
*
      INTEGER CALflt(1000,1000)
      common /global/ CALflt
      real grmotion
      DIMENSION grmotion(20)
*
*         ** plot acceleration **
      m = 1
      n = 1
  10  read(1,100,end=30) (grmotion(j), j=1,20)
        do 20, i=1,20
```

```
           if (grmotion(i) .LT. 6) then
             CALflt(m,n) = 0
           else
             if (grmotion(i) .LT. 20) then
               CALflt(m,n) = 1
             else
               if (grmotion(i) .LT. 40) then
                 CALflt(m,n) = 2
               else
                 if (grmotion(i) .LT. 60) then
                   CALflt(m,n) = 3
                 else
                   if (grmotion(i) .LT. 80) then
                     CALflt(m,n) = 4
                   else
*                  **{grmotion GT .50}**
                     CALflt(m,n) = 5
                   endif
                 endif
               endif
             endif
           endif
         if (m .EQ. 111) then
           if (n .EQ. 101) goto 30
           m = 1
           n= n + 1
         else
           m = m + 1
         endif
   20    continue
         goto 10
   30  continue
*
  100 format(10F6.0)
*
      return
      end
*
*********************************************************
*
      subroutine plot6in
*
*  this subroutine inputs the soil data for plotting
*  a soil amplification map.
*
      integer i1, j1, i2, j2, i3, j3, i4, j4, i5, j5
      real A1, A2, A3, A4, A5
      integer zero
      data zero /0/
*
*
   10 read(1,100,end=20) i1,j1,A1,i2,j2,A2,i3,j3,A3,
     +                   i4,j4,A4,i5,j5,A5
      if (i5.GT.zero) then
        call geology(i1,j1,A1)
        call geology(i2,j2,A2)
        call geology(i3,j3,A3)
```

```
        call geology(i4,j4,A4)
        call geology(i5,j5,A5)
      else
      if (i4.GT.zero) then
        call geology(i1,j1,A1)
        call geology(i2,j2,A2)
        call geology(i3,j3,A3)
        call geology(i4,j4,A4)
      else
      if (i3.GT.zero) then
        call geology(i1,j1,A1)
        call geology(i2,j2,A2)
        call geology(i3,j3,A3)
       else
       if (i2.GT.zero) then
         call geology(i1,j1,A1)
         call geology(i2,j2,A2)
       else
         call geology(i1,j1,A1)
      endif
      endif
      endif
      endif
      goto 10
*
   20 continue
  100 format(5(1x,I4,1x,I4,F5.2))
*
      return
      end
*
*********************************************************
*
      subroutine geology(i,j,soilsite)
*
*  this subroutine determines the color of the array CALflt
*  based on the soil amplifications read in plot6in.
*
      INTEGER CALflt(1000,1000)
      common /global/ CALflt
      integer i,j
      real soilsite
      real geol1, geol2, geol3, geol4, geol5, geol6
      data geol1, geol2, geol3 /0.5,0.9,1.3/
      data geol4, geol5, geol6 /1.5,2.4,5.6/
*
      if (soilsite .GT. geol6) then
       CALflt(i,j) = 10
      else
        if (soilsite .GT. geol5) then
          CALflt(i,j) = 11
        else
          if (soilsite .GT. geol4) then
            CALflt(i,j) = 12
          else
            if (soilsite .GT. geol3) then
              CALflt(i,j) = 13
```

```
            else
              if (soilsite .GT. geol2) then
                CALflt(i,j) = 14
              else
                if (soilsite .GT. geol1) then
                  CALflt(i,j) = 15
                else
                  CALflt(i,j) = 0
                endif
              endif
            endif
          endif
        endif
      endif
*
      return
      end
*
*********************************************************
*
*********************************************************
*********************************************************
*
      subroutine screencolor
*
      logical BW
      common /screen/ BW
      INTEGER wkid
      common /sun/ wkid
*
      if (BW) then
        call gscr (wkid,0,1.0,1.0,1.0)
        call gscr (wkid,1,0.99,0.99,0.99)
        call gscr (wkid,2,0.85,0.85,0.85)
        call gscr (wkid,3,0.65,0.65,0.65)
        call gscr (wkid,4,0.45,0.45,0.45)
        call gscr (wkid,5,0.1,0.1,0.1)
        call gscr (wkid,6,0.0,0.0,0.0)
        call gscr (wkid,7,0.0,0.0,0.0)
        call gscr (wkid,8,0.0,0.0,0.0)
        call gscr (wkid,9,0.0,0.0,0.0)
        call gscr (wkid,10,0.05,0.05,0.05)
        call gscr (wkid,11,0.4,0.4,0.4)
        call gscr (wkid,12,0.66,0.66,0.66)
        call gscr (wkid,13,1.0,1.0,1.0)
        call gscr (wkid,14,0.92,0.92,0.92)
        call gscr (wkid,15,0.995,0.995,0.995)
      else
*      **{color}**
*       {black}
       call gscr (wkid,0,0.0,0.0,0.0)
*        {blue}
       call gscr (wkid,1,0.0,0.0,1.0)
*        {light blue}
       call gscr (wkid,2,0.65,0.7,1.0)
*        {purple}
       call gscr (wkid,3,0.75,0.0,0.85)
```

```
*         {pink}
         call gscr (wkid,4,1.0,0.7,0.9)
*         {dark red}
         call gscr (wkid,5,0.8,0.0,0.1)
*         {white}
         call gscr (wkid,6,1.0,1.0,1.0)
*         {red}
         call gscr (wkid,7,1.0,0.0,0.0)
*         {yellow}
         call gscr (wkid,8,1.0,1.0,0.0)
*         {off white}  (for faults in bkgnd)
         call gscr (wkid,9,0.7,0.7,0.7)
*         {soil red}
         call gscr (wkid,10,0.8,0.0,0.0)
*         {orange}
         call gscr (wkid,11,1.0,0.7,0.0)
*         {light yellow}
         call gscr (wkid,12,1.0,1.0,0.2)
*         {very light blue}
         call gscr (wkid,13,0.8,0.85,1.0)
*         {green}
         call gscr (wkid,14,0.0,0.85,0.1)
*         {dark blue}
         call gscr (wkid,15,0.0,0.08,0.9)
      endif
*
      return
      end
*
**********************************************************
*
      subroutine plothaz
*
*  this subroutine plots a cell array (the seismic hazard)
*
      INTEGER wkid, CALflt(1000,1000)
      common /sun/ wkid
      common /global/ CALflt
      logical checkshift
      common /check/ checkshift
      integer xmax, ymax, cellat, cellong, cellpoints
      common /cellscale/ xmax, ymax, cellat, cellong, cellpoints
      real xscale, yscale, northB, southB, westB, eastB
      common /coord/ xscale, yscale, northB, southB, westB, eastB
      real xcenter, ycenter, xshift, yshift
      common /centerline/ xcenter, ycenter, xshift, yshift
      integer dimx, dimy, ncs, nrs, dx,dy
      integer tranum
      real px, py, qx, qy, cellxscale, cellyscale
      data dimx, dimy /1000,1000/
      data tranum /1/
*
*
      cellxscale = xscale * (cellpoints/10)
      cellyscale = yscale * (cellpoints/10)
*
      call gswn (tranum,0.0,cellxscale,0.0,cellyscale)
```

```
      call gselnt (tranum)
*
      ncs = 1
      nrs = 1
      px = xshift * 10.
      py = yshift * 10.
      dx = xmax
      dy = ymax
      qx = px + dx
      qy = py + dy
*
      if (checkshift) calflt(cellong,cellat) = 8
      call gca(px,py,qx,qy,dimx,dimy,ncs,nrs,dx,dy,CALflt)
*
      return
      end
*
*****************************************************************
*
      subroutine hazlabel
*
      character*10 accdim, veldim
      character*20 title
      dimension title(6)
      character*12 explain
      dimension explain(36)
      integer tranum, plot
      common /pltype/ plot
      real xoffset, yoffset, Txoffset, Tyoffset
      common /movexy/ xoffset, yoffset, Txoffset, Tyoffset
      real x1, x2, x3, x4, x5, y1, y2
      real x,y, xl(2), yl(2)
      data tranum /1/
* **{underline}**
      data y1, y2 /-0.4,-0.4/
      data x1, x2, x3, x4, x5, x6 /7.0,5.5,8.0,10.5,10.0,7.3/
* **{plot1}**
      data title(1) /'NUMBER'/
      data explain(1) /'   0'/, explain(2) /' 1 - 4'/
      data explain(3) /' 5 - 8'/, explain(4) /' 9 - 12'/
      data explain(5) /'13 - 16'/, explain(6) /'  > 16'/
* **{plot2}**
      data title(2) /'YEARS'/
      data explain(7) /' >1000'/, explain(8) /'500 - 1000'/
      data explain(9) /'250 -  499'/, explain(10) /'100 -  249'/
      data explain(11) /' 50 -  99'/, explain(12) /'   < 50'/
* **{plot3}**
      data title(3) /'PROBABILITY'/
      data explain(13) /'  < 0.01'/, explain(14) /'0.01 - 0.19'/
      data explain(15) /'0.2  - 0.39'/, explain(16) /'0.4  - 0.59'/
      data explain(17) /'0.6  - 0.79'/, explain(18) /'0.8  - 1.0'/
* **{plot4}**
      data title(4) /'ACCELERATION'/
      data explain(19) /'  < 0.05'/, explain(20) /'0.05 - 0.09'/
      data explain(21) /'0.10 - 0.19'/, explain(22) /'0.20 - 0.29'/
      data explain(23) /'0.30 - 0.49'/, explain(24) /'  > 0.50'/
* **{plot5}**
```

```
      data title(5) /'VELOCITY'/
      data explain(25) /'  < 6'/, explain(26) /' 6 - 19'/
      data explain(27) /'20 - 39'/, explain(28) /'40 - 59'/
      data explain(29) /'60 - 79'/, explain(30) /'  > 80'/
* **{plot6}**
      data title(6) /'GEOLOGIC UNIT'/
      data explain(31) /' Qm'/, explain(32) /' Qal'/
      data explain(33) /' QTs'/, explain(34) /' TMzs'/
      data explain(35) /' KJf'/, explain(36) /' Kg'/
* **{dimensions}**
      data accdim, veldim /'(g)','(cm/s)'/
*
*
      call gswn (tranum,0.0,40.0,0.0,31.945)
      call gselnt (tranum)
* **{plot5}**
      call gstxfp(-7,2)
      call gstxci(6)
*
* **{write explaination}**
      call gschh(0.6)
      x = xoffset + 2.3
      y = yoffset - 0.6
      yl(1) = y1 + yoffset
      yl(2) = y2 + yoffset
      if (plot .EQ. 1) then
      j=1
      xl(2) = x1
      else
        if (plot .EQ. 2) then
          j=7
          xl(2) = x2 + xoffset
        else
          if (plot .EQ. 3) then
            j=13
            xl(2) = x3 + xoffset
          else
            if (plot .EQ. 4) then
              j=19
              xl(2) = x4 + xoffset
            else
              if (plot .EQ. 5) then
                j=25
                xl(2) = x5 + xoffset
              else
                j=31
                xl(2) = x6 + xoffset
              endif
            endif
          endif
        endif
      endif
      do 20, i=1,6
      y = y - 1.5
      call gtx (x,y,explain(j))
      j = j + 1
   20 continue
```

```
*
* **{write title}**
      if (plot .GT. 2) then
        call gschh(0.8)
        if (plot .EQ. 6) call gschh(0.6)
        x = xoffset + 0.1
        xl(1) = x
      else
        call gschh(1.0)
        x = xoffset + 0.5
        xl(1) = x
      endif
      y = yoffset
      call gtx (x,y,title(plot))
*
* **{write dimensions}**
      if (plot .GT. 3) then
        call gschh(0.6)
        if (plot .EQ. 4) then
          x = xoffset + 9.4
          call gtx(x,y,accdim)
        endif
        if (plot .EQ. 5) then
          x = xoffset + 6.5
          call gtx(x,y,veldim)
        endif
      endif
* **{underline}**
      call gpl (2,xl,yl)
*
      return
      end
*
***************************************************************
*
      subroutine hazcode
*
      integer plot
      common /pltype/ plot
      real xoffset, yoffset, Txoffset, Tyoffset
      common /movexy/ xoffset, yoffset, Txoffset, Tyoffset
      real px(4), py(4), X(5), Y(5)
      integer tranum, color
      data tranum /1/
*
*
      call gswn (tranum,0.0,40.0,0.0,31.945)
      call gselnt (tranum)
*
      call gsfais(1)
      if (plot.LT.6) then
        color = 5
      else
        color = 15
      endif
      px(1) = xoffset + 0.5
      px(2) = px(1)
```

```
      px(3) = xoffset + 2.0
      px(4) = px(3)
*
      py(1) = yoffset - 11.5
      py(2) = yoffset - 10.0
      py(3) = py(2)
      py(4) = py(1)
      do 20, i=1,6
        do 10, j=1,4
          py(j) = py(j) + 1.5
   10   continue
        call gsfaci(color)
        call gfa (4,px,py)
        color = color - 1
   20 continue
*
      call gsplci(6)
      py(1) = yoffset - 11.5
      py(2) = yoffset - 10.0
      py(3) = py(2)
      py(4) = py(1)
      do 40, i=1,6
        do 30, j=1,4
          py(j) = py(j) + 1.5
          X(j) = px(j)
          Y(j) = py(j)
   30   continue
        X(5) = px(1)
        Y(5) = py(1)
        call gpl (5,X,Y)
   40 continue
*
      return
      end
*
********************************************************
*
      subroutine faultcode
*
      integer tranum, color
      real px, py
      dimension px(4), py(4)
      data tranum /1/
      data px(1), px(2) /16.0,26.0/
*
*
      call gswn (tranum,0.0,150.0,0.0,119.8)
      call gselnt (tranum)
*
      py(1) = 10.0
      py(2) = 10.0
      color = 5
      do 20, i=1,3
        do 10, j=1,2
          py(j) = py(j) + 5.0
   10   continue
        color = color + 1
```

```
        call gsplci(color)
        call gpl (2,px,py)
   20 continue
*
      return
      end
*
***************************************************************
*
      subroutine faultlabel
*
      character*20 title
      character*20 explain
      dimension explain(3)
      integer tranum
      real x, y, xl, yl
      dimension xl(2), yl(2)
      data tranum /1/
      data xl(1), xl(2), yl(1), yl(2) /2.0,5.,3.3,3.3/
      data title /' FAULTS'/
      data explain(1) /'Quaternary Rate'/
      data explain(2) /'Plio-Miocene Rate'/
      data explain(3) /'No Rate'/
*
*
      call gswn (tranum,0.0,15.0,0.0,11.98)
      call gselnt (tranum)
*
      call gstxfp(-7,2)
      call gstxci(6)
      call gschh(.2)
      x = 3.
      y = 3.0
      do 20, i=1,3
      y = y - .55
      call gtx (x,y,explain(i))
   20 continue
      call gschh(.4)
      x = 2.0
      y = 3.5
      call gtx (x,y,title)
      call gsplci(6)
      call gpl (2,xl,yl)
*
      return
      end
*
****************************************************************
****************************************************************
*
      subroutine faultseg(numfile,segcolor)
*
*   this program reads steve's california fault input
*   file and plots all the faults.
*
*
      character*1 skip, age
```

```
      logical hazplot, bold
      common /fltplt/ hazplot, bold
      integer  segcolor, numfile
      INTEGER wkid
      common /sun/ wkid
      real xscale, yscale, northB, southB, westB, eastB
      common /coord/ xscale, yscale, northB, southB, westB, eastB
      real xcenter, ycenter, xshift, yshift
      common /centerline/ xcenter, ycenter, xshift, yshift
      INTEGER dlat, dlong, sdlat, sdlong, numseg, endtst, color
      real mlat, mlong, smlat, smlong, lat, long
      DIMENSION dlat(100), mlat(100), dlong(100), mlong(100)
      DIMENSION lat(100), long(100)
      integer tranum, numseg
      data tranum /1/
*
*
      call gswn (tranum,0.0,xscale,0.0,yscale)
      call gselnt (tranum)
*
*
      xtotalshift =  xshift + xcenter
      ytotalshift =  yshift + ycenter
*
   40 read(numfile,*,end=90) skip
      read(numfile,100) numseg
      numpoints = numseg + 1
      if (numseg .EQ. 1) then
*     **{read single segment fault}**
        read(numfile,101) dlat(1), mlat(1), dlong(1), mlong(1),
     +              dlat(2), mlat(2), dlong(2), mlong(2), age
   50   read(numfile,102) endtst
        if (endtst .NE. -1) goto 50
      else
*     **{read multisegment fault}**
        read(numfile,101) dlat(1), mlat(1), dlong(1), mlong(1),
     +              sdlat, smlat, sdlong, smlong, age
        do 60, i=2,numpoints
        read(numfile,101) sdlat, smlat, sdlong, smlong,
     +                dlat(i), mlat(i), dlong(i), mlong(i), skip
   60   continue
   70   read(numfile,102) endtst
        if (endtst .NE. -1) goto 70
      endif
*
      do 80, i=1,numpoints
        lat(i) = dlat(i) + (mlat(i)/60.0)
        lat(i) = (10.0 * (lat(i) - southB)) + ytotalshift
        long(i) = dlong(i) + (mlong(i)/60.0)
        long(i) = (10.0 * (westB - long(i))) + xtotalshift
   80 continue
      if ( (age .EQ. 'h') .OR. (age .EQ. 'q') ) then
        color = 8
      else
        if ( (age .EQ. 'p') .OR. (age .EQ. 'm') ) then
          color = 7
        else
```

```
*       **{no rate}**
          color = 6
        endif
      endif
*
      if (hazplot) color = segcolor
      if (bold) then
        call gslwsc(3.0)
        color = segcolor
      endif
      call gsplci(color)
      call gpl(numpoints,long,lat)
*
      goto 40
   90 continue
*
  100 format(I5)
  101 format(4x,I2,F5.1,I4,F5.1,I4,F5.1,I4,F5.1,36x,A1)
  102 format(I6)
*
      return
      end
*
************************************************************************
*
*
      subroutine statebound
*
*   this subroutine plots the state boundary, coastline,
*   and lakes from the COMMON array temp.
*
      logical segflag
      INTEGER wkid, numtemp
      common /sun/ wkid
      real temp
      DIMENSION CALflt(1000,1000), temp(10000)
      common /global/ CALflt
      common /plotline/ numtemp, temp
      real xscale, yscale, northB, southB, westB, eastB
      common /coord/ xscale, yscale, northB, southB, westB, eastB
      real xcenter, ycenter, xshift, yshift
      common /centerline/ xcenter, ycenter, xshift, yshift
      real X, Y
      DIMENSION X(2000), Y(2000)
      integer tranum, numseg
      data tranum /1/
*
*
      call gswn (tranum,0.0,xscale,0.0,yscale)
      call gselnt (tranum)
*
*
      xtotalshift = xshift + xcenter
      ytotalshift = yshift + ycenter
*
      call gsplci(6)
      call gslwsc(1.0)
```

```
      j = 1
      segflag = .false.
      do 10, i=1,numtemp,2
       if (temp(i) .GT. 90.0) then
         numseg = j - 1
         if (segflag) call gpl(numseg,X,Y)
         j = 1
         segflag = .false.
       else
*       **  valid lat, long pair  **
         X(j) = (10 * (westB - temp(i+1))) + xtotalshift
         Y(j) = (10 * (temp(i) - southB))+ ytotalshift
         j = j + 1
         segflag = .true.
       endif
   10 continue
      return
      end
*
************************************************************************
************************************************************************
      subroutine frame
*
*   this subroutine puts a frame around the plot
*       subroutines:  blackout
*
      logical crop
      common /testframe/ crop
      logical checkshift
      common /check/ checkshift
      INTEGER wkid
      common /sun/ wkid
      real tempnorthB, tempsouthB, tempwestB, tempeastB
      common /cropB/ tempnorthB, tempsouthB, tempwestB, tempeastB
      real xscale, yscale, northB, southB, westB, eastB
      common /coord/ xscale, yscale, northB, southB, westB, eastB
      real horizshift, vertshift
      real xcenter, ycenter, xshift, yshift
      common /centerline/ xcenter, ycenter, xshift, yshift
      REAL latBx(2), longBx(2), latLy(2), longLy(2)
      REAL latTx(2), longTx(2), latRy(2), longRy(2)
      real xtotalshift, ytotalshift
      integer tranum, numpoints, color
      data tranum, numpoints,color /1,2,6/
*
*
      call gswn (tranum,0.0,xscale,0.0,yscale)
      call gselnt (tranum)
*
      vertshift = 0.0
      horizshift = 0.0
      if (crop) then
      vertshift = 10.0 * (tempsouthB - southB)
      horizshift = 10.0 * (tempwestB - westB)
      westB = tempwestB
      eastB = tempeastB
      northB = tempnorthB
```

```
      southB = tempsouthB
      endif
      xtotalshift =  xshift + xcenter + horizshift
      ytotalshift =  yshift + ycenter + vertshift
*
      latBx(1) =  ytotalshift
      latBx(2) =  ytotalshift
      longBx(1) = xtotalshift
      longBx(2) = (10.0 * (westB - eastB))  + xtotalshift
*
      latLy(1) =  ytotalshift
      latLy(2) = (10.0 * (northB - southB)) + ytotalshift
      longLy(1) = xtotalshift
      longLy(2) = xtotalshift
*
      latTx(1) = (10.0 * (northB - southB)) + ytotalshift
      latTx(2) = (10.0 * (northB - southB)) + ytotalshift
      longTx(1) = xtotalshift
      longTx(2) = (10.0 * (westB - eastB))  + xtotalshift
*
      latRy(1) = ytotalshift
      latRy(2) = (10.0 * (northB - southB)) + ytotalshift
      longRy(1) = (10.0 * (westB - eastB))  + xtotalshift
      longRy(2) = (10.0 * (westB - eastB))  + xtotalshift
*
      call blackout(longLy(1),longRy(1),latBx(1),latTx(1))
*
      call gslwsc(3.0)
      call gsplci(color)
      call gpl(numpoints,longBx,latBx)
      call gpl(numpoints,longLy,latLy)
      call gpl(numpoints,longTx,latTx)
      call gpl(numpoints,longRy,latRy)
*
      if (checkshift)
     + call crosshair(longLy(1),longRy(1),latBx(1),latTx(1))
*
      return
      end
*
**********************************************************************
*
      subroutine blackout(leftB,rightB,bottomB,topB)
*
*   this subroutine blacks out areas outside the plot
*   It is a subroutine to frame.
*
      logical hazplot, bold
      common /fltplt/ hazplot, bold
      INTEGER wkid
      common /sun/ wkid
      real xscale, yscale, northB, southB, westB, eastB
      common /coord/ xscale, yscale, northB, southB, westB, eastB
      real leftB, rightB, bottomB, topB
      integer tranum, numpoints
      real edge
      real xl(4), yl(4), xr(4), yr(4)
```

```
      real xb(4), yb(4), xt(4), yt(4)
      data tranum, numpoints /1,4/
      data edge /40.0/
      data xl(1), yl(1), xl(2), yl(4) /0.0,0.0,0.0,0.0/
      data yr(1), yr(4) /0.0,0.0/
      data xt(2) /0.0/
*
*
      call gswn (tranum,0.0,xscale,0.0,yscale)
      call gselnt (tranum)
*
      yl(2) = topB
      xl(3) = leftB
      yl(3) = topB
      xl(4) = leftB
*
      xr(1) = rightB
      xr(2) = rightB
      yr(2) = topB
      xr(3) = rightB + edge
      yr(3) = topB
      xr(4) = rightB + edge
*
      xb(1) = xl(4)
      yb(1)= yl(4)
      xb(2) = leftB
      yb(2) = bottomB
      xb(3) = rightB
      yb(3) = bottomB
      xb(4) = xr(1)
      yb(4) = yr(1)
*
      xt(1) = xl(2)
      yt(1) = yl(2)
      yt(2) = topB + edge
      xt(3) = rightB + edge
      yt(3) = topB + edge
      xt(4) = rightB + edge
      yt(4) = topB
*
*    **{set blackout parameters}**
      call gsfais(1)
      call gsfaci(0)
*
*    **{plot black boxes outside frame}**
      call gfa (numpoints,xl,yl)
      call gfa (numpoints,xr,yr)
      call gfa (numpoints,xb,yb)
      call gfa (numpoints,xt,yt)
*
*
      return
      end
*
************************************************************************
*
      subroutine prtitle(plotitle)
```

```
*
*   this subroutine blacks out areas outside the plot
*   It is a subroutine to frame.
*
      character*20 plotitle
      integer tranum, color
      real xoffset, yoffset, Txoffset, Tyoffset
      common /movexy/ xoffset, yoffset, Txoffset, Tyoffset
      data tranum, color /1,6/
*
      call gswn (tranum,0.0,40.0,0.0,31.945)
      call gselnt (tranum)
*
      call gsplci(color)
      call gschh(1.0)
      call gtx (Txoffset,Tyoffset,plotitle)
*
      return
      end
*
*********************************************************************
*
      subroutine crosshair(leftB,rightB,bottomB,topB)
*
      INTEGER wkid
      common /sun/ wkid
      real xscale, yscale, northB, southB, westB, eastB
      common /coord/ xscale, yscale, northB, southB, westB, eastB
      real xcenter, ycenter, xshift, yshift
      common /centerline/ xcenter, ycenter, xshift, yshift
      integer xmax, ymax, cellat, cellong, cellpoints
      common /cellscale/ xmax, ymax, cellat, cellong, cellpoints
      real lathair, longhair, hairxcoord, hairycoord
      common /haircoord/ lathair, longhair
      real testyh(2), testxh(2), testyv(2), testxv(2)
      real xtotalshift, ytotalshift
      integer tranum, numpoints, color
      data tranum, numpoints, color /1,2,14/
*
*
      call gswn (tranum,0.0,xscale,0.0,yscale)
      call gselnt (tranum)
*
      xtotalshift = xshift + xcenter
      ytotalshift = yshift + ycenter
      hairxcoord = WestB - longhair
      hairycoord = lathair - southB
*
      testyh(1) = (10.0 * hairycoord) + ytotalshift
      testyh(2) = (10.0 * hairycoord) + ytotalshift
      testxh(1) = leftB
      testxh(2) = rightB
*
      testyv(1) = bottomB
      testyv(2) = topB
      testxv(1) = (10.0 * hairxcoord) + xtotalshift
      testxv(2) = (10.0 * hairxcoord) + xtotalshift
```

```
*
      call gslwsc(2.0)
      call gsplci(color)
      call gpl(numpoints,testxh,testyh)
      call gpl(numpoints,testxv,testyv)
*
      return
      end
*
**********************************************************************
**********************************************************************
*
      subroutine prtarray
*
*    this subroutine prints the color array in 5 files -
*    color1.b, color2.b, color3.b, color4.b, color5.b.
*    these can be cut and pasted to form large hard copy
*    array in matrix form.
*
      INTEGER CALflt(1000,1000)
      common /global/ CALflt
*
*   ****{read and format data}****
*
      OPEN (unit=1, file='color1.b', err=20, status='unknown',
     +       access='sequential', form='formatted')
*
      OPEN (unit=2, file='color2.b', err=20, status='unknown',
     +       access='sequential', form='formatted')
*
      OPEN (unit=3, file='color3.b', err=20, status='unknown',
     +       access='sequential', form='formatted')
*
      OPEN (unit=4, file='color4.b', err=20, status='unknown',
     +       access='sequential', form='formatted')
*
      OPEN (unit=5, file='color5.b', err=20, status='unknown',
     +       access='sequential', form='formatted')
*
      do 10, i=1,101
          write(1,100) (CALflt(m,i), m=31,55)
          write(2,100) (CALflt(m,i), m=56,80)
          write(3,100) (CALflt(m,i), m=81,105)
          write(4,100) (CALflt(m,i), m=106,130)
          write(5,100) (CALflt(m,i), m=131,141)
   10 continue
  100 format(1x,25I3)
*
      close(1)
      close(2)
      close(3)
      close(4)
      close(5)
      return
   20 write(*,*) 'error in open statement'
      close(1)
      close(2)
```

```
      close(3)
      close(4)
      close(5)
      return
      end
*
*
************************************************************************
```

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