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Seismic reflection evidence for a northeast-dipping Hayward fault near Fremont, California: Implications for seismic hazard

Robert A. Williams,[1] Robert W. Simpson,[2] Robert C. Jachens,[2] William J. Stephenson,[1]
Jack K. Odum,[1] and David A. Ponce[2]

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[1] A 1.6-km-long seismic reflection profile across the creeping trace of the southern Hayward fault near Fremont, California, images the fault to a depth of 650 m. Reflector truncations define a fault dip of about 70 degrees east in the 100 to 650 m depth range that projects upward to the creeping surface trace, and is inconsistent with a nearly vertical fault in this vicinity as previously believed. This fault projects to the Mission seismicity trend located at 4–10 km depth about 2 km east of the surface trace and suggests that the southern end of the fault is as seismically active as the part north of San Leandro. The seismic hazard implication is that the Hayward fault may have a more direct connection at depth with the Calaveras fault, affecting estimates of potential event magnitudes that could occur on the combined fault surfaces, thus affecting hazard assessments for the south San Francisco Bay region.

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1. Introduction

[2] The Hayward fault, located on the east side of the densely populated San Francisco Bay, is better characterized in the upper 10 m (by trenching studies) and below 2 km (by earthquake hypocenters) than in the intervening depth range [*Lienkaemper et al.*, 2002; *Waldhauser and Ellsworth*, 2002]. Defining faults in this missing depth range is critical for understanding the connection between surface fault traces and seismicity, especially for faults like the southern Hayward fault where seismicity diverges from the surface trace. A new high-resolution seismic reflection profile across the southern portion of the Hayward fault near Fremont, California (Figure 1), addresses this uncertainty by focusing on the 100 to 650 m depth interval. The data were acquired along a reach of the fault that is creeping at the Earth's surface about 5 mm/yr [*Lienkaemper et al.*, 2001] to help constrain the model of the southern Hayward fault and the adjacent Calaveras fault, specifically, to examine whether the fault is vertical and aseismic [*Waldhauser and Ellsworth*, 2002] or east dipping with a possible connection to the Mission seismicity trend [*Manaker et al.*, 2005]. The Hayward fault zone, which includes both the active and other older traces, is predominantly a strike-slip right-lateral fault feature with about 100 km of offset during the past 12 Ma and at least a few hundred meters of east-up displacement over the past 2 Ma [*Kelson and Simpson*, 1995; *Graymer et al.*, 2002].

[3] The Hayward fault produced ground rupture in the study area during the 1868 magnitude ~6.8 earthquake [*Lawson*, 1908]. Together with its northern extension, the Rodgers Creek fault, it has been identified as the most likely candidate in the Bay region (27% chance) to produce a magnitude 6.7 or greater earthquake before the year 2032 [*Working Group on California Earthquake Probabilities*, 2003]. *Lienkaemper et al.* [2003] have found evidence for at least nine southern Hayward fault ruptures in Fremont during the past 2000 years (J. J. Lienkaemper, personal communication, 2005). Because the area near the Hayward fault is now crossed by important transportation, water, gas, and electricity lines, a repeat of the 1868 earthquake would probably cause billions of dollars in damage and significant loss of life.

2. Data Acquisition and Processing

[4] We acquired the 1.6-km long seismic reflection profile on a flat gravel road along Alameda Creek in the Niles District northeast of Fremont, California (Figure 2). The profile is underlain by Quaternary alluvial fan deposits (mostly extensive layers of gravel and sand interbedded with some layers of silt and clay, which are exposed in several nearby active and abandoned sand and gravel quarries) cyclically eroded from the hills to the east [*Koltermann and Gorelick*, 1992]. *Koltermann and Gorelick* [1992] indicated that the maximum thickness of Quaternary deposits is about 270 m, which, as we show later, appears to be too thin by almost a factor of two. We positioned the profile so that it would cross the main trace of the Hayward fault shown on the map of *Lienkaemper* [1992] (Figure 2).

[5] P-wave seismic reflection data were collected using a single 6382 kg Minivib II vibroseis truck. At each vibration point (VP) we stacked 4, 14-s-long, 10–200 Hz sweeps and generated a 2-s correlated record with 1.0 ms sample interval. The VP station interval was 10 m over the eastern 950 m of the profile, but was changed to 20 m for the remaining 640 m of the western end of the profile. Single 8-Hz geophones were placed at 10 m intervals over the length of the profile. We fixed the recording array to the maximum number of channels available (159), and moved the source through this stationary spread. Maximum stack fold reaches 125 in the middle of the profile and tapers to 1 relatively evenly at the ends.

[6] Within the 0.1 to 0.6 s two-way travel time range, data quality was excellent over the length of the profile as

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[1] U.S. Geological Survey, Golden, Colorado, USA.
[2] U.S. Geological Survey, Menlo Park, California, USA.

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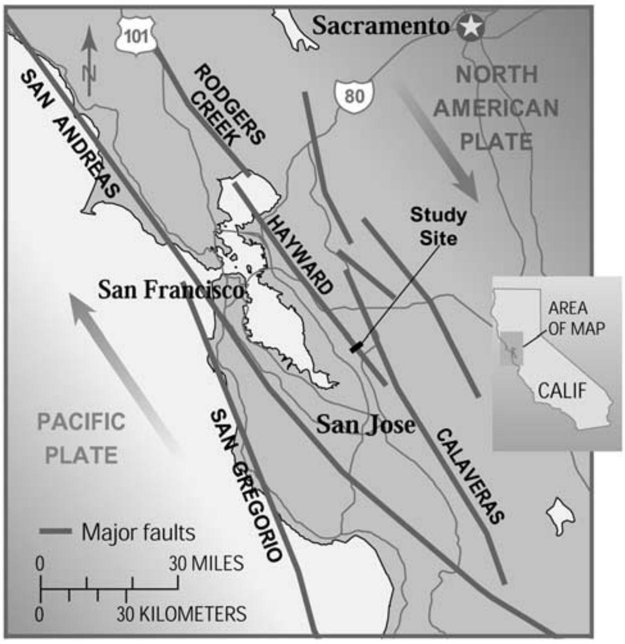

Figure 1. Major faults in the San Francisco Bay region with seismic profile location shown as short heavy black line across the southern Hayward fault.

evidenced by prominent reflections, such as the ones labeled F and G on the shot records (Figure 3). The F and G reflections, which, as described in the next section, probably represent the top of the Franciscan Complex, F (apparent on every shot record), and Great Valley Sequence G. Reflections above F and G are also observed (Figure 3), but no clear reflections below F and G are obvious in any of the shot records or the stacked data. The geophone station interval and 0.1 km minimum imaging depth probably preclude detection of any Holocene layers.

[7] Data processing consisted of trace editing, automatic gain control (500 ms), band-pass filtering (10-20-80-120 Hz), a 60 Hz notch filter, ground roll muting, elevation statics, surface-consistent residual statics, CDP stacking, post-stack time migration, and time-to-depth conversion. This data processing sequence resulted in an average spectrum peaked at 25 Hz. At 25 Hz and with a stacking velocity of 2300 m/s, the minimum vertical resolution limit is about 25 m in the vicinity of the F reflection. Vertical resolution improves to about 7 m for the reflections above the F and G reflections.

3. Interpretation of the Seismic Profile

[8] The migrated seismic depth section is characterized by two distinct reflection groups separated by the Hayward fault (Figure 4), each underlain by strong basal reflections (F and G reflections). The reflection group east of the surface trace is clearly tilted toward the west about 20° while the reflection group west of the surface trace is generally flat-lying. Basal reflections on both sides of the fault underlie higher frequency reflections from the mainly Quaternary-aged section.

[9] The Hayward fault is imaged as a narrow zone of truncated reflectors that projects to the surface trace of the fault. The most prominent reflection discontinuity is formed by a basal reflector (F) at about 500 m depth that is abruptly truncated about 200 m east of the surface trace of the fault. East of the surface trace the other basal reflection (G) is generally west-tilted, but appears deflected upwards along the fault, perhaps by fault drag or compression. The position of the surface trace and these reflector truncations define the fault dip in the 100 to 650 m depth range to be about 70° east. Above 100 m depth, the fault may steepen and splay into multiple traces to accommodate the variable, but commonly steep dips found in paleoseismic trenches at the surface (J. J. Lienkaemper, personal commununication).

[10] Several lines of evidence, including seismic velocities, gravity data, nearby drill holes, and local surficial geology, lead us to conclude that the basal reflection F west of the fault probably represents the top of the Franciscan Complex, whereas the basal reflection G east of the fault probably represents the top of the Cretaceous Great Valley Sequence (GVS). The presence of two different rock types on either side of the fault is consistent with its strike-slip history. Interval velocities derived from the stacking velocities indicate that the F (3000 m/s) and G (2300 m/s) reflectors are different rock types, however, our seismic spread length was too short to record refracted phases from the basement reflector F that would have helped constrain its identification. Regional gravity and a gravity profile coincident with our seismic profile indicate a generally flat-lying basement surface along the length of the seismic profile at roughly 460 to 500 m depth, with little or no change in basement depth and no anomaly across the fault (Figure 4). The gravity data imply that this basement surface gradually shallows westward approaching the Coyote Hills, where Franciscan rocks are exposed at the surface about 8 km west of the seismic profile [*Graymer et al.*, 1996]. Between the Coyote Hills and the west end of the seismic profile, three drill holes that reach Franciscan basement also

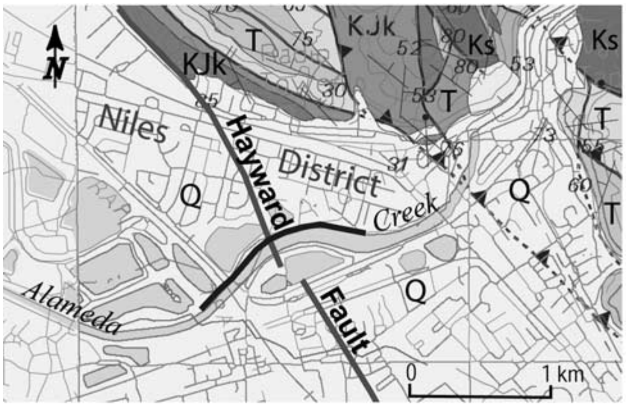

Figure 2. Geologic map in the vicinity of the seismic profile (heavy line along Alameda Creek) showing the Hayward fault trace through Niles and across Alameda Creek. Lightest gray areas are Quaternary alluvium (Q), darker gray areas to the north and east of the seismic profile are Mesozoic (KJk and Ks) rocks of the Great Valley Sequence and Tertiary rocks (T). Modified from *Graymer et al.* [1996].

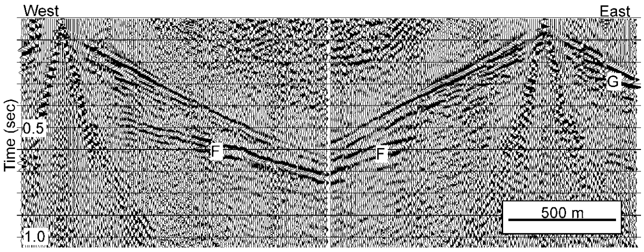

Figure 3. Example of two shot records showing prominent reflections F and G.

show the basement surface gradually shallowing to the west [*Hazelwood*, 1976].

[11] The lack of a gravity signature across the fault is confirmed by a 2-dimensional gravity model based on the reflection depth section (Figure 4). The model assumes Franciscan bedrock (2.67 g/cm^3) west of the fault, and lower density GVS bedrock (2.57 g/cm^3), east of the fault (similar to the rocks that crop out 1 km north of the seismic profile [*Graymer et al.*, 1996]), all overlain by alluvium (2.12 g/cm^3). The possibly surprising lack of a pronounced gravity anomaly across the fault results from the shallower bedrock east of the fault being less dense than that to the west, and the 70° east dip of the Hayward Fault, which places low-density alluvium beneath the GVS bedrock. We do not image layering within the GVS, apparently because it is dipping too steeply, from 50 to 80 degrees east as observed in the outcrops north of the seismic profile [*Graymer et al.*, 1996]. Instead, we image what appears to be a relatively smooth and undulating erosional surface.

4. Discussion: East Dipping Fault and the Mission Seismicity Trend

[12] The geometry of the southern Hayward fault has been a puzzle since seismicity data began to define a consistent pattern of hypocenters that were not located vertically below the surface trace [*Oppenheimer et al.*, 1993]. Although we know that the 1868 M ~ 6.8 earthquake ruptured the ground surface to southern Fremont [*Lawson*, 1908], and the fault trace is currently creeping at 5–9 mm/yr, beginning at about San Leandro, seismicity diverges to the southeast from the surface trace of the Hayward fault, in what is known as the Mission Seismicity Trend (henceforth, Mission trend) as shown in Figure 5a [*Wong and Hemphill-Haley*, 1992; *Oppenheimer et al.*, 1993; *Andrews et al.*, 1993]. In the vicinity of our seismic profile this seismicity trend is located about 2 to 3 km east of the surface trace of the Hayward fault (Figure 5a). This "off-fault" pattern, or lack of seismicity directly below the fault, has led some to infer that the southern Hayward fault at depth is locked between major events, and that the Mission trend marks a secondary deep structure that con-

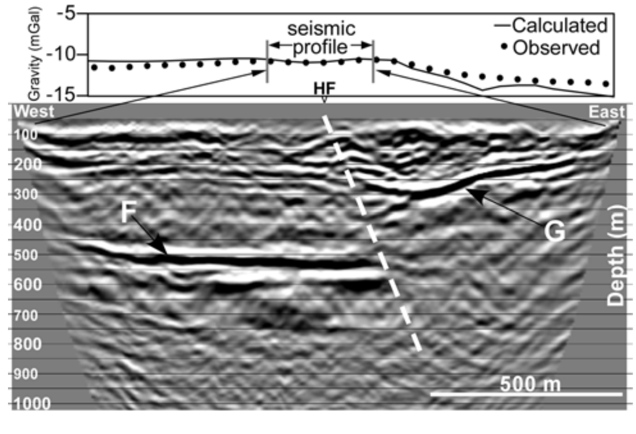

Figure 4. (top) Observed and calculated gravity along the seismic profile and across the Hayward fault. (bottom) Migrated depth section from seismic reflection profile showing location of the east-dipping Hayward fault (dashed line) and its projection to the mapped surface trace (HF). Reflections labeled F (top of Franciscan Complex) and G (top of Great Valley Sequence) are the same as those labeled in Figure 3.

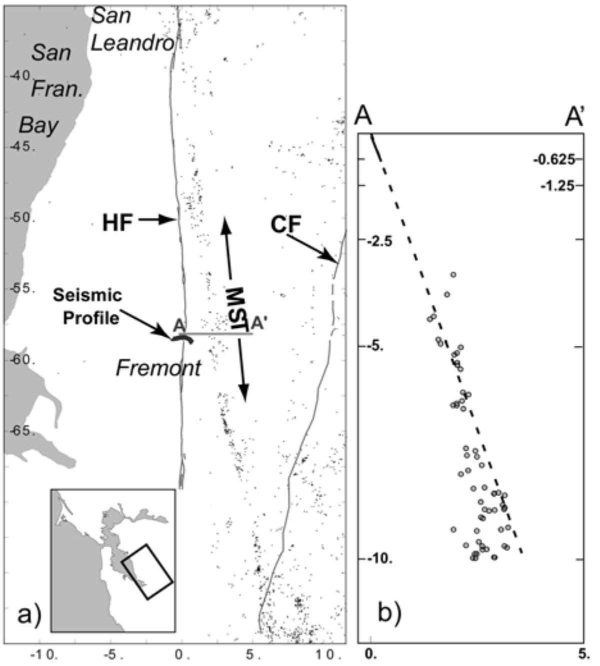

Figure 5. (a) Map view showing the surface trace of the creeping Hayward Fault (HF), the Calaveras Fault (CF), and the Mission Seismicity Trend (MST) connecting the two faults at depth at the south end of the MST. Small dots show the epicenters of double-difference (d-d) relocated earthquakes [*Waldhauser and Ellsworth*, 2002]. The numbers along the left and bottom sides follow *Lienkaemper* [1992] and are the distances in kilometers along the Hayward Fault trend measured from Point Pinole where the fault goes offshore. The Hayward fault traces were digitized from *Lienkaemper* [1992], and the Calaveras Fault came from *Jennings* [1977]. Gray dashed line A–A′ is the location of the seismicity cross section shown in Figure 5b. (b) Cross-section view of seismicity along A–A′. Circles show the hypocenters of d-d relocated earthquakes. The numbers along the left and bottom indicate depth and distance in kilometers. Hayward fault dip at 70° interpreted from seismic reflection profile shown as heavy line in the near surface. Projection of 70° dip down to seismicity shown by dashed line.

nects the Calaveras and Hayward faults [*Oppenheimer et al.*, 1993; *Andrews et al.*, 1993; *Waldhauser and Ellsworth*, 2002]. *Wong and Hemphill-Haley* [1992] suggested that the Mission trend represents the possibility of a seismically-active buried trace of the Hayward fault located east of its mapped trace. *Manaker et al.* [2005], *Simpson et al.* [2004], and *Ponce et al.* [2003], alternatively, suggested that the mapped southern Hayward fault dips to the east to connect with the deeper seismicity trends in the 3 to 6 km depth range. Further support of the relatively simple interpretation presented in this study comes from *Manaker et al.* [2005], who concluded that most of the seismicity along the northern portion of the Mission trend appears to lie on a single northeast-dipping fault plane.

[13] This study provides the first direct evidence that the southern Hayward fault dips about 70° east in the 100 to 650 m depth range, projects upward to the mapped creeping surface trace, and projects downward to connect with the "off-fault" east-dipping Mission trend in the 3 to 10 km depth range (Figure 5b). This interpretation implies that the southern Hayward fault at depth is not a vertical fault lacking microseismicity, but that the Mission trend, rather than being an independent structure, actually represents the main Hayward fault trace at depth. There is little evidence of any dip-slip faulting along the Mission trend [*Wong and Hemphill-Haley*, 1992; *Andrews et al.*, 1993; *Waldhauser and Ellsworth*, 2002], although there are few focal mechanisms showing oblique right-lateral slip, particularly near San Leandro, which may be the result of secondary reverse faults located near the main trace [*Oppenheimer et al.*, 1993]. Recent studies show that focal mechanisms along the Hayward fault are consistent with large-scale right-lateral slip and that strike-slip events predominate over reverse dip-slip events on the southern Hayward fault [*Hardebeck et al.*, 2004; *Manaker et al.*, 2005]; however, the lack of dip-slip mechanisms does not preclude a future large earthquake with significant reverse motion. The proposed geometry, in fact, requires such deformation [*Andrews et al.*, 1993].

[14] The 3D geometry of the Hayward fault at depth has importance not only for inferring the locations of the locked patches that may generate the next large earthquake on the southern part of the fault [e.g., *Schmidt et al.*, 2005], but for modeling scenarios of such an event in order to predict locations of severe ground shaking and potential damage. More speculatively, if the main surface of the Hayward fault does indeed directly connect at depth with the Calaveras fault, thus lengthening potential fault rupture, this might affect the estimates of potential event magnitudes that could occur on the combined fault surfaces, which in turn could affect hazard assessments for the San Francisco Bay region.

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J. K. Odum, W. J. Stephenson, and R. A. Williams, U.S. Geological Survey, MS966, Box 25046, Golden, CO 80225, USA. (rawilliams@usgs.gov)

R. C. Jachens, D. A. Ponce, and R. W. Simpson, U.S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025–3591, USA.