Dipping San Andreas and Hayward faults revealed beneath San Francisco Bay, California

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ABSTRACT

The San Francisco Bay area is crossed by several right-lateral strike-slip faults of the San Andreas fault zone. Fault-plane reflections reveal that two of these faults, the San Andreas and Hayward, dip toward each other below seismogenic depths at 60° and 70°, respectively, and persist to the base of the crust. Previously, a horizontal detachment linking the two faults in the lower crust beneath San Francisco Bay was proposed. The only near-vertical-incidence reflection data available prior to the most recent experiment in 1997 were recorded parallel to the major fault structures. When the new reflection data recorded orthogonal to the faults are compared with the older data, the highest amplitude reflections show clear variations in moveout with recording azimuth. In addition, reflection times consistently increase with distance from the faults. If the reflectors were horizontal, reflection moveout would be independent of azimuth, and reflection times would be independent of distance from the faults. The best-fit solution from three-dimensional traveltime modeling is a pair of high-angle dipping surfaces. The close correspondence of these dipping structures with the San Andreas and Hayward faults leads us to conclude that they are the faults beneath seismogenic depths. If the faults retain their observed dips, they would converge into a single zone in the upper mantle ~45 km beneath the surface, although we can only observe them in the crust.

INTRODUCTION

The San Francisco Bay area occupies a unique part of the San Andreas fault system; just south of the region, the fault splays into several segments that are east and west of the bay. Two major right-lateral strike-slip strands—the peninsular segment of the San Andreas and the Hayward fault (Fig. 1)—have sustained lethal earthquakes during historic time. Regionally, earthquakes are observed at 0–15 km depths (e.g., Hill et al., 1990), and their distribution indicates that the major strike-slip faults are near vertical in the seismogenic crust. However, many researchers have proposed that a low-angle detachment fault between 15 and 20 km depth could link slip between the San Andreas and Hayward faults (e.g., Furlong, 1993; Brocher et al., 1994; Bürgmann, 1997). In this paper we present new seismic reflection data showing that the lower crust is cut by both the San Andreas and Hayward faults beneath the maximum depth of seismicity, limiting the role for a detachment fault in accommodating deep slip. Furthermore, we show that these two faults dip toward each other in the lower crust.

The U.S. Geological Survey has been conducting active- and passive-source seismic studies in the San Francisco Bay area in an effort to characterize the deep structure of the San Andreas fault zone (Bay Area Seismic Imaging Experiments, BASIX). Large airgun sources were recorded in the bay on moored hydrophones in 1991, but strong tidal currents made the data quality poor. Preliminary interpretation of those data supported the presence of a horizontal detachment surface (Brocher et al., 1994). In 1995, data quality was improved by deploying a 2.4-km-long ocean-bottom hydrophone cable at fixed locations in San Francisco Bay, parallel to the major faults (Fig. 1). Airgun sources were detonated in the bay and through the Golden Gate that were recorded at the hydrophone cable deployments. High-amplitude reflected energy was recorded to 9 s two-way traveltime (twtt) on the cables and was especially prominent at 6–7 s twtt. In 1995, a land reflection spread was also deployed on San Francisco Peninsula, southwest of and orthogonal to the San Andreas fault, that recorded large chemical explosive sources. Analysis of the land data showed high-amplitude reflections that came from the lower crust beneath the surface trace of the Hayward fault; it was concluded that those events reflected from a 70°SW dipping Hayward fault between 18 and 24 km depth (Parsons, 1998). In addition, a three-dimensional velocity model of the San Francisco Bay area was developed from earthquake traveltimes (Parsons and Zoback, 1997).

NEW RESULTS FROM BENEATH THE BAY

We conducted a marine seismic experiment in 1997 to localize the source of high-amplitude reflections beneath San Francisco Bay. High-amplitude reflections were observed from many consecutive airgun blasts between 6 and 9 s twtt throughout the bay (Figs. 1, 2, and 3) and required only minor data processing (gain, bandpass filtering). We applied the same operational procedure described for the 1995 marine experiment except that an effort was made to gather more data orthogonal to the major faults because of the observation of out-of-plane reflections on the 1995 land reflection profiles on San Francisco Peninsula. For example, to determine if the previously observed high-amplitude, 6–9 s twtt reflections came from a horizontal surface, we deployed bottom cables in a crossing pattern where reflections were known to occur (Fig. 4).

We find strong variation in reflection moveout as a function of the bottom-cable azimuth. A reflection from a horizontal interface arrives at the

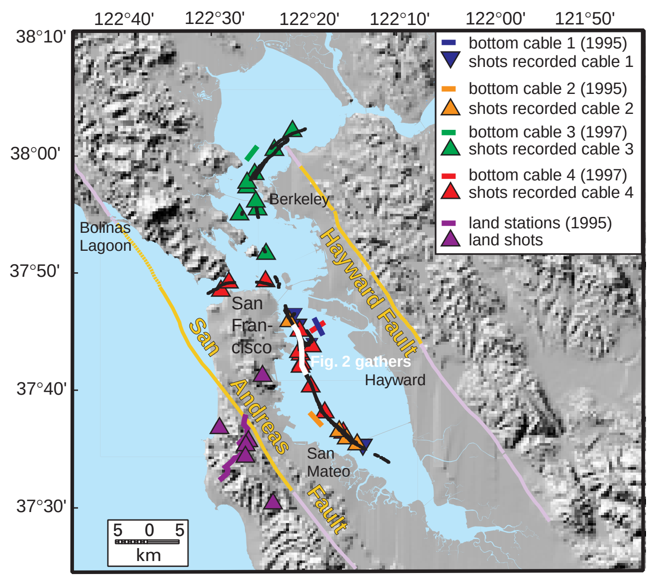

Figure 1. Location of land and marine seismic source and receiver groups used to model lower crustal extent of San Andreas and Hayward faults. Bottom cables and their corresponding sources are color coded. Each source point marked is modeled gather from group of at least 5–20 consecutive airgun shots (plotted as black dots) like those shown in Figure 2. Parts of San Andreas and Hayward faults from which we observe dipping reflections are colored yellow. Sequence of shot gathers shown in Figure 2 is highlighted with white line.

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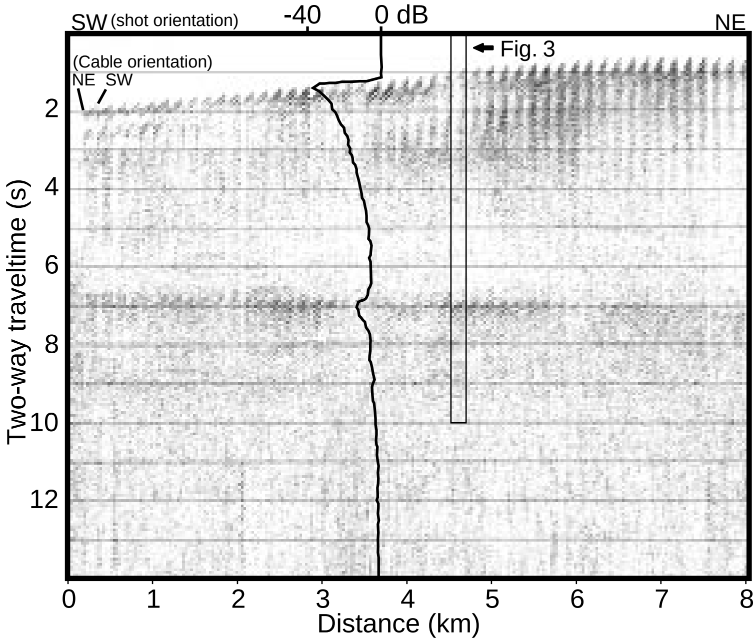

Figure 2. Consecutive shot gathers showing prominent (~8 dB above background) reflections at 7 s two-way traveltime. These gathers were recorded on bottom cable 4 (red line in Fig. 1) from shots shown by white line in Figure 1. Boxed area identifies gather displayed in Figure 3, and reflection modeled in Figure 4B. There is little variation from one shot to next, so representative gathers were modeled from runs of shots like this one as identified by black dots in Figure 1.

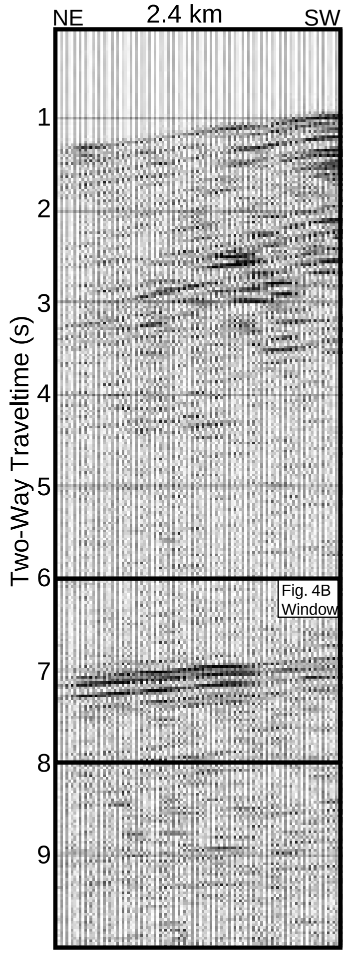

Figure 3. Complete shot gather from sequence shown in Figure 2. Prominent reflection at 7 s is modeled in Figure 4, and represents style of reflection modeled in this paper.

surface as a hyperbolic function in time with increasing offset; this effect is known as moveout and obeys the approximate relation $(x_2^2 - x_1^2)/2V^2t_0$, where x denotes observation positions, V is velocity, and t_0 is the zero-offset reflection time. The expected moveout across the 2.4 km recording cable from a horizontal reflector at 7 s twtt for a shot positioned 2.5 km away from the cable is about 40 ms. Much larger moveout values (hundreds of milliseconds) imply a dipping reflector. Reflections recorded parallel to the San Andreas fault are nearly horizontal at about 7 s twtt (Fig. 4A), whereas reflections recorded orthogonal to the San Andreas fault dip down to the northeast (more than 200 ms difference in moveout over a 2.4 km distance compared to the reflections recorded parallel to the fault) (Fig. 4B). If the reflector were horizontal, moveout would be independent of azimuth. Thus the reflector must dip down to the northeast. We find a consistent pattern of azimuthal dependence of moveout throughout San Francisco Bay (Fig. 4C).

We employ three-dimensional finite-difference traveltime calculations (Hole and Zelt, 1995) to isolate the northeast-dipping surface responsible for the high-amplitude reflections recorded in San Francisco Bay. We apply a three-dimensional velocity model for the bay area developed from earthquake sources (Parsons and Zoback, 1997) in combination with an extrapolation of a two-dimensional lower crustal velocity model (Holbrook et al., 1996). The reflector that best satisfies all the northeast-dipping reflection traveltimes[1] dips 60° down beginning at 12 km depth and parallels the strike of the San Andreas fault in our study area (Figs. 1 and 5). The modeled reflector dip begins beneath the downward vertical projection from the surface trace of the San Andreas fault (Fig. 5). The uniqueness of this model is tested by a large variety of shot-receiver offsets and reflection angles (Figs. 4, 5, and 6). For example, in Figure 6A, the traveltime of the same reflection event progressively increases with increasing shot distance from the San Andreas fault. Such a relationship can only be explained by a steep dip down to the northeast. We observe a dependence of reflection traveltime on distance from the San Andreas fault throughout the bay (Fig. 6C).

All the reflection traveltimes were fit to within a root-mean-square (RMS) 240 ms static shift (measured at the center of each reflection). The reflection moveout variation was fit to within an 80 ms RMS error (measured from end to end); the spread in moveout vs. azimuth in Figure 4C is the result of a two-dimensional projection of varying shot-receiver geometry and velocity variations. These errors are less than the uncertainties inherent in the three-dimensional velocity model that we apply (370 ms) (Parsons and Zoback, 1997). The fits to the example reflections in Figures 4 and 6 and the depth points shown in Figure 5 were made by using the three-dimensional model. The collective moveout observations constrain a range in dip from 55° to 62°; the best fit is at 60°.

Repeated reflection observations at different offset ranges provide the overlapping depth coverage that limits the possible solutions. The sources identified in Figure 1 in San Francisco Bay represent groups of airgun shots ranging from at least 5 to 20 sequential reflection observations. Thus, although 33 modeled source points are marked in Figure 1, there are actually hundreds of repeated observations (plotted as black dots in Fig. 1). The airgun spacing was about 100 m, generating only very small variations in reflection time and moveout between adjacent shots. However, the repeated sequential reflection observations give us confidence in their validity. The distribution in the source and receiver locations produces reflection depth points on the 60°NE dipping structure along the strike of much

[1]GSA Data Repository item 9973, Reflection shot gathers from San Francisco Bay with three-dimensional traveltime fits, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, editing@geosociety.org, or at www.geosociety.org/pubs/drpint.htm.

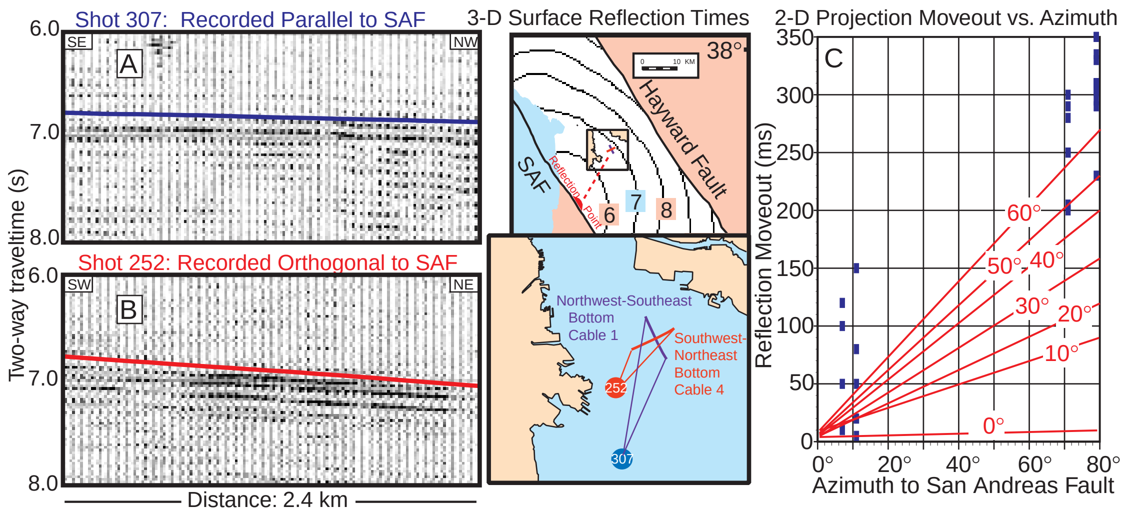

Figure 4. Example reflections are shown from two crossing bottom cable profiles oriented (A) parallel and (B) orthogonal to strike of San Andreas (SAF) and Hayward faults. If these events reflected from horizontal or low-angle impedance contrast, azimuth of recording cables would be unimportant, and both events would appear nearly flat. However, strong dependence on receiver azimuth is noted: more than 200 ms greater moveout is observed on cable orthogonal to San Andreas fault than on that parallel to it. This observation tells us that reflector dips down to northeast. Both arrivals are closely fit by a 60°NE dipping reflector that parallels San Andreas fault and begins at 12 km depth. Reflected traveltime contours from three-dimensional modeling (Hole and Zelt, 1995) of events are shown in map view; two-dimensional cross-section view is presented in Figure 3. C: Reflection moveout plotted vs. recording cable azimuth with respect to San Andreas fault for all 33 modeled reflection gathers. Events with greatest moveout are observed on orthogonal cables. Expected moveout from variety of dips is plotted on observations. Spread in moveout observations results from this two-dimensional projection of three-dimensional geometry that includes varying source-receiver offsets and local velocity changes. Root-mean-square misfit of three-dimensional moveout is 80 ms.

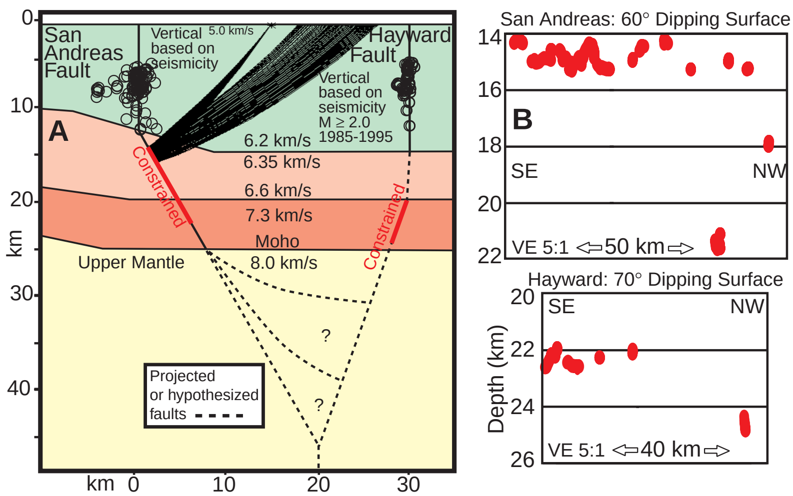

Figure 5. A: Cross-section view of San Andreas and Hayward faults as modeled from reflections. Earthquake hypocenters show that faults are near vertical in upper ~12 km. Fault planes colored red show depth extent that reflections from them are modeled. Dashed lines show projected and conjectural relationships between two faults in upper mantle. B: Subsurface reflection depth point coverage on San Andreas and Hayward faults projected onto two-dimensional planes associated with segments identified in Figure 1. Points represent only 33 modeled gathers; complete data coverage is more continuous. Three-dimensional model planes have constant dip, but bend where vertical parts of faults bend.

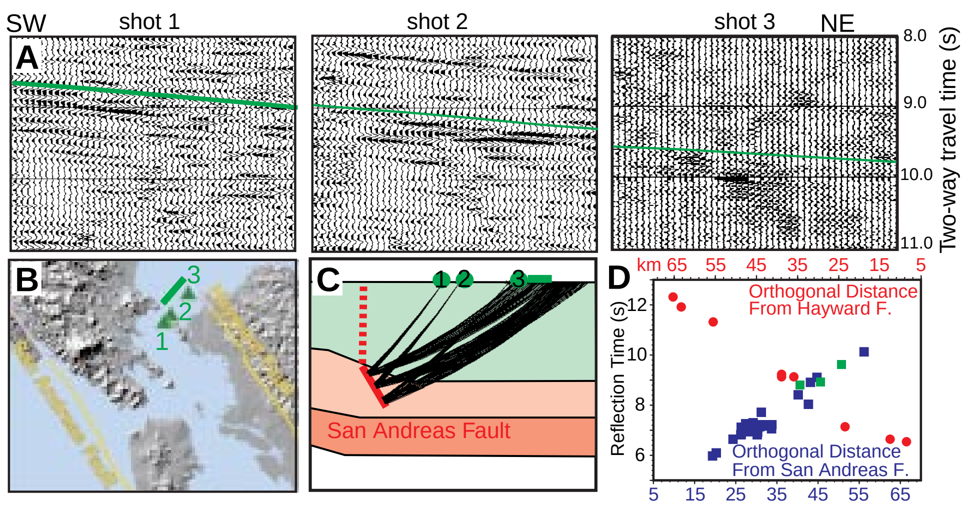

Figure 6. A: Three shot gathers recorded in (B) northern San Francisco Bay, each showing same reflection event from San Andreas fault. Traveltime is progressively later with increasing shot distance northeast of fault, consequence of dipping reflector as illustrated in C. Calculated three-dimensional reflection traveltimes from 60° modeled reflector are superimposed on data plots. D: Reflection times to center of all modeled reflections as function of their distance from San Andreas (blue squares) or Hayward (red dots) faults. Those source-receiver pairs located farthest from faults have reflections with latest arrivals. Three green squares represent data examples shown in A.

of the San Andreas fault, from the north at Bolinas Lagoon to the city of San Mateo, a distance of 50 km (Fig. 1). The depth coverage on the dipping structure ranges from 14 to 22 km (Fig. 5B). This dipping horizon passes beneath a right step in the San Andreas fault where the 1906 M_w = 7.8 San Francisco earthquake is thought to have been initiated offshore of San Francisco (Zoback et al., 1999). We model the right step as a slight bend in the fault at depth (Fig. 1).

A previously defined model of the dipping Hayward fault (Parsons, 1998) (Fig. 5A) is reinforced by a separate group of southwest-dipping reflections from beneath San Francisco Bay (Fig. 6). Among the 33 groups of airgun sources shown in Figure 1, 10 produced reflections from a 70°SW dipping structure between 22 and 24 km depth paralleling the Hayward fault east of San Francisco Bay (Figs. 1 and 5). These observations support the conclusions made from reflections recorded on land in 1995 (Parsons, 1998) (Fig. 1). We observe the dipping structure associated with the Hayward fault from north of the city of Berkeley to the city of Hayward, an along-strike distance of 34 km (Fig. 1). The combined land and marine depth coverage ranges from 18 to 24 km. The Hayward fault is older than the peninsular segment of the San Andreas fault, has more cumulative slip (50–70 km compared with 19–23 km) (McLaughlin et al., 1996; Cummings, 1968), and appears to have a steeper dip that begins deeper in the crust. Virtually all of the coherent, high-amplitude reflections recorded beneath San Francisco Bay at near-vertical incidence have been fit to dipping structures associated with either the San Andreas or Hayward faults. No continuous high-amplitude horizontal reflections were observed from the Moho or the top of the lower crust, although weaker, discontinuous events were observed on some gathers that might be from lower angled horizons beneath the bay.

The reflections we observe from beneath San Francisco Bay are typically high amplitude (~8 dB above background). Such high amplitudes require that the reflectors represent strong acoustic impedance contrasts. Possible sources include sharp lithologic contrasts, highly sheared and metamorphosed rocks, or fluid-filled zones. The dipping structures do not appear to be symmetrical about the fault traces because no analogous northeast-dipping reflections were recorded on bottom cables located east of the Hayward fault despite high signal-to-noise ratios. Because of the long, fault-coincident continuity of the modeled reflectors and high reflection amplitudes, we conclude that these dipping, lower crustal horizons represent the San Andreas and Hayward fault zones at depth.

IMPLICATIONS AND CONCLUSIONS

The San Andreas and Hayward faults pierce the entire crust and dip toward each other at constant dip below seismogenic depths. Theoretically, no low-angle detachment surface is required anywhere beneath San Francisco Bay to balance seismogenic strain, provided that the observed dipping faults can accommodate all the aseismic strain. Our direct observation of strike-slip faults in the deep crust supports the results of Holbrook et al. (1996) and Henstock et al. (1997), who observed offset structure and/or velocity contrasts in the lower crust across the San Andreas fault, and King et al. (1987) and Sanders (1990), who inferred deep slip from geodetic and seismicity studies.

It is important to note that the results presented here do not dispute the observation of a regional high-velocity layer previously observed at long source-receiver offsets (Brocher et al., 1994; Holbrook et al., 1996). Wide-angle reflections can be returned from a velocity gradient that is transparent at near-vertical incidence. Our results show that the higher resolution, near-vertical-incidence reflections do not correspond to the top of the high-velocity, mafic composition, lower crustal layer, as previously interpreted.

If the observed lower crustal fault dips persist beneath the crust, the two faults would intersect one another at about 45 km depth, 20 km into the upper mantle (Fig. 5). Below that depth, a single fault might accommodate all the relative Pacific–North American plate motion. Our observations of the fault-plane reflections are limited to crustal depths because the constraints of marine recording in San Francisco Bay prohibit the long source-receiver offsets required to observe deeper, dipping reflections. We thus can only speculate about the sub-Moho geometry of the faults (Fig. 5A). It is possible that the faults could change dip after crossing the rheologic boundary at the Moho; the initiation of fault dip appears to be related to layer boundaries (seismic velocity steps), identified by wide-angle seismic methods, that also represent rheologic boundaries (Holbrook et al., 1996). Thus a lower angle fault might still be present in the upper mantle (Fig. 5A), although we observe no reflections from any near-horizontal boundaries at later traveltimes that could be observed at near offsets.

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