Appendix A

Seismic Sources

A.1 CHARACTERIZATION OF POTENTIAL SEISMIC SOURCES

Two types of earthquake sources are characterized in this seismic hazard analysis: (1) fault sources; and (2) areal source zones. Fault sources are modeled as three-dimensional fault surfaces and details of their behavior are incorporated into the source characterization (Section A.2). Areal source zones are regions where earthquakes are assumed to occur randomly (Section A.3). Figures 1 and 2 is the fault map showing the significant and contributing sources used in the In-Delta Storage seismic hazard analysis. Seismic sources are modeled in the hazard analysis in terms of geometry and earthquake recurrence. A source characterization model is presented in Figure 3.

The geometric source parameters for faults include fault location, segmentation model, dip, and thickness of the seismogenic zone. The recurrence parameters include recurrence model, recurrence rate (slip rate or average recurrence interval for the maximum event), slope of the recurrence curve (*b*-value), and maximum magnitude. Clearly the geometry and recurrence are not totally independent. For example, if a fault is modeled with several small segments instead of large segments, the maximum magnitude is lower, and a given slip rate requires many more small earthquakes to accommodate a cumulative seismic moment. For areal source zones, only the areas, maximum magnitude, and recurrence parameters (based on the historical earthquake record) need to be defined.

Uncertainties in the source parameters are included in the hazard model using logic trees. In the logic tree approach, discrete values of the source input parameters have been included along with our estimate of the likelihood that the discrete value represents the actual value. In this probabilistic analysis, generally all input parameters have been represented by three values (Figure 3); the values represent a distribution about the best estimate.

A.1.1 Source Geometry

In the probabilistic analysis, it is assumed that earthquakes of a certain magnitude may occur randomly along the length of a given fault or segment. The distance from an earthquake to the site is dependent on the source geometry, the size and shape of the rupture on the fault plane, and the likelihood of the earthquake occurring at different points along the fault length. The distance to the fault is defined to be consistent with the specific attenuation relationship used to calculate the ground motions. The distance, therefore, is dependent on both the dip and depth of the fault plane, and a separate distance function is calculated for each geometry and each attenuation relationship. The size and shape of the rupture on the fault plane are dependent on the magnitude of the earthquake, with larger events rupturing longer and wider portions of the fault plane.

A.1.2 Probability of Activity

Fault activity is expressed in terms of probability of activity [P(a)]. A fault with a P(a) of 1.0 is definitely active, whereas a fault with a P(a) of 0.0 is completely inactive. Faults that clearly offset or deform Holocene strata are considered to be active and have a P(a) of 1.0. Faults that deform or offset Late Pleistocene strata are considered to be potentially active and have a P(a) of 0.75. As much of the upland regions of the San Francisco Bay region is undergoing contractional reactivation, it is possible that an active fault may not rupture to the Earth's surface, therefore it may not offset Holocene strata. To account for activity on such 'blind' structures, faults which are favorably oriented for reactivation in the current stress regime that have been active during the Pleistocene but do not appear to have been active during the Holocene are assigned a P(a) of 0.5 to 0.75. The Western East Bay Hills thrust fault zone is an example of this type of faulting.

A.1.3 Maximum Magnitudes

Consistent with current state-of-the-practice, we estimate the maximum magnitudes based on empirical relations between expected rupture dimensions (i.e., fault rupture length and rupture area) and magnitude. Estimates of maximum earthquakes from empirical data such as rupture length and rupture area are limited by uncertainties in the empirical data, range of variation of rupture parameters during different events, and uncertainties in the assessment of rupture parameters for the fault under investigation. Therefore, the final assessment of maximum magnitude is a judgment that incorporates an understanding of specific fault characteristics, the regional tectonic environment, similarity to other faults in the region, and seismicity data (Schwartz *et al*., 1984).

The most common approach to estimating maximum magnitude is through a comparison of fault rupture length and magnitude. However, considerable uncertainty often exists in the selection of the appropriate rupture length to be used in the analysis (Schwartz *et al*., 1984). Rupture lengths of past surface-rupture events on a specific fault may provide direct evidence. Where there is evidence for a change in fault behavior or there is a significant change in fault geometry, we have divided the faults into rupture segments.

The empirical relationships for surface rupture length and rupture area used in this maximum magnitude assessment are those developed by Wells and Coppersmith (1994), Working Group on California Earthquake Probabilities (WGCEP; 1999), Somerville *et al.* (1999), Stirling *et al.* (2002), and Hanks and Bakun (2002). In general, the correlation coefficients for the regressions indicate very strong correlation and the standard deviations are approximately 0.30 magnitude unit (Wells and Coppersmith, 1994). The maximum magnitude for each active or potentially active faults in the study region and rupture length are listed in Table 1.

In the probabilistic seismic hazard analysis, the geometry of the seismic sources and recurrence need to be defined. As in some cases, because the fault geometries are not well-constrained, a number of fault rupture scenarios have been considered for each fault (typically three fault dips and three depths for the seismogenic crust, giving rise to nine possible rupture areas). For the majority of faults in the region, the dip is constrained by seismic reflection data and the focal mechanisms of instrumentally-recorded earthquakes.

A.1.4 Fault Recurrence Models

The recurrence relationships for the faults are modeled using the exponentially truncated Gutenberg-Richter, characteristic earthquake, and the maximum magnitude recurrence models. These models are weighted to represent our judgment on their applicability to the sources. For the areal source zones, only an exponential recurrence relationship is assumed appropriate.

We have used the general approach of Molnar (1979) and Anderson (1979) to arrive at the recurrence for the exponentially truncated model. The number of events exceeding a given magnitude, *N(m)*, for the truncated exponential relationship is

$$N(m) = a\,(m^o)\,\frac{10^{-b(m-m^o)} - 10^{-b(m^u-m^o)}}{1 - 10^{-b(m^u-m^o)}} \tag{4}$$

where $a(m^o)$ is the annual frequency of occurrence of earthquake greater than the minimum magnitude, m^o; b is the Gutenberg-Richter parameter defining the slope of the recurrence curve; and m^u is the upper-bound magnitude event that can occur on the source. A m^o of moment magnitude (**M**) 5 was used for the hazard calculations because smaller events are not considered likely to produce ground motions with sufficient energy to damage well designed structures.

The model that the faults rupture with a "characteristic" magnitude on specific segments has been included. This model is described by Aki (1983) and Schwartz and Coppersmith (1984). We have used the numerical model of Youngs and Coppersmith (1985) for the characteristic model. For the characteristic model, the number of events exceeding a given magnitude is the sum of the characteristic events and the non-characteristic events. The characteristic events are distributed uniformly over ± 0.3 magnitude unit around the characteristic magnitude and the remainder of the moment rate is distributed exponentially using the above equation with a maximum magnitude one unit lower than the characteristic magnitude (Youngs and Coppersmith, 1985).

The maximum magnitude model can be regarded as an extreme version of the characteristic model. We adopted the model proposed by Wesnousky (1986). In the maximum magnitude model, there is no exponential portion of the recurrence curve, i.e., no events can occur between the minimum magnitude of **M** 5.0 and the distribution about the maximum magnitude.

The recurrence rates for the fault sources are defined by either the slip rate or the average return time for the maximum or characteristic event and the recurrence *b*-value. The slip rate is used to calculate the moment rate on the fault using the following equation defining the seismic moment:

$$M_o = \mu\, A\, D \tag{5}$$

where M_o is the seismic moment, μ is the shear modulus, A is the area of the rupture plane, and D is the slip on the plane. Dividing both sides of the equation by time results in the moment rate as a function of slip rate:

$$\dot{M}_o = \mu\, A\, S \tag{6}$$

where $\dot{M}_o$ is the moment rate and S is the slip rate. M_o has been related to **M**, by Hanks and Kanamori (1979):

$$\mathbf{M} = 2/3 \log M_o - 10.7 \tag{7}$$

Using this relationship and the relative frequency of different magnitude events from the recurrence model, the slip rate can be used to estimate the absolute frequency of different magnitude events.

The average return time for the characteristic or maximum magnitude event defines the high magnitude (low likelihood) end of the recurrence curve. When combined with the relative frequency of different magnitude events from the recurrence model, the recurrence curve is established.

Based on our review of published and unpublished data, and on regional geological and seismological studies, the active and potentially active seismogenic faults listed on Table 1 are considered to be seismic sources significant to the potential In-Delta Storage sites in terms of strong ground shaking. For the purpose of investigating crustal fault activity, the site region encompasses an area within a radius of about 100 km of these sites. Beyond this distance, the potential contribution of crustal faults to ground motions at the site becomes negligible.

A.1.5 Fault Recurrence Rates

A lack of reliable paleoseismic data means that the recurrence rates for many of the faults within the Bay area are either poorly understood or unknown. Fault activity is therefore expressed as an average annual slip rate (in mm/yr) rather than as an interseismic period. Slip rate is calculated by dividing the amount of offset, approximated from the displacement of geomorphic features or erosion surfaces of geologic units, by the inferred age of these features or units. Since the amount of offset during individual events is not known, slip rates cannot be converted into return periods for faulting events. The uncertainty in the slip rates and the other input parameters are accommodated in the probabilistic hazard through the use of logic trees.

A.2 SIGNIFICANT SEISMIC SOURCES IN THE SAN FRANCISCO BAY REGION

Based on our review, active crustal faults or fault zones in the site region have been identified and characterized (Table 1; Figures 1 and 2). The structures include late Quaternary faults in the vicinity of the Delta as well as more distant faults capable of producing large magnitude earthquakes and significant ground shaking. These faults are described as “active” or “potentially active” as defined below. Only faults displaying late Quaternary movement are described in this section.

A fault is considered to be “active” and is considered to be a potential source of future earthquakes if there is compelling evidence for repeated displacement during the Holocene (last 10,000 years), and/or if historical seismicity has been associated with the structure. A fault is considered “potentially active” and is considered a potential source of future earthquakes if there is compelling evidence for displacement during the late Pleistocene and the age of the most recent event is unknown, or if it is likely that seismicity is associated with the fault.

Within the immediate Delta area, a number of potentially active faults have been identified. The characteristics of each fault system are described in more detail in the following sections. Each seismic source has been characterized using the latest geologic, geophysical, and paleoseismic data (both published and unpublished) and the currently accepted models of fault behavior developed by various U.S. Geological Survey Working Groups (WGCEP, 1999; Working Group on Northern California Earthquake Potential, 1996).

A.2.1 San Gregorio Fault Zone

This northwest-striking fault is the principal active fault west of the San Andreas fault in the coastal region of central California. The fault extends from just offshore of Point Sur, northward to Bolinas Lagoon, where it merges with the North Coast segment of the San Andreas. The majority of the fault is located offshore, with only two short sections, at Seal Cove and Moss Beach, occurring on land. Because of the limited onshore extent of the fault, the fault is relatively poorly understood. Jennings (1994) shows the fault as two distinct segments, separated by a prominent step in Monterey Bay. Simpson *et al.* (1997) carried out one of the few paleoseismic investigations along the fault. They demonstrated late Holocene right-lateral movement on the Seal Cove section of the fault. The most recent surface faulting event on the fault occurred sometime after A.D. 1270 to A.D. 1400, but prior to 1775. A penultimate event occurred between A.D. 680 and A.D. 1400 (Simpson *et al.*, 1997).

Based on geological and paleoseismic data, the San Gregorio fault is divided into two segments: a northern segment extending from Bolinas Lagoon to Monterey Bay and a southern segment from Monterey Bay to just north of Point Sur. The fault is modeled as either unsegmented, where the entire fault ruptures, generating an earthquake of **M** 7.6, or segmented, where the northern and southern segments rupture independently, generating earthquakes of **M** 7.4 and 7.2, respectively. We also consider a **M** 6.9 'floating' earthquake which can rupture any part of the fault. The northern segment of the San Gregorio fault is located approximately 100 km west of the Delta. Estimates of slip along the San Gregorio fault are highly variable. We adopted a preferred slip rate of 7 mm/yr for the unsegmented and northern segment models, with lower and upper bound estimates of 4 mm/yr and 10mm/yr, respectively. The slip rate for the southern segment is 6 mm/yr (± 4 mm/yr).

A.2.2 San Andreas Fault Zone

The dominant active fault structure in this region is the San Andreas fault. The fault extends from the Gulf of California, Mexico, to Point Delgada on the Mendocino Coast in northern California, a total distance of 1,200 km. The San Andreas fault accommodates the majority of the motion between the Pacific and North American plates. This fault is the largest active fault in California and is responsible for the largest known earthquake in Northern California, the 1906 **M** 7.9 San Francisco earthquake (Wallace 1990). Movement on the San Andreas fault is right-lateral strike-slip, with a total offset of some 560 km (Irwin 1990). In northern California, the San Andreas fault is clearly delineated, striking northwest, approximately parallel to the vector of plate motion between the Pacific and North American plates. Over most of its length, the San Andreas fault is a relatively simple, linear fault trace. Immediately south of the Bay, however, the fault splits into a number of branch faults or splays, including the Calaveras and Hayward faults (each is discussed below). In the Bay Area, the main trace of the San Andreas fault forms a linear depression along the Peninsula, occupied by the Crystal Springs and San Andreas Lake reservoirs. Geomorphic evidence for Holocene faulting includes fault scarps in Holocene deposits, right-laterally offset streams, shutter ridges, and closed linear depressions (Wallace, 1990). The 1906 earthquake resulted from rupture of the fault from San Juan Bautista north to Point Delgada, a distance of approximately 475 km. The average amount of slip on the fault during this earthquake was 5.1 m in the area to the north of the Golden Gate and 2.5 m in the Santa Cruz Mountains (Working Group on Northern California Earthquake Potential [WGNCEP], 1996).

Based on differences in geomorphic expression, fault geometry, paleoseismic chronology, slip rate, seismicity, and historic fault ruptures, the San Andreas fault is divided into a number of fault segments. Each of these segments is capable of rupturing either independently or in conjunction with adjacent segments. In the Bay Area, these segments include the Santa Cruz Mountains, the Peninsula, and the North Coast segments. These fault segments have calculated maximum earthquakes of **M** 7.2, 7.3, and 7.7, respectively. The North Coast segment may also be subdivided into two shorter segments with a boundary at Point Arena. These northern and southern North Coast segments are capable of generating earthquakes of **M** 7.5 and 7.7, respectively. The North Coast segment, or an adjacent fault branch, was the source of the August 18, 1999 **M** 5.0 earthquake located near Bolinas.

South of the Golden Gate, the fault slip rate is 17 - 3/+ 7 mm/yr (Hall *et al.*, 1999). North of the Golden Gate, the slip rate increases to 24 ± 5 mm/yr (Niemi and Hall, 1992). The Working Group on California Earthquake Probabilities (1999) assigns a recurrence interval of 361 years to a **M** 8.0 1906-type event on the San Andreas fault, with a 21 percent probability of a **M** 6.7 or larger earthquake on the San Andreas in northern California in the time period 2000 to 2030. Recent investigations by Niemi *et al.* (2002) indicate that the repeat time for large earthquakes on the North Coast segment may be less than 250 years.

A.2.3 Foothill Thrust Belt

The southwestern margin of the Santa Clara Valley is bounded by the rugged, young southern Santa Cruz Mountains. Late Cenozoic uplift of the mountains has occurred, in part, along a series of northwest-striking reverse faults, known as either the Loma Prieta domain (Aydin and Page, 1984) or Foothills thrust belt (Bürgmann *et al.*, 1994), bordering the northeastern margin of the range front. Bounded by the main trace of the San Andreas fault to the west, this sequence of southwest-dipping thrusts, associated with a restraining left bend in the San Andreas fault, has been responsible for the uplift of the Santa Cruz Mountains (Bürgmann *et al.*, 1994). These faults offset the Pliocene and Pleistocene Santa Clara Formation, and locally offset and deform overlying Quaternary sediments and geomorphic surfaces within the range-front communities of Palo Alto, Los Altos Hills, Cupertino, Saratoga, and Los Gatos, located along the southwestern margin of the Santa Clara Valley (Hitchcock and Kelson 1999; Hitchcock *et al.* 1994). The up-dip projection of the blind Loma Prieta fault, which is interpreted to have been the source of the 1989 **M** 6.9 Loma Prieta earthquake (Bürgmann *et al.*, 1994), coincides with the Foothills thrust belt.

Historical records indicate that a **M** 6.5 earthquake in 1865 may have occurred on a fault east of the San Andreas fault, possibly along the northeastern flank of the Santa Cruz Mountains (Toppozada and Borchardt, 1998; Tuttle and Sykes, 1992a; Tuttle and Sykes, 1992b). Based on the magnitude of aseismic deformation of the northeastern Santa Cruz Mountains following the 1989 Loma Prieta earthquake, it is possible that a large component of the total slip on the Foothills thrust belt occurs aseismically in association with slip on the nearby San Andreas fault (Hitchcock and Kelson 1999). It is also possible that one or more segments of the system may rupture in a single event, producing a moderate- to large-magnitude earthquake (Zoback *et al.*, 1999).

The Berrocal fault is located along the range front between Saratoga and Los Gatos, and extends for 55 km within the range block. Southeast of Los Gatos, the Berrocal fault merges with, or intersects, the Sargent fault. To the northwest, the fault either dies out or merges with the Monte Vista fault. The Berrocal fault is also linked to the San Andreas fault by the north-striking Lexington fault along Los Gatos Creek. Scattered seismicity along and to the southwest of the mapped fault trace may be related to either the Berrocal fault, or a related northeast-vergent blind thrust fault. Significant compressional surface deformation was observed along the Berrocal fault in the Los Gatos and Saratoga areas during the Loma Prieta earthquake (Langenheim *et al.*, 1997).

The 54-km-long Monte Vista fault is one of the primary range-front faults and probably the most extensively studied fault in the Foothills thrust belt. The exposed fault strikes northwest and places Franciscan, Miocene, Santa Clara Formation, and Pleistocene alluvium over Pleistocene and older strata. To the south, the fault merges with the Shannon fault, while at its northern end it intersects the San Andreas, via the Hermit fault, between Woodside and Redwood City. Limited exploratory trenching indicates that the Monte Vista fault has had late Quaternary and possibly Holocene displacement. Recent geomorphic mapping by Hitchcock *et al.* (1994) shows that late Pleistocene fluvial terraces flanking Stevens Creek are deformed. The style of late Quaternary deformation affecting these terrace surfaces is consistent with reverse faulting on the Monte Vista fault. Hitchcock and Kelson (1999) estimated an average late Pleistocene slip rate of 0.17 ± 0.09 mm/yr for the Monte Vista fault.

The Shannon fault, which extends from near Saratoga, south to Coyote Creek near New Almaden, consists of several *en echelon*, southwest-dipping, thrust or reverse fault strands and several subsidiary northeast-dipping normal fault strands. Geomorphic investigations provide evidence of probable late Pleistocene deformation associated with these southwest-dipping, northeast-vergent reverse fault strands (Hitchcock *et al.*, 1994). Trench exposures at the Senator mine west of New Almaden show that the southern segment of the Shannon fault deforms Miocene rock and cuts a paleosol with an estimated age less than 20,000 years (R. McLaughlin, U.S. Geological Survey, *pers. comm*., to C. Hitchcock, WLA, 1993). As with the Berrocal, Sargent, and Monte Vista faults, compressional surface deformation was locally concentrated along the Shannon fault, in the Los Gatos and Campbell areas, during the Loma Prieta earthquake.

The Cascade fault traverses the coalescent alluvial-fan complex underlying the Santa Clara Valley approximately 2 to 6 km northeast of the Santa Cruz Mountains range front. Hitchcock *et al.* (1994) show a strong correlation between the mapped trace of the Cascade fault and fault-related geomorphic features, including vegetation lineaments, closed depressions, linear drainages, stream profile convexities, and high-sinuosity stream reaches. These features are developed in late Pleistocene and possibly Holocene deposits; thus, they provide evidence for late Pleistocene (and possibly Holocene) displacement along the Cascade fault. Between Los Altos Hills and Los Gatos, most of the major streams show longitudinal-profile convexities where they cross the mapped trace of the Cascade fault. In general, the crests of the convexities coincide with the zone of lineaments. These relations indicate late Pleistocene uplift along this section of the Cascade fault (Hitchcock *et al.*, 1994). Although this provides little or no information on the sense of slip and the amount and direction of fault dip, it is likely that the

Cascade fault is a southwest-dipping, northeast-vergent reverse fault similar to, but perhaps having a shallower dip in the near surface than the Monte Vista, Berrocal, and Shannon faults.

The faults of the Foothill thrust belt are considered active and capable of generating large-magnitude earthquakes. The Thrust Fault Subgroup of the WGCEP (1999) considered these faults capable of generating earthquakes of **M** 6.2 to 7. Fault slip rates are considered to be in the range 0.2 to 0.8 mm/yr, with 0.5 mm/yr being the preferred estimate. Estimates for the maximum earthquake within this source zone range from **M** 6¼ to 7.

A.2.4 Sargent fault

The 56-km-long Sargent fault zone is a northwest-striking, northeast-verging, reverse-oblique fault zone that intersects the San Andreas fault to the north near Lake Elsman, and the Calaveras fault to the south beneath the southern Santa Clara Valley near Hollister. The fault exhibits a prominent component of right-lateral slip, as shown by geomorphic offsets and fault plane slickensides exposed near Loma Prieta (Bryant *et al.*, 1981). Prescott and Burford (1976) measured 3 ± 1 mm/yr creep along the southern third of the Sargent fault. Like several of the faults in the Foothills thrust belt, the Sargent fault experienced triggered slip during the 1989 **M** 6.9 Loma Prieta earthquake (Aydin *et al.*, 1992). From a trenching investigation along the southern part of the fault, Nolan *et al.* (1995) calculated a preliminary slip rate of only 0.6 mm/yr, and a recurrence interval of 1,200 years for the southernmost part of the fault; however, these estimates are based on poorly constrained data. Based on its proximity to the San Andreas fault, the WGNCEP (1996) did not consider the northern two-thirds of the Sargent fault to be an independent seismic source. This fault is modeled as a single rupture segment with a slip rate of 3.0 ± 1.5 mm/yr. The maximum magnitude for the Sargent fault is estimated to be **M** 7.1.

A.2.5 Hayward Fault

The Hayward fault extends for 100 km from the area of Mount Misery, east of San Jose, to Point Pinole on San Pablo Bay. At Point Pinole, the Hayward fault runs into San Pablo Bay. The northern continuation of this fault system is the Rodgers Creek fault. The two faults are separated by a 5-km-wide right step beneath San Pablo Bay (the Rodgers Creek fault is discussed below). Systematic right-lateral geomorphic offsets and creep offset of cultural features have been well documented along the entire length of the fault (Lienkaemper, 1992). The last major earthquake on the Hayward fault, in October 1868, occurred along the southern segment of the fault. This **M** 6.8 event caused toppling of buildings in Hayward and other localities within about 5 km of the fault. The surface rupture associated with this earthquake is thought to have extended for approximately 30 km, from Warm Springs to San Leandro, with a maximum reported displacement of 1 m. The Hayward fault is considered the most likely source of the next major earthquake in the Bay Area (WGCEP, 1999). As well as undergoing displacement earthquake ruptures, the Hayward fault also moves by aseismic creep. Measurements along the fault over the last two decades show that the creep rate is 5 to 9 mm/yr (Lienkaemper and Galehouse, 1997).

Recent research of historical documents has led to the conclusion that an earthquake in 1836, previously thought to have occurred on the northern Hayward fault, occurred elsewhere

(Toppozada and Borchardt, 1998), thereby increasing the time since the last earthquake on this segment of the fault. Recent paleoseismic trenching along the northern Hayward fault indicates that the last surface rupturing earthquake along this part of the fault was sometime between 1626 and 1724 (Lienkaemper *et al.*, 1997). This study also indicated at least four surface-rupturing earthquakes in the last 2,250 years. The WGCEP (1999) assigns maximum earthquakes of **M** 6.6 and 6.9, and recurrence intervals of 387 and 371 years, for the northern and southern segments of the Hayward fault, respectively. Rupture of the entire fault zone would generate an earthquake of **M** 7.1. Using more recent rupture area – magnitude relationships, we assign **M** 6.9, 7.1, and 7.3 to rupture of the northern and southern segments, and entire Hayward fault, respectively. We also incorporate a third Hayward fault segment – the southeast extension – that has an estimated maximum earthquake of **M** 6.5. This part of the fault only has a slip rate of 3 ± 2 mm/yr. The WGCEP (1999) considers the Hayward-Rodgers Creek fault system the most likely source of the next **M** 6.7 or larger earthquake in the Bay Area, with a 32 percent probability of occurring in the time period 2000 to 2030. Our model also incorporates a scenario where the Hayward fault ruptures along with the Rodgers Creek fault. Rupture of the entire length of both faults would generate a maximum earthquake of **M** 7.6. Rupture of the Rodgers Creek fault and the northern segment of the Hayward fault would generate a maximum event of **M** 7.4.

A.2.6 Hayward Southeast Extension

The northeastern margin of Santa Clara Valley, including Evergreen Valley, is marked by a northeast-dipping sequence of thrusts that are part of the East Bay Hills structural domain (Aydin and Page, 1984) or Graymer's (1995) Fremont subzone of the southern Hayward fault. This sequence of southwest-verging, reverse faults is located in the restraining left-step between the Calaveras and Hayward faults. The faults include the Piercy, Coyote Creek, Silver Creek, Evergreen, Quimby, Berryessa, Crosley, and Warm Springs faults. Like the Foothill thrust belt on the western side of Santa Clara Valley, this series of reverse and reverse-oblique faults marks the margin of a region of rapid late Cenozoic uplift. The Crosley, Berryessa, and Warm Springs faults have been interpreted as structures that may transfer slip from the southern Hayward fault to the Calaveras fault (Graymer *et al.*, 1995). Jones *et al.* (1994) show these faults as a steeply dipping zone of thrusts that roots in the Calaveras fault at an approximately 6.2 mile (10 km) depth. Outcrop mapping, however, suggests that many of these faults are moderate to relatively low-angle features that may root into the Calaveras fault at shallower depths. The thrust fault traces are slightly oblique, rotated about 10º to 15º counterclockwise, to the main strike-slip faults.

Although seismicity in this area is diffuse, relocation of microearthquake epicenters indicates that contemporary seismicity may be associated with faults that dip moderately to the east (Woodward-Clyde Consultants, 1994). Earthquake focal mechanisms also indicate northwest-striking reverse faulting. No large, historical earthquakes have been conclusively attributed to the thrust faults along the eastern Santa Clara Valley margin (Oppenheimer *et al.*, 1990). Jaumé and Sykes (1996) suggest that the July 1, 1911, **M** 6.2 earthquake may have occurred on a thrust fault parallel to the Calaveras fault; however, macroseismic intensity data indicate that this event is more likely to have occurred on the Calaveras fault (Bakun, 1999; Toppozada, 1984). The recent activity of many of these faults is inconclusive, and in some cases it is unclear whether the mapped trace is of tectonic or landslide origin. The range front along the northeastern side of Santa Clara Valley is modified by many large-scale slope failures.

The Evergreen fault is typical of faults in this area. This fault is an east-dipping reverse or reverse-oblique fault striking northwest across the piedmont of Evergreen Valley, east of San Jose. A recent trenching investigation at this site showed that the Evergreen fault is a moderate to low-angle (less than 45º) thrust fault, displacing Knoxville shale, up to the east, against gravels of the Santa Clara Formation (Fenton *et al.*, 1995). The fault plane was observed to cut up through the gravels and paleosol horizons estimated to be late Pleistocene in age. Overlying gravels were also observed to have been warped. The trench exposures were interpreted as indicating that the Evergreen fault had experienced coseismic rupture during the late Pleistocene, but that this rupture had not propagated to the surface. Rather, it had just resulted in warping of the ground surface. Slickensides on the fault surface indicated that fault slip was not purely reverse, but incorporated a small component of lateral movement.

The WGNCEP (1996) assigns a maximum earthquake of **M** 6.4 with a recurrence interval of 220 years for the Hayward Southeast Extension.

A.2.7 Rodgers Creek Fault

As indicated previously, the Hayward fault runs into San Pablo Bay at Point Pinole. The northern continuation of this fault system is the Rodgers Creek fault. The two faults are separated by a 5-km-wide right step beneath San Pablo Bay. The Rodgers Creek fault is 44 km long and has a similar geomorphic expression to the Hayward. At its northern end, the Rodgers Creek fault is separated from the Healdsburg fault by a 3-km-wide right step, and separated from the Maacama fault by a 10-km-wide right step (Wagner and Bortugno, 1982). Holocene activity along the Rodgers Creek is indicated by a series of fault scarps in Holocene deposits, side-hill benches, right-laterally offset streams, and closed linear depressions. Paleoseismic investigations by Schwartz *et al.* (1992) revealed three events in 925 to 1,000 years. This gives a preferred recurrence of 230 years for a maximum earthquake of **M** 7.2. The calculated slip rate for the Rodgers Creek fault is 9 ± 2 mm/yr.

A.2.8 Calaveras Fault

This fault is a main component of the San Andreas system, branching off the main San Andreas fault south of Hollister, and extending northwards for approximately 120 km to die out in the area of Danville. The predominant sense of motion on the Calaveras fault is right-lateral, strike-slip. A smaller component of vertical displacement is evident in some areas along the fault trace. The Calaveras fault can be divided into two distinct sections, northern and southern, with the boundary located at Calaveras Reservoir. Oppenheimer and Lindh (1992) suggest that rupture of the entire 40-km-long northern Calaveras fault is possible and could generate a **M** 7 earthquake. The Calaveras fault has generated a number of moderate-size earthquakes in historic time, including (1) the 1861 Richter local magnitude (M_L) 5.9 event, (2) the 1886 M_L 5.4 event, (3) the 1897 M_L 6.2 event, (4) a probable M_L 6.5 event in 1911, (5) the 1988 M_L 5.1 Alum Rock event, (6) the 1979 M_L 5.9 Coyote Lake event, and (7) the 1984 M_L 6.2 Morgan Hill event.

To the south of Calaveras Reservoir, microseismicity clearly delineates the active trace of the fault. Little microseismicity is associated with the northern section of the fault, and only the 1861 earthquake can be attributed to this portion of the fault. This event is reported to have caused 8.1 miles (13 km) of surface rupture, extending from San Ramon to Dublin (Toppozada *et al.*, 1981). The lack of a well-defined fault and the diffuse nature of seismicity at the northern end of the San Ramon Valley suggest that the Calaveras fault may die out just to the south of Walnut Creek, with strain being transferred across the East Bay Hills and onto the Hayward fault (Aydin 1982). The northern section of the fault may, therefore, be less active than the southern section. The long-term slip rate and contemporary creep rate for the southern Calaveras fault are approximately 15 ± 3 mm/yr (WGCEP, 1999), while the northern Calaveras fault has a creep rate of approximately 6 mm/yr (Prescott and Lisowski 1983) and a long-term geologic slip rate of 6 ± 1 mm/yr (Simpson *et al*. 1999). The WGCEP (1999) suggests a recurrence interval of 359 years for a maximum earthquake of **M** 7.0 on the northern Calaveras fault. The recurrence interval for a maximum event of **M** 6.7 on the southern Calaveras fault is approximately 546 years.

Several rupture scenarios, including a floating **M** 6¼ are considered for this fault (Table 1). The WGCEP (1999) assigned a **M** 7.1 and 7.3 for rupture of the south-central and central Calaveras fault segments, respectively. However, recent paleoseismic investigations on the central Calaveras fault indicate that there have been no large, surface rupturing earthquakes along this reach of the fault in the last 2,700 years (Kelson and Baldwin, 2002).

A.2.9 Concord-Green Valley Fault

The Concord fault, and its continuation on the northern side of Suisun Bay, the Green Valley fault, is a northwest-striking right-lateral strike-slip fault of the San Andreas system. The Concord fault extends for 18 km along the eastern margin of Ygnacio Valley, from the northern slopes of Mount Diablo to Suisun Bay. North of the Bay, the Green Valley fault extends northwards for a distance of approximately 43 km. The northern end of the Green Valley fault is defined by a change in fault strike and a gap in microseismicity (WGCEP 1999). The WGCEP (1999) also included the Cordelia fault within the Concord-Green Valley fault system.

Both the Concord and Green Valley faults exhibit aseismic creep. Galehouse (1992) measured a creep rate of 3 to 6 mm/yr. Relatively few paleoseismic data exist for either fault. Wills *et al*. (1994) showed 30 to 60 m of right-lateral offset has occurred across the Concord fault during the Holocene (the last 10,000 years). Snyder *et al*. (1994) estimate a slip rate range of 2.6 to 10.8 mm/yr. The WGCEP (1999) has assigned a slip rate of 4 ± 2 mm/yr for the Concord and 5 ± 2 mm/yr for the Green Valley fault. Baldwin *et al*. (2001) calculates a slip rate of 3.8 to 4.8 mm/yr for both the Concord and southern Green Valley faults. Based on differences in geomorphic expression, fault geometry, paleoseismic chronology, slip rate, and seismicity, the Concord-Green Valley fault is divided into three fault segments: the Concord fault, the southern Green Valley, and northern Green Valley faults. The segment boundary between the Concord and Green Valley faults is taken to be the middle of Suisun Bay. The boundary between the southern and northern Green Valley segments is located at the northern end of Green Valley, north of Cordelia. Rupture of the Concord and Green Valley faults, independently of each other, would generate maximum earthquakes of **M** 6.5 and 7.0, respectively. The Green Valley fault may also rupture as independent north and south segments, generating maximum earthquakes of **M** 6.7. A rupture along the entire length of both faults would generate a maximum earthquake of **M** 7.1.

A.2.10 Cordelia Fault

This fault is a north-striking right-lateral strike-slip fault that has often been assumed to be part of the Green Valley fault system. Paleoseismic investigations, however, have indicated that the

Cordelia fault has a much lower slip rate than the Green Valley fault and, therefore, may be an independent seismic source (Kieffer *et al.*, 1994). The Cordelia fault extends from south of Cordelia to the western shore of Lake Curry as a series of discontinuous north and north-northwest-striking fault strands. The geomorphic expression of the fault is more subdued than that of the Green Valley fault, being confined to tonal lineaments in Holocene deposits and right-lateral deflections of small drainages (Bryant, 1981). No contemporary seismicity is recorded along the fault (Wong, 1990). Based on differences in geomorphic expression and fault geometry, the Cordelia fault is divided into two fault segments: the northern and southern Cordelia fault. The boundary between the two fault segments is considered to be the subtle change in fault strike north of Cordelia. This presents three possible rupture models: independent rupture of the north and south segments, and rupture of the entire fault. These scenarios would generate maximum earthquakes of **M** 6.5, 6.2, and 6.6, respectively. Fault activity is expressed in terms of slip rate, as determined by recent paleoseismic investigations (Kieffer *et al.*, 1994). The preferred slip rate is 0.6 mm/yr, with a minimum of 0.05 mm/yr and a maximum of 1.0 mm/yr.

A.2.11 Coast Range-Sierran Block Boundary (CRSB)

The CRSB is a complex zone of thrust faulting that marks the boundary between the Coast Range block and the Sierran basement rocks that are concealed beneath the Great Valley sedimentary rocks of the Sacramento and San Joaquin valleys. The basal detachment within the CRSB is a low-angle, west-dipping thrust accommodating eastward thrusting of the Coast Range block over the Sierran block. Above this detachment is a complex array of west-dipping thrusts and east-dipping back-thrusts. The CRSB extends for over 500 km, from near Red Bluff in the northern Sacramento Valley to Wheeler Ridge in the southern San Joaquin Valley (Wakabayashi and Smith, 1994; Wong *et al.*, 1988).

The CRSB was the probable source of the two **M** 6¼ to 6½ 1892 Vacaville-Winters earthquakes and the 1983 **M** 6.5 Coalinga earthquake (Wong *et al.*, 1988). Although the faults themselves do not rupture to the surface, the CRSB is marked along much of its length by an alignment of fault-propagation folds such as the Rumsey Hills. This relatively simple geomorphic expression is interrupted by the Delta where the CRSB takes a right-step between the Montezuma Hills to the north and the Los Medanos Hills to the south (Wakabayashi and Smith, 1994). This complexity is most likely the result of the interaction of right-lateral strike-slip faulting and left-stepping restraining bends on these faults that belong to the San Andreas fault system (Unruh *et al.*, 1997; Wakabayashi and Smith, 1994).

Based on differences in geomorphic expression and fault geometry, Wakabayashi and Smith (1994) divided the CRSB into a number of segments. Working Group on Northern California Earthquake Potential (1996) has since modified this segmentation model, using the rupture geometry of the 1983 Coalinga earthquake as a "characteristic" event. Recent investigations by Unruh and Hector (1999) and O'Connell *et al.* (2001) have further refined the segmentation of the CRSB in the region surrounding the Delta. These faults are discussed in the following sections. The CRSB faults are considered as independent seismogenic sources, capable of generating maximum earthquake in the range **M** 6.5 to 7.0. Where no further information is available, fault activity is expressed in terms of slip rate as determined by Wakabayashi and

Smith (1994) and refined by WGNCEP (1996). The preferred geologic slip rate is 1.5 mm/yr, with an error of ±0.5 mm/yr.

CRSB North of the Delta

Recent investigations carried out by U.S. Bureau of Reclamation along the western margin of the Sacramento Valley north of Vacaville have greatly increased the understanding of the fault geometry in the fold and thrust belt of the CRSB (O'Connell and Unruh, 2000; O'Connell *et al.*, 2001). Previous models of faulting in this area had inferred a wedge back-thrust geometry (Unruh *et al.*, 1997). These recent investigations have revealed a fault-propagation fold geometry, with the main active structures being a series of west-dipping blind thrusts separated by lateral tears faults or oblique folds above lateral ramps (O'Connell *et al.*, 2001). Three main fault sources are considered in this area, from north to south, the Mysterious Ridge, Trout Creek, and Gordon Valley blind thrusts. These sources are considered capable of generating earthquakes of **M** 6.5 to 6.9. The structural complexity of this zone of faulting and the considerable structural elevation differences among these segments indicates that multi-segment rupture is unlikely.

Sacramento Delta Faults

Recent investigations in the Delta region have revealed a number of Quaternary active thrust faults beneath a series of right-stepping *en echelon* anticlines to the north of Mount Diablo (Unruh and Hector, 1999; Weber-Band, 1998). These faults include the Roe Island thrust, Potrero Hills thrust fault, Pittsburg-Kirby Hills fault, and the Midland fault.

Previous models for seismic sources in the Delta region have assumed a through-going buried or blind thrust fault representing the local continuation of the CRSB (Wakabayashi and Smith, 1994) through the central part of the Delta. The lack of Coalinga-type anticlines through the Delta region indicates that blind thrusts of the CRSB, if present, must have a lower slip rate than the "type" structures of the CRSB to the south. Unruh and Lettis (1998) proposed an alternative kinematic model for the deformation in this region that does not involve a through-going CRSB thrust structure; instead, they have a series of smaller, less active thrust faults.

The Roe Island thrust underlies the asymmetric Roe Island anticline in Suisun Bay. This fold and the underlying thrust fault are well documented from gas exploration wells and seismic reflection data (Unruh and Hector, 1999). The northeast-dipping thrust fault is considered capable of generating a maximum earthquake of **M** 5.5 to **M** 6.0 (Unruh and Hector, 1999). Slip-rate estimates range from 0.3 to 0.7 mm/yr, with a preferred value of 0.5 mm/yr.

The Los Medanos thrust is interpreted by Unruh and Hector (1999) to underlie the asymmetric, southwest-tilted Los Medanos and Concord anticlines. Based on an estimate of potential fault rupture area from the length of the overlying folds and the down-dip width from structural cross sections, Unruh *et al.* (1997) estimated a maximum earthquake magnitude of **M** 6 for the Los Medanos thrust fault. However, due to uncertainties on the fault geometry and the interaction of the fault with neighboring faults, namely the Roe Island thrust to the northwest and the Pittsburg-Kirby Hills fault to the east, the maximum event for the Los Medanos thrust ranges from **M** 5¾ to **M** 6¼. Estimates for the slip rate on the Los Medanos thrust range from 0.3 to 0.7 mm/yr.

Although they have slightly different geometries, the Los Medanos and Rose Island thrusts may merge at a common decollement horizon, thus there is a possibility that they may rupture simultaneously, generating a maximum earthquake of **M** 6.6.

The Potrero Hills thrust fault underlies the north-tilted Potrero Hills anticline, located just south of Fairfield. Unruh and Hector (1999) consider this fault capable of generating a maximum earthquake of **M** 6. Estimates of fault slip-rate range from 0.1 to 0.6 mm/yr, with 0.3 mm/yr representing the best estimate for the long-term slip rate.

The Pittsburg-Kirby Hills fault (PKHF) is a right-lateral tear fault that bounds the eastern margin of a series of folds and thrusts in the Grizzly Bay-Van Sickle Island area (Unruh *et al.*, 1997). The PKHF is highlighted by a linear alignment of microseismicity, which is unusual in that it occurs at depths of 20 to 25 km (Wong *et al.*, 1988). Weber-Band (1998) argued that the PKHF is an east-dipping reverse fault, however, focal mechanisms indicate that the movement on the fault is almost pure right-lateral strike-slip. The 1889 **M** 6 Antioch earthquake may possibly have occurred on the PKHF (Unruh and Lettis, 1998). Empirical relationships among fault length, fault rupture area, and earthquake magnitude indicate that the maximum earthquake for the PKHF is **M** 6.7. Estimates for the slip rate of the PKHF range from 0.3 to 0.7 mm/yr.

The Midland fault is a west-dipping fault located along the eastern margin of the Montezuma Hills. This fault accommodated subsidence of the Sacramento basin during early Tertiary time. From detailed analysis of seismic reflection data, late Cenozoic reactivation of the Midland fault to accommodate reverse slip and horizontal crustal shortening has been documented (Weber-Band, 1998). This reverse reactivation of the Midland fault has resulted in uplift of the eastern Montezuma Hills. From the offset of known Cenozoic reflectors, the Midland fault is estimated to have a slip rate of 0.1 to 0.6 mm/yr. The preferred estimate is 0.15 mm/yr (Jeff Unruh, William Lettis and Associates, Inc., *pers. comm*., 1999). The maximum earthquake for the Midland fault is **M** 6.3 ± 0.3.

CRSB South of the Delta

Previous models for segmentation of the CRSB south of the Sacramento River inferred a continuous zone of faulting along the eastern side of the Diablo Range (Wakabayashi and Smith, 1994; WGNCEP, 1996). More recent studies have shown that the regional fault geometry is more complex. Instead of one, continuous through-going fault zone, there is in fact a broad zone of *en echelon* folds and thrusts, including the Mount Diablo blind thrust, between the Sacramento River delta and the Livermore Valley. The CRSB *sensu stricto* begins again along the eastern range front of the Altamont Hills. Two segments of this southern part of the CRSB are of importance to ground shaking hazard to the In-Delta storage project. These are the range front west of Tracy (herein called the 'Tracy segment') and the range front west of Vernalis (the 'Vernalis' segment). The geometry of these structures is not known, but from analogy with other sections of the CRSB, it is assumed that these are west-dipping blind thrusts located beneath east-facing monoclinal warps (a fault-propagation fold geometry). Assuming a 15° dip and a 'Coalinga-type' geometry (fault extending from 4 km to 10 km depth), the Tracy and Vernalis blind thrusts are considered capable of generating maximum earthquake of **M** 6.8 and 6.6, respectively. Rupture of both segments would generate a maximum earthquake of **M** 7.0. The slip rate for these faults is between 0.29 and 2.3 mm/yr, with a preferred estimate of 0.42 mm/yr based on vertical separation rates calculated by Sowers *et al.* (2000).

A.2.12 Mount Diablo 'Blind' Thrust

This thrust fault is a northeast-dipping, southwest propagating thrust fault beneath the Mount Diablo anticline. Unruh and Sawyer (1995) proposed that slip on the northern Greenville fault appears to die out northward because the fault steps to the northwest (left) across Mount Diablo to join with the right-lateral Concord fault. This model argues that the Mount Diablo anticline is a contractional left-stepover between the Greenville and Concord faults. Unruh and Sawyer (1995) specifically proposed that Mount Diablo is an asymmetric, southwest-vergent fault-propagation fold underlain by a northeast-dipping blind thrust fault that links the northern Greenville fault to the Concord fault.

Long-term average Quaternary shortening rates across the Mount Diablo region, estimated from construction of balanced cross sections, are 3.4 ± 0.9 mm/yr (Unruh and Sawyer, 1997). Considering the likely fault geometry, an average slip rate for the Mount Diablo thrust would be approximately 4.1 ± 1.4 mm/yr. The likely geometry of this blind thrust fault indicates that it is capable of generating a maximum earthquake of **M** 6.9. Along-strike complexities indicate that the Mount Diablo thrust may be segmented, with the segments being separated by northeast-striking tear faults. If this is the case, then the maximum earthquake for each segment would be **M** 6.2 to 6.6. Based on an average coseismic slip during the maximum event and the calculated slip rate, Unruh and Sawyer (1997) proposed an average recurrence of approximately 230 to 740 years for the Mount Diablo thrust.

A.2.13 Greenville Fault

This fault is a north-northwest- to northwest-striking strike-slip fault of the San Andreas system in the northern Diablo Range. The fault extends from Bear Valley to just north of Livermore Valley. Evidence for right-lateral displacement on the Greenville fault includes right-laterally offset drainages and sidehill benches, and right-lateral surface offsets observed along traces of the fault following the January 1980 Livermore earthquake sequence (Hart, 1981). Seismicity associated with the fault is characterized by a subvertical alignment of epicenters extending to depths of approximately 17 km at the latitude of Livermore Valley (Hill *et al.*, 1990). Focal mechanisms indicate primarily right-lateral strike-slip motion on northwest-striking nodal planes (Oppenheimer and Macgregor-Scott, 1992). The Greenville fault generally is assumed to continue north of Livermore Valley as the Marsh Creek-Clayton system; however, the well-defined surface trace of the fault dies out or diminishes markedly several km north of Livermore Valley, and the Marsh Creek-Clayton fault system is considerably less active than the northern Greenville fault east of Livermore. The restraining step over model of Unruh and Sawyer (1997) indicates that slip from the Greenville fault is transferred to the Concord fault, and therefore the Clayton-Marsh Creek fault is either inactive or not part of the Greenville fault system.

Available data on the late Quaternary slip rate of the Greenville fault are sparse and have significant uncertainties. Based on correlation of terraces south of Livermore Valley offset by the Greenville fault, Wright *et al.* (1982) documented approximately 90 m of Pleistocene displacement. The deformed terraces were estimated by Wright *et al.* (1982) to be 125,000 to 180,000 years old, based on soil profile development, thus implying a slip rate of 0.5 to 0.7 mm/yr. Paleoseismic trench investigations across one of the strands of the northern Greenville fault documented evidence for Holocene surface-rupturing events, using an assumed 1:3 ratio of vertical to horizontal separation. Wright *et al.* (1982) estimated a horizontal slip rate of approximately 0.1 to 0.3 mm/yr. The WGNCEP (1996) assigned a maximum earthquake of **M** 6.9 and a minimum slip rate of 2 mm/yr to the Greenville fault. The recurrence interval is estimated to be on the order of 550 years. Recent investigations by Sawyer and Unruh (1998, 2002) indicate a 70-km length for the active Greenville fault. Preliminary Holocene slip rate estimates from a site at the northern end of the Livermore Valley are 4.1 ± 1.8 mm/yr (Sawyer and Unruh, 2002).

A.2.14 Ortigalita Fault

The Ortigalita fault is a 66-km-long, north-northwest-striking, right-lateral strike-slip fault located in the southern Diablo Range. The fault extends from Panoche to southeast of Mount Stakes. The fault consists of two distinct geometric sections, separated by a 5-km-wide right-step across San Luis Reservoir. Much of the fault is delineated by persistent microseismicity. The fault is marked by geomorphic indicators of recent strike-slip faulting, including deflected drainages, shutter ridges, sidehill benches, and vegetation lineaments (Anderson *et al.*, 1982, 2001). Paleoseismic trenching investigations have estimated a slip rate of 0.5 to 2.5 mm/yr for the fault north of San Luis Reservoir. South of the reservoir, the slip rate is considerably less, approximately 0.2 to 1.0 mm/yr (Anderson *et al.*, 2001). The maximum earthquake for rupture of the entire Ortigalita fault is **M** 7.4. Independent rupture of the northern segment would generate a maximum earthquake **M** 7.0 while the southern segment would generate a maximum earthquake of **M** 7.2. The geometric complexity of the southern part of the Ortigalita, generally forming 17 to 27 km long fault strands, would more likely rupture as smaller earthquakes, of **M** 6.5 to 6.7.

A.2.15 Mt. Oso Anticline

The Mount Oso anticline is located in the left-step between the Ortigalita and Greenville faults. The location of this fold, in what is considered a restraining step between two active right-lateral strike-slip faults, indicates that it may be undergoing active contractional deformation. In addition, the southwest-vergent geometry of this fold suggests that it may be underlain by a northwest-dipping blind thrust, similar to that beneath Mount Diablo (Jeff Unruh, Wm. Lettis & Associates, Inc., p*ers. comm.*, 2002). The geometry and activity of this structure is the subject of speculation. Without further information, we assign this zone a probability of activity of 0.5. Conservatively, we assume that the entire zone beneath Mt. Oso between the Greenville and Ortigalita faults is underlain by a blind thrust dipping at 20°. We also assume that the fault is capable of generating a maximum earthquake similar to the Mount Diablo blind thrust.

A.2.16 East Bay Thrust Domains

The East Bay Hills are a region of youthful, elevated topography between the Hayward and Calaveras faults. Late Cenozoic crustal shortening across this region is shown by folded

Miocene and Pliocene rocks, and the presence of discrete thrust faults that repeat parts of the Neogene stratigraphy. Geomatrix Consultants (1998) have documented evidence for late Pleistocene and possibly Holocene surface faulting on secondary structures related to the Franklin fault near Walnut Creek. Wakabayashi and Sawyer (1998) have also obtained paleoseismic evidence for late Pleistocene to Holocene surface rupture on the Miller Creek fault. Based on the elevated topography, late Cenozoic folding, and paleoseismic evidence for surface-rupturing earthquakes, the Thrust Faults Subgroup of the 1999 WGCEP (Jeff Unruh, unpublished memo, 1998) concluded that active thrust-related seismic sources exist within the East Bay hills. However, given the limited amount of paleoseismic information, rather than characterize individual faults, the Thrust Fault Subgroup defined a series of areal source zones, rather than try to characterize discrete fault sources. These zones are:

- The Western East Bay Hills domain, bounded by the Hayward fault to the west and the Moraga-Miller Creek-Palomares faults to the east. This domain contains the active Miller Creek thrust fault (Wakabayashi and Sawyer, 1998). This elongate zone is considered capable of generating a maximum earthquake of **M** 6. The slip rate, considered to be comparable to measured uplift rates in this area (Kelson and Simpson, 1996), is approximately 1.0 mm/yr.
- The southern East Bay Hills domain is roughly a triangular region bounded to the west by the Western East Bay Hills domain, by the northern Calaveras fault to the east, and by the Bollinger thrust fault to the north and northeast. The maximum length of thrust faults in this domain is about 15 km. This domain is considered capable of generating earthquakes of **M** 6¼ to 6½. Slip rates, calculated from measured uplift rates and assuming slip on thrust faults that dip 30° to 45°, are in the range 0.1 to 1.0 mm/yr, with 0.3 mm/yr representing the best-estimate value.
- The northern East Bay Hills domain is the region that lies north of the Bollinger thrust fault and west of the western domain. This domain contains the Pinole, Southampton, and Franklin faults. Geomatrix Consultants (1998) assigned a maximum earthquake of **M** 6¾ to the Franklin fault. The Thrust Fault Subgroup assigned a maximum earthquake of **M** 6¼ to 6¾ to the northern domain. The slip rate for this domain is 1.0 to 4.0 mm/yr. The higher value assumes that slip from the northern Calaveras fault is transferred through this region (Aydin 1982).

A.2.17 West Napa Fault

This fault is a north-northwest-striking right-lateral strike-slip fault comprising a series of *en echelon* fault strands along the western side of the Napa Valley, from south of Napa to Yountville, a distance of approximately 25 km. The fault is characterized by well-defined active fault features, including tonal lineaments, fault scarps in Holocene deposits, closed depressions, and right-laterally offset drainages. Very little contemporary seismicity is associated with this fault (Wong, 1990). To date, no independent paleoseismic data exist for the West Napa fault. Current estimates of 1 mm/yr for the slip rate and 700 years for the recurrence interval are based upon "regional strain book-keeping" (WGNCEP 1996).

Based on differences in geomorphic expression and fault geometry, the West Napa fault is divided into two segments: a northern segment along the western side of the Napa Valley from

Napa to just north of Yountville and a southern segment from Napa across the Napa Valley towards American Canyon. This presents three possible rupture models: independent rupture of the north and south segments, and rupture of the entire fault. These rupture models are capable of generating maximum earthquakes of **M** 6.6, 6.4, and 6.8 for the north, south, and entire rupture, respectively. Fault activity is defined in terms of the 1.0 mm/yr proxy slip rate determined by the WGNCEP (1996). The minimum and maximum slips rates are 0.5 and 2.0 mm/yr, respectively.

A.3 BACKGROUND EARTHQUAKES

To account for the hazard from background (floating or random) earthquakes in the probabilistic seismic hazard analysis that are not associated with known or mapped faults, regional seismic source zones were used. In most of the western U.S., the maximum magnitude of earthquakes not associated with known faults usually ranges from **M** 6 to 6½. Repeated events larger than these magnitudes generally produce recognizable fault-or-fold related features at the earth's surface (e.g., dePolo, 1994). An example of a background earthquake is the 1986 **M** 5.7 Mt. Lewis earthquake that occurred east of San Jose.

Earthquake recurrence estimates in the region are required to quantify the hazard. The site region was divided into two regional seismic source zones: the Coast Ranges and Central Valley. The recurrence parameters for the Coast Ranges source zone was adopted from the WGCEP (1999) and Dreger (2000). The *b*-values, 0.91 and 0.86, respectively, were assigned equal weights in the hazard analysis. The recurrence values for the Central Valley zone were adopted from URS Corporation (2001). Maximum earthquakes for both zones of **M** 6.5 ± 0.3 were used in the analysis.

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