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Earthquake Potential Along the Hayward Fault, California

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INTRODUCTION

The Loma Prieta event probably marks a renewed period of major seismic activity in the San Francisco Bay Area. Particularly ominous is the historic record of major events a few years apart on opposite sides of the Bay in 1836 (N. Hayward fault) and 1838 (N. Peninsula, San Andreas fault) and 1865 (Loma Prieta segment, San Andreas fault), and 1868 (S. Hayward fault) (Figure 1). Recent preliminary measurements of the Holocene geologic slip rate of the Hayward fault are as much as 9 mm/yr (Lienkaemper and others 1989)--about 80% greater than the first Holocene measurements determined as recently as 1987 (Borchardt and others 1987). Aseismic slip, as measured from monuments and offsets of cultural features, varies along the fault from 3 to 9 mm/yr and averages 5 mm/yr (Lienkaemper and others 1990). Although the earthquake potential calculated from such data are greatly affected by initial assumptions, the extremes are instructive: Method I assumes that the fault is freely slipping along the entire fault plane and that, until aseismic slip ceases, no major events are possible. Method II assumes that aseismic slip occurs throughout the 10-km deep seismogenic zone, but that strain continues to build at the deficit rate about 4 mm/yr and strain builds at slightly less than the geologic rate (9 mm/yr). Assuming that 1.1 to 1.2 m of displacement occurs at depth during M 6.8 events (Slemmons and Chung, 1982), calculated recurrences range from 120 to 300 years. Thus, in view of the time elapsed since the two previous events (123 and 155 years), we have entered the "earthquake window" for the Hayward fault. The new geologic rate has increased the estimates of 30 year probabilities for major events from 20% to 28% on the north half of the fault and from 20% to 23% on the southern half (compare WGCEP of 1988 and 1990).

TECTONIC SETTING

The Hayward fault is a right-lateral strike-slip feature, ancillary to the nearby San Andreas fault, and is part of the transform continental margin in central California. The San Andreas transform accommodates movement along the margin of the Pacific and North American plates between two crustal spreading centers, the East Pacific Rise, off the coast of Central Mexico, and the Gorda Ridge, north of the Mendocino trench. North of Cape Mendocino, a convergent tectonic boundary exists with the expanding Pacific Plate being subducted directly beneath the North American Plate.

The San Andreas transform is a unique link on the East Pacific Rim, juxtaposing the Pacific plate directly against the North American Plate. To the north and south of the San Andreas the Pacific Plate is unseen, as it is subducted under the over-riding North American Plate. Most workers believe that the ancient San Andreas transform began following the almost total subduction of the Farallon Plate, between 30 and 32 million years ago (Ma) (Atwater, 1970). At this time, a fore-arc basin existed west of the Sierra Nevada Mountains. Around Middle Miocene time (roughly 15 Ma) strike-slip faulting began in earnest along the California coastal margin. Around 13 Ma, regional uplift began in the region between the present position of the San Andreas and Hayward faults, in the proximity of what is now San Francisco Bay (Graham and others, 1984). Around 10 Ma, initial rupture of the Hayward fault zone followed the uplift. This early faulting likely initiated in response to tectonically induced regional stresses aligned at N55°E, to the strike of the fault (Figure 2). We can infer that such a field was induced by collision and apparent shortening of the Pacific Plate under the thicker North American mass.

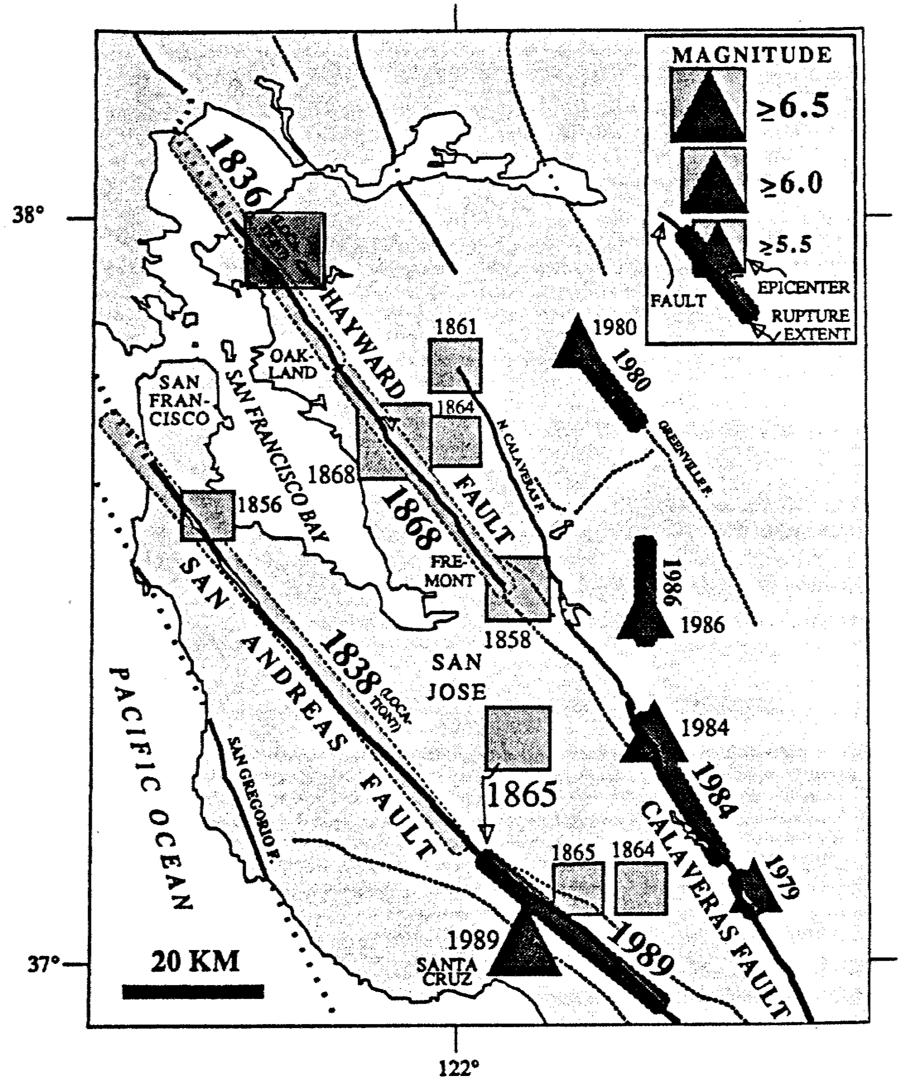

Figure 1 - *San Francisco Bay Area showing the locations of the Hayward fault and the mid-nineteenth century earthquakes (modified from Lienkaemper and others, 1990).*

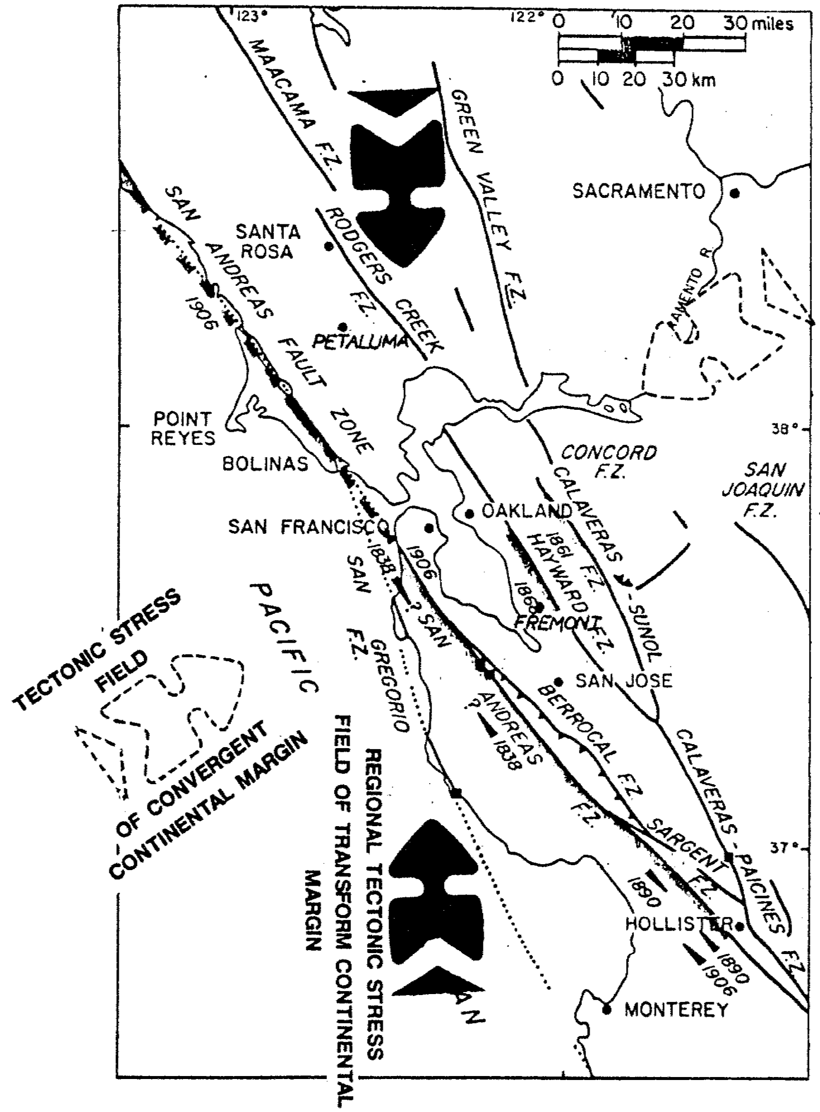

Figure 2 - *Inferred alignment of regional tectonic stress field at the margin of the Pacific and North American plates in central California. Folding axes should be aligned normal to this regional stress field while strike slip faulting would eventually be aligned, as shown, at 45-Ø/2 degrees to the maximum principal stress (modified from Herd, 1979).*

Graham and others (1984) tell us that between 10 and 7 Ma, there was localized volcanism along the Hayward rift. Some time later, between 8 and 6 Ma, a similar pattern of uplift and drainage reversal (to the east) also began along what is now the Calaveras fault. Individual basins were created between these progressively younger strike-slip fault segments east of the San Andreas. During Pliocene time (5.3 to 1.6 Ma) uplift on the Hayward rift supplied Franciscan debris to nearby subsiding areas. During Pleistocene time (last 1.6 Ma) the San Francisco Bay block, which had been elevated at about 13 Ma, subsided, and debris from both sides of the newly formed basin spilled into it. The first outlet from San Francisco Bay to the ocean was probably cut through a bedrock gap in the San Francisco peninsula, adjacent to the San Andreas fault, between 400,000 and 500,000 years ago (Clifton, 1990).

To gain an appreciation of the shallow, plate-boundary nature of the San Andreas, and its subordinate Hayward and Calaveras branches, it is necessary to view a speculative cross section through the N55°E - directed subduction of the Pacific Plate under North America (Crane, 1988; Figure 3). As the thin oceanic crust is carried below the thick continental massif, fracture can be accomplished most easily where the overriding plate is thinnest. According to Crane (1988), the Hosgri-San Gregorio and San Andreas faults are shallower, and therefore, presumably develop less friction than the progressively deeper and younger Hayward and Calaveras zones to the east (Figure 3).

Much geologic evidence suggests that the faults comprising the San Andreas transform system have alternately been active, almost as if to be "taking turns" at absorbing strain build-up and release through aseismic creep or coseismic rupture. In attempting to explain the observed progressive disturbance of Merced Formation sediments adjacent to the San Andreas fault, Clifton (1990) has tentatively concluded that the San Andreas has become increasingly active on the San Francisco Peninsula in the last 200,000 years. More major structural offsets occur along either side of the current San Andreas trace, along the San Bruno fault several kilometers to

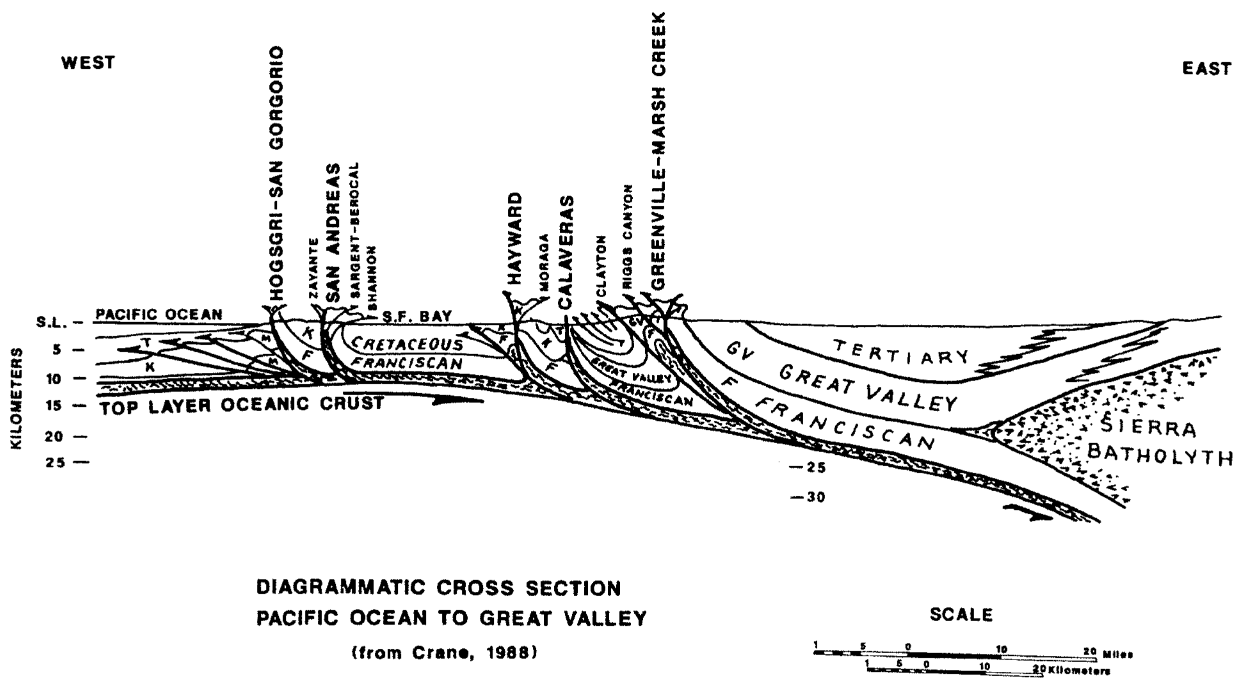

Figure 3 - *Diagrammatic cross section from the Pacific Ocean to California's Central Valley according to Crane (1988). The San Andreas transform and its ancillary fault zones ride atop the subducting Pacific plate. Both aseismic and coseismic activity cease abruptly at the zone of subduction, which can locally be deep or shallow, depending on the thickness and density of the subducted crust. In general, the ancillary faults east of the San Andreas become deeper and less active with distance from the San Andreas. This may be due to increased frictional drag resulting from the increased contact area engendered by deep confinement. The Hosgri and the San Andreas likely exchange roles as the most active player along the transform.*

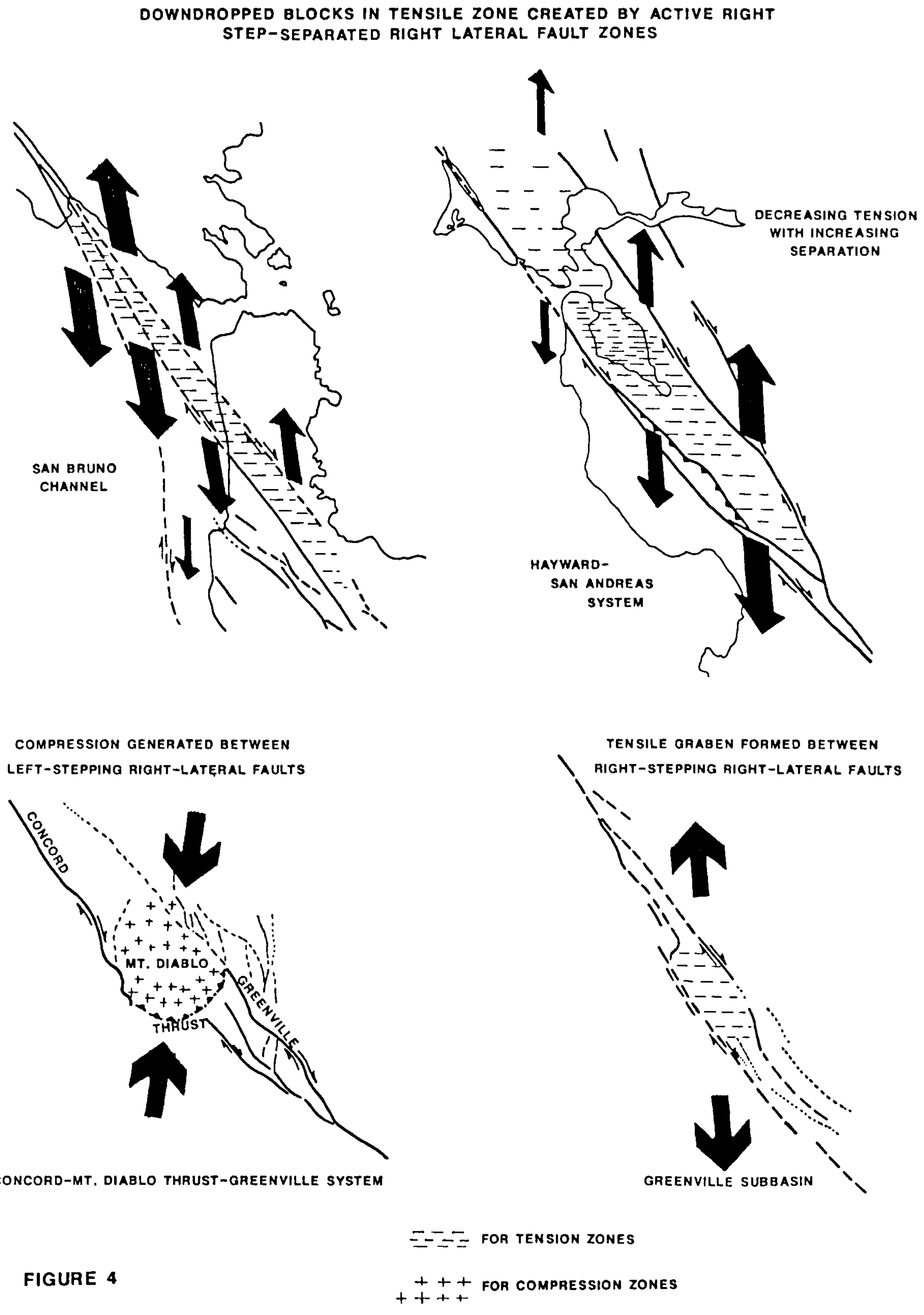

Figure 4 - *Examples of step-over induced tensile and compressional fractures seen in the California coastal borderland. The magnitude of the inter-block stress field generated depends on the respective strain rates of the adjacent strike-slip faults.*

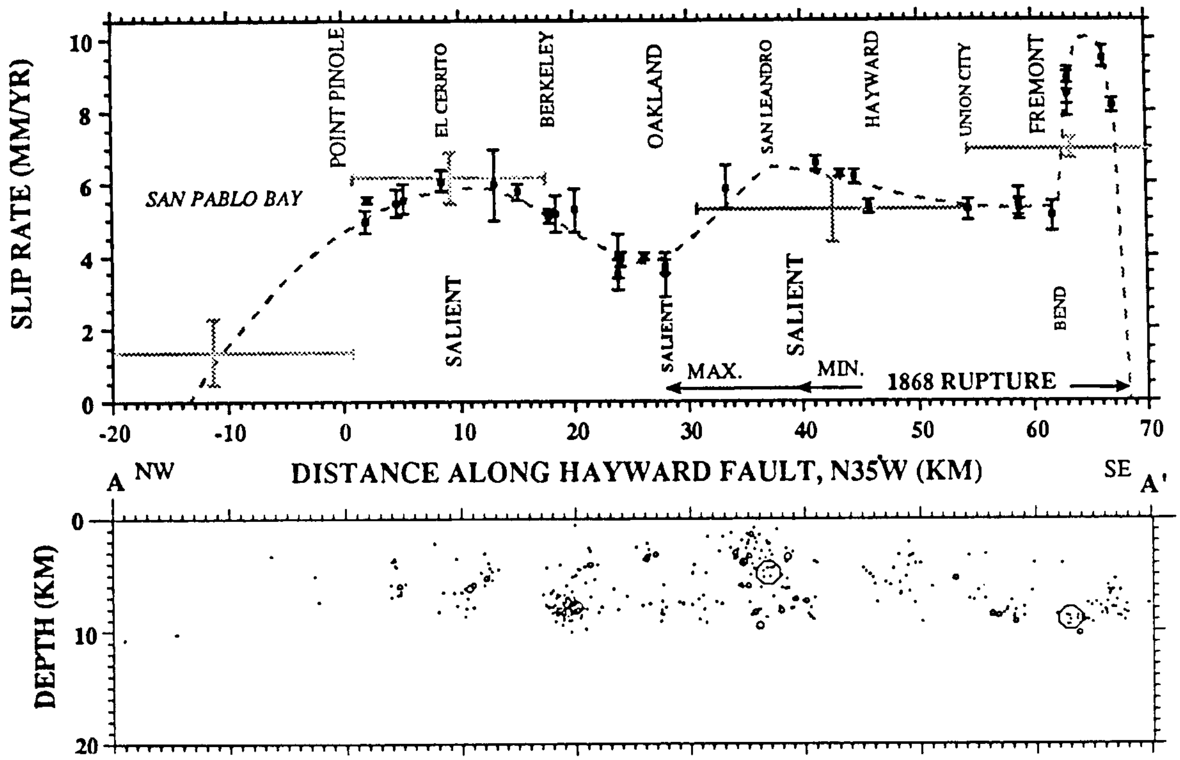

Figure 5 -*Historic creep rates along the Hayward fault, taken from Lienkaemper and others (1990). Most of the data are from precise surveys of cultural features. Bars represent U.S.G.S. geodolite survey lines from the mid-1970's to 1988. Microseismic events for the interim 1969-89 are presented below, with the largest event being a M 4.7.*

the east, and the Hosgri-San Gregorio fault, a few kilometers to the west. In this fashion, simultaneous movement along two active strike-slip faults alternately produce intra-block basins, subjected to either tensional or compressional stress fields. This explains the apparent reversal from compression to tension of the San Francisco Bay block between the Hayward and San Andreas Faults during late Pleistocene time. Several representative examples of fault-offset induced stress fields are possible (Figure 4).

The Hayward fault abruptly ceases microseismic activity at a depth of around 10 km (Figure 5). This is likely due to the vertical fault plane's termination at that depth as it is absorbed into the underlying subducted oceanic crust. According to Crane's model, the Calaveras may extend to 15 km, the Greenville-Marsh Creek zone may extend to 25 km, and faults under the Sierra Nevada may extend to even greater depths.

EARTHQUAKE HISTORY AND FUTURE PROSPECTS

The October 17, 1989 Loma Prieta event served notice that major earthquake activity has been renewed along the San Andreas system in the San Francisco Bay Area. As in the late 1800's, strain release through seismic activity seems to be marching inexorably northward, toward the most densely populated part of the Bay Area (Figure 1). The paired earthquakes of 1836/1838 and 1865/1868 may have involved an ominous, alternating release of strain along the San Andreas and Hayward faults on either side of San Francisco Bay. The characteristics of these long-ago events are still being evaluated as we continue to discover additional historical data (e.g. Photograph 1). The northern and southern portions of the Hayward fault have been without major earthquakes for 155 and 123 years, respectively.

The Hayward fault traverses a highly urbanized area and therefore, possesses greater potential for damage than any other fault in the Bay Area (Steinbrugge and others, 1986; 1987). Most of the potable water and all the natural gas supply lines for the San Francisco Peninsula and the East Bay comes through aqueducts and pipelines crossing the fault. All the major petroleum fuel terminals, such as those at major airports and marine facilities, are supplied by pipelines that cross the fault. Sudden movement along the fault would affect the rapid transit trains that speed through the Berkeley

Hills tunnel each day. Below we reassess the earthquake potential of the Hayward fault in light of the most recent data.

GEOLOGIC SLIP RATES

Calculations of the geologic slip rate of the Hayward fault range between 0.7 and 9.7 mm/yr for the last 6 to 10 Ma (Graham and others, 1984; Fox and others, 1985; Sarna-Wojcicki and others, 1986; Liniecki-Laporte and Anderson, 1988). Until recently, however, geologic rates for the more meaningful Holocene period were unavailable. The first Holocene slip rate determined for the fault was a minimum (5.0 mm/yr) determined on one strand of the fault for an offset of buried channel deposits in Fremont (Borchardt and others 1987; 1988a; 1988b). Still more recent preliminary measurements of the offset of an alluvial fan yield slip rates between 7 and 9 mm/yr for the last 4 to 14 ka (Lienkaemper and others, 1989; Lienkaemper and Borchardt, 1990). We consider this the best estimate of the geologic slip rate, upon which we base much of the remainder of this discussion. Being up to 80% greater than the earlier Holocene slip rate, as well as the aseismic slip rate, it obviously demands new calculations of the earthquake potential of the fault.

ASEISMIC SLIP

Aseismic slip, as measured from monuments and offsets of cultural features, varies along the fault from 3 to 10 mm/yr and seems to have averaged about 5 mm/yr during the last 50 years (Lienkaemper and Borchardt, 1988; Lienkaemper and others, 1990). A 4 km section south of Irvington creeps at about 9.5 mm/yr. Lienkaemper and others (1990) have identified three bends, or *salients*, along the Hayward fault between Fremont and Point Pinole (Figure 6). These salients may behave like macro-asperities, absorbing strain energy and perturbing aseismic slip.

METHODS OF CALCULATING EARTHQUAKE POTENTIAL

Although the earthquake potential calculated from geologic and aseismic slip rates is greatly affected by initial assumptions, the extremes are instructive: Method I assumes that the fault is freely slipping along the entire fault plane and that until aseismic slip ceases no major events are possible. Method II assumes that aseismic slip occurs throughout the 10- km deep seismogenic zone but that strain continues to build at the deficit rate. Method III assumes that aseismic slip occurs only in the upper few kilometers and that the fault plane is locked at depth. Method IV assumes that aseismic slip is a decreasing function of confinement pressure.

Assumptions Common to the Four Methods

(1) The 1836 event was M 6.8 and ruptured 50 km of the northern part of the fault.

Written history concerning the 1836 event is sparse. There is even some doubt about whether the earthquake of June 21 actually occurred on the Hayward fault. Local historic accounts maintain that the 1836 quake was more severely felt by the residents of Oakland than the well-documented 1868 quake that had its epicenter further south (Alameda County Gazette, 1868). Louderback (1947) is generally cited as the first to consider it a Hayward event. From the evidence cited by Louderback, Jennings (1975) considered the event to have occurred on the northern part of the fault. The "fissures that opened at the foot of the East Bay Hills" have generally been taken as the result of fault displacement rather than seismically induced landslide (SIL) features and as Loma Prieta taught, in the absence of deep artificial cuts, most SIL evidence in the Bay Area seems to develop very near the causative fault. Existing landslides (Bishop and others, 1973), particularly along the northern Hayward fault, are likely to respond in a similar manner.

The occurrence of an equally large event along the southern part of the Hayward fault only 32 years later further indicates that the northern part was the causative fault for the 1836 event. The 50-km rupture was calculated from Louderback's cited evidence and was used by WGCEP (1988, 1990) fpr their probabity estimates. The 6.8 magnitude was assigned by Toppozada and others (1981) based on its being felt strongly from San Pablo to Mission San Jose, with shaking of VII (Rossi-Forel) in Monterey and Mission Carmel. These effects were in many respects similar to that of the 1868 event.

(2) The 1868 M 6.8 event ruptured 41 km of the southern part of the fault.

The magnitude of this event was assigned by Toppozada and Parke (1982) based on felt effects. The 1868 event produced less than 0.9 m amount of displacement with a rupture length estimated variously at 48 km (Slemmons and Chung, 1982), 50 km (Radbruch, 1967; Toppozada and Parke, 1982), 41 km (Lienkaemper and others, 1990), and 32 km (Lawson and others, 1908; Byerly, 1951; WGCEP, 1988; 1990). Following the reasoning of Lienkaemper and others (1990), we chose 41 km for the rupture length.

(3) The next major earthquake on the Hayward fault will be M 6.8 with hypocentral displacement being 1.4 m.

This assumption follows from the historical evidence used to deduce the first two assumptions. Slemmons and Chung (1982), however, estimate a maximum credible earthquake (MCE) of M 7.0 ± 1/4 for the Hayward fault. Similarly, WGCEP (1990) assumed a M 7 in calculating the probabilities of events on the fault. Further, the earthquake planning scenario for the Hayward fault used a M 7.5 event with up to 3 m of right-lateral displacement along its entire 100-km length (Steinbrugge and others, 1986; 1987). This worst-case scenario was most suited to emergency planning, following the precedent set by the U.S. Geological Survey (1981) who calculated a M 7.4 for the same rupture. Both the M 7.5 and M 7.4 scenarios consider the Hayward fault as one-half of the Healdsburg-Rodgers Creek-Hayward fault system (Figure 2). Although the Hayward fault may indeed be part of this system and although its complete rupture may not be impossible, we consider the historical evidence for M 6.8 events to be most compelling and most suitable for earthquake prediction. The strain required for a M 6.8 event obviously will be reached much sooner than that required for M 7 or M 7.5 events.

The choice of hypocentral displacement also will be affected by this conservative approach to prediction. Lienkaemper and others (1990) calculate 1.4 ± 0.7 m of coseismic slip for a 50-km rupture on the north and 1.2 ± 0.6 m of coseismic slip for a 41-km rupture on the south for M 6.8 and M 6.7 events, respectively.

Method I

Method I assumes that at the present time the fault is freely slipping along the entire fault plane and that until its mode of behavior changes, the fault poses no significant earthquake threat. The change to the seismogenic mode will be signaled by a cessation of aseismic slip, at which time strain will begin to build at the geologic rate.

Although few, if any, investigators currently support the additional assumptions behind this method, it must be considered in the analysis of earthquake potential along the fault. Prescott and others (1981, p. 10853) wrote that "along the Hayward and Calaveras faults, all motion appears to take place as slip directly on the fault, with no accumulation of strain in the adjacent crust. ...The absence of strain accumulation in the east bay is surprising since the Hayward and Calaveras faults have been the site of large earthquakes in the past." Model I received further support when the first Holocene geologic slip rate was measured at Fremont City Hall (Borchardt and others, 1987; 1988a). The geologic slip rate and the aseismic slip rate on the well-studied western trace of the fault were nearly identical. Similarly, the first aseismic slip rates at the Irvington warehouse and the curb on Camellia Street, both further to the southeast, were much higher than elsewhere (10±1 mm/yr) (Cluff and Steinbrugge, 1966; Burford and Sharp, 1982). These were later corroborated at about 9 mm/yr (Lienkaemper and Borchardt, 1988; Lienkaemper and others 1990) and were similar to the Holocene geologic rate determined on the only trace of the fault at Union City (Lienkaemper and others, 1989; Lienkaemper and Borchardt, 1990). Thus it appears that about 4 km of the fault is indeed freely slipping in the Irvington area (Figure 5).

The fact that ground rupture occurred in this "freely slipping area" and most likely also along the "freely slipping western trace" at Fremont City Hall (Lawson and others, 1908; Radbruch, 1967) remains a conundrum. The data beg the question "How can a fault that is freely slipping also produce major earthquakes along with ground rupture?" To address this question, Method I must also assume that the fault changes from an aseismic to seismic mode at some point in its earthquake cycle. Presumably, this will be signaled by a cessation in aseismic slip and the beginning of strain build-up.

The results of Method I imply that no major earthquakes will occur on the Hayward fault in the near future and that aseismic slip should be carefully monitored. We give little credence to this method because of the ob-

Photograph 1 - *Previously unpublished photo of the Edmunson warehouse in Hayward which collapsed in the 1868 Hayward earthquake.*

vious discrepancy or deficit between the geologic rate and the aseismic rate along most sections of the fault (Lienkaemper and others, 1990).

Method II

Method II assumes that aseismic slip occurs throughout the 10-km deep seismogenic zone, but that strain continues to build at the deficit rate (the geologic rate minus the aseismic rate). From geodetic and aseismic slip measurements, Prescott and Lisowski (1982) calculated a deficit rate of about 4 mm/yr. Similarly, from the preferred geologic slip rate (9 mm/yr, Lienkaemper and others, 1989) and the preferred aseismic slip, averaged along the fault (5 mm/yr, Lienkaemper and others, 1990), we also calculate a deficit rate of 4 mm/yr.

Exactly how strain is partially stored and partially released along the fault plane is not clear. This method, however, assumes that "stuck patches" (Prescott and Lisowski, 1982) exist at various places and at various depths along the fault plane. Fault gouge and soft rocks apparently deform plastically around such patches.

Method III

Method III assumes that aseismic slip occurs only in the upper few kilometers and that the fault plane is locked at depth (Lienkaemper and others, 1990; Figure 7). Because the locked portion comprises most of the fault plane, strain build-up is highly dependent on the geologic slip rate. Model III also fits the geodetic measurements indicating that seismic strain on the fault is about 4 mm/yr at the surface and up to 10 mm/yr at depth (Prescott and Lisowski, 1982; 1983).

If we assume that the fault is locked at depth and stores no more that 4 mm/yr of strain at the surface, then the northern section (last event 155 years ago) now stores enough strain to produce a 1.4-m displacement at depth and 0.6 m at the surface. The southern section (last event 123 years ago) now stores enough strain to produce a 1.1-m displacement at depth and 0.5 m at the surface. The M 7.1 Loma Prieta event had 1.9 m of right-lateral displacement at the 18 km depth and none at the surface (U.S. Geological Survey Staff, 1990)--slightly larger, though comparable values. Such speculations demonstrate that a major earthquake on the Hayward fault is possible in the near future.

Method IV

Method IV assumes that aseismic slip along the fault plane is a decreasing function of confinement pressure (Figure 8). In this model the characteristics of the rocks along the fault plane and the characteristics of the overburden determine the ability of the fault to store strain energy at any particular point. As confinement increases, greater friction is generated along the slip surface boundary. In this manner, increasing elastic strain energy is stored, leading to periodic rupture through cyclic "stick-slip." This mechanism is especially likely, given the shallow depth of the fault plane (10 km). In deep-seated faults, the propensity to store elastic strain energy is somewhat diminished due to increasing plasticity of rock with depth. As in Method III, recurrence varies from 120 to 300 years.

Summary of Methods

Assuming that 1.1 to 1.8 m of displacement occurs at depth during M 6.8 events, calculated recurrences range from 120 to 300 years. Thus, in view of the time elapsed since the two previous events (123 and 155 years), we have entered the "earthquake window" for the Hayward fault. Published estimates of recurrences for the Hayward fault range from 130 (Lienkaemper and others, 1990) to 556 years (Wesnousky, 1986).

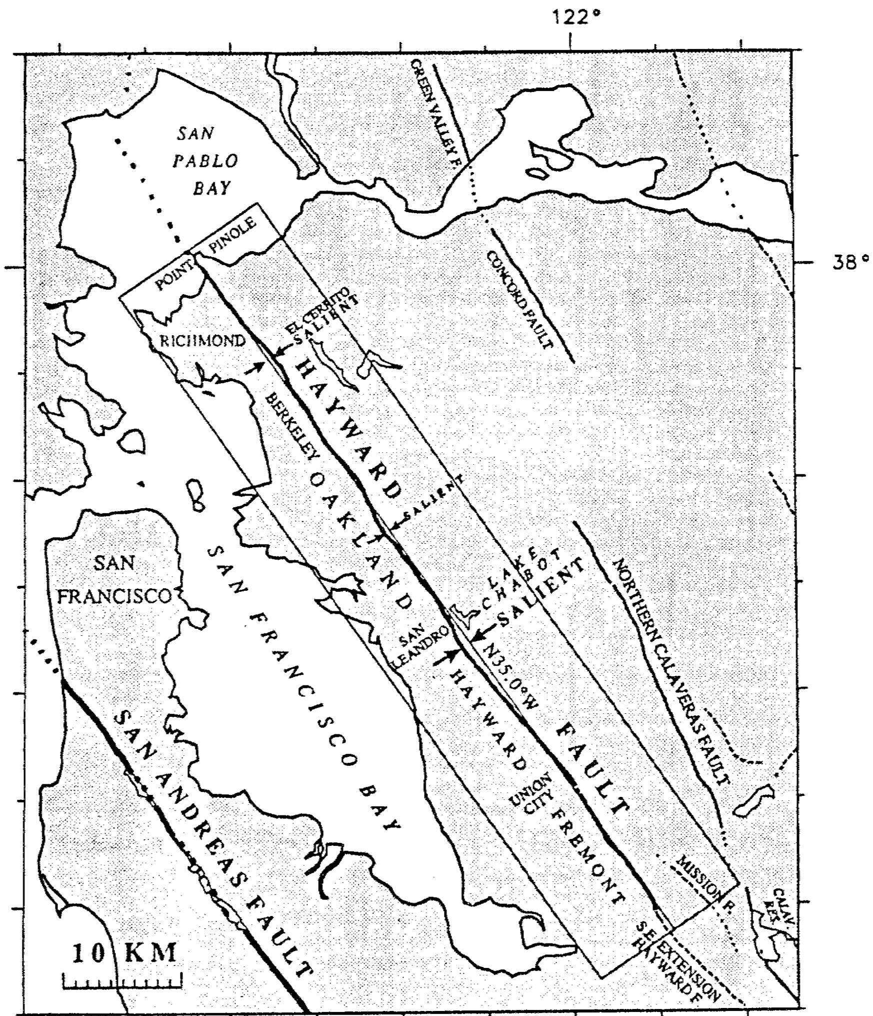

Figure 6 - *Plan view of Holocene trace of the Hayward fault showing distinct bends, or salients, identified by Lienkaemper and others, (1990). The largest salient is opposite San Leandro where the fault trace verges 0.7 km out of line.*

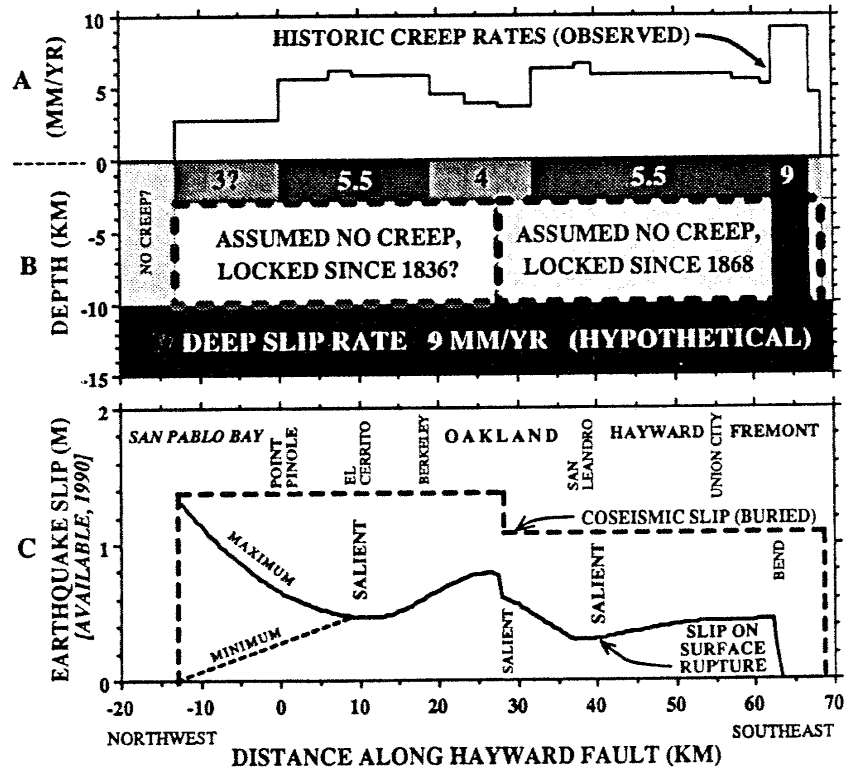

Figure 7 - *Model of the fault plane according to Lienkaemper and others (1990) showing the 3-km deep aseismic zone above the 7-km seismogenic zone.*

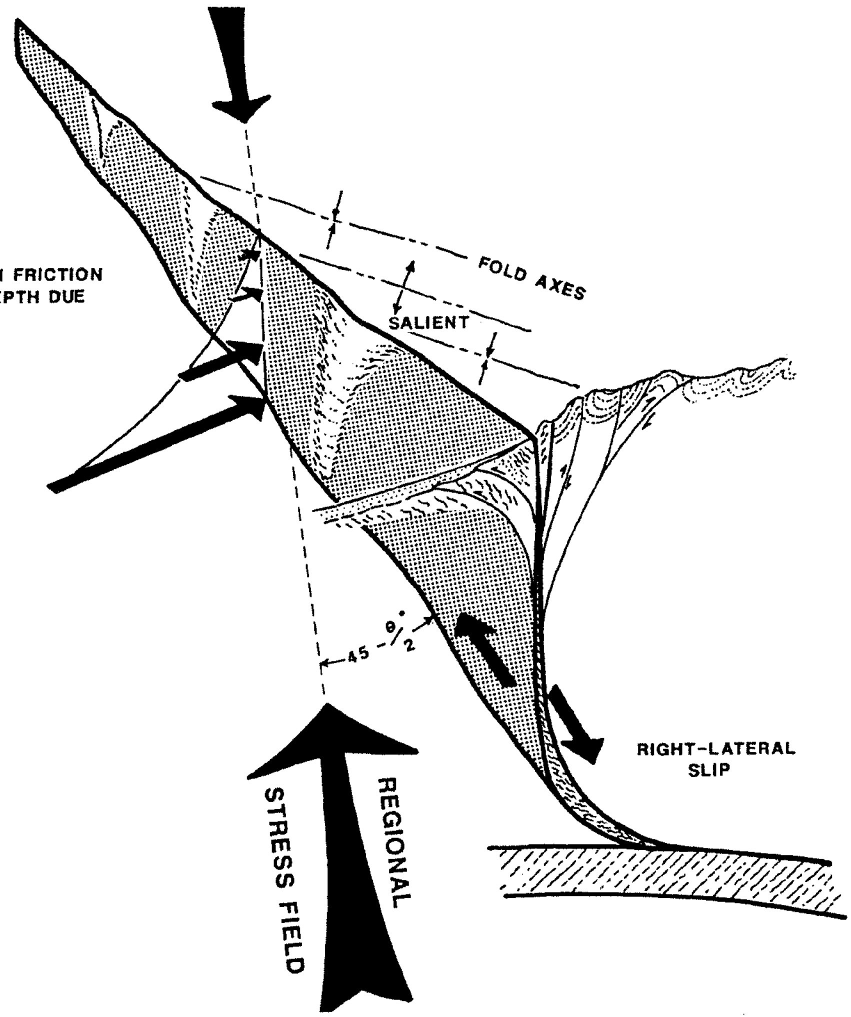

Figure 8 - *Conceptual representation of macro forces promoting slippage along the Hayward Fault and likely increase of lateral confinement with depth. This increase in confinement promotes increased shear strength with depth which must be overcome to accomodate fault plane rupture.*

PROBABILITIES

The new geologic rate increases the 30-year probabilities for major events. Early probability estimates for a major earthquake on either the northern or southern portions of the Hayward fault were 20% in the next 30 years (WGCEP, 1988). Because those calculations assumed a geologic slip rate of only 7.5 mm/yr for the fault, probability estimates have been revised upward as a result of the new 9-mm/yr geologic slip rate (WGCEP, 1990). The new calculations are 28% for the northern part and 23% for the southern part of the fault.

CONCLUSIONS

It now seems unlikely that aseismic slip is relieving all strain on the Hayward fault. Rather, several alternative models involving varying degrees of stick-slip all seem to yield strain build-ups that could produce over a meter of coseismic slip on either the northern or southern portions of the fault at any time. As long as the preferred geologic slip rate remains at or below 9 mm/yr, none of the models produce over 1.8 m of hypocentral slip, more or less assuring us that an earthquake greater than M 7.1 probably is not possible at present. Assuming that aseismic slip has been roughly constant since the events of 1836 and 1868, surface ground rupture will be diminished accordingly. This would be a maximum of 0.6 m in the north and 0.5 m in the south.

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