Active detachment faulting in the San Francisco Bay area?

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ABSTRACT

Measurements of crustal deformation may help determine if mid-crustal reflectors imaged at ~15 km depth below the San Francisco Bay area, California, are active detachment horizons that accommodate strike-slip shear and/or convergence across the region. Elastic dislocation models predict distinguishable secular surface displacements for fault geometries involving vertical shear zones or horizontal detachments only where faults step, bend, or branch along their trace. In the southern San Francisco Bay area, the San Andreas, Hayward, and Calaveras fault zones splay from a single trace of the creeping central segment of the San Andreas fault. Whereas measured horizontal surface displacements in the central and northern bay area are equally well predicted by models of strike-slip faults below the major faults and by models involving a detachment, a zone of fault-normal motion observed in the southern bay area is not well explained by models involving only vertical strike-slip faults. A model involving detachment slip parallel to the San Andreas fault appears more consistent with the observations. We find no evidence for significant San Andreas fault-normal regional contraction or detachment faulting. However, additional data and better models are required to more confidently constrain the three-dimensional active fault architecture.

INTRODUCTION

The San Andreas fault system in central California is a transform plate boundary accommodating ~40 mm/yr of right-lateral motion between the Pacific plate and the Sierra Nevada–Great Valley block (Fig. 1) (Argus and Gordon, 1991). Geodetic measurements of plate boundary deformation agree to within a few millimeters per year with geologic estimates (Argus and Gordon, 1991; Lisowski et al., 1991). Regional contraction across the San Andreas fault system has occurred at rates of ~1–5 mm/yr since 3–5 Ma (Argus and Gordon, 1991; Harbert, 1991). Whereas the overall nature of the plate boundary (strike-slip with small amounts of contraction) is relatively unambiguous, the deep architecture and mechanics of the San Andreas fault system have proven enigmatic.

One view of the subsurface geometry of strike-slip faults suggests that faults continue at depth in subvertical shear zones throughout the lithosphere (Fig. 2B). Strain weakening may favor the localization of deformation in such tabular crustal shear zones (Gilbert et al., 1994). To represent vertical shear zones at depth, mechanical models of interseismic deformation commonly utilize buried vertical dislocations below 10–20 km to predict secular strain patterns (Savage and Burford, 1970; Lisowski et al., 1991; Bürgmann et al., 1994).

Another class of models assumes the existence of a viscous lower crust in which strain is broadly distributed (Savage and Prescott, 1978; Thatcher, 1983; Prescott and Yu, 1986). Models based on an elastic layer over a viscous substrate have been used successfully to predict time-dependent deformation following large strike-slip earthquakes (Thatcher, 1983; Pollitz and Sacks, 1992); however, they can be difficult to distinguish from vertical fault models (Savage, 1990). Related models propose that the subvertical strike-slip faults in the upper 10–15 km abut at a regional detachment horizon (Prescott and Yu, 1986). These subhorizontal shear zones may accommodate large amounts of transform-parallel motion and may transfer strike-slip shear between major strike-slip faults (Furlong and Verdonck, 1994). Regional detachments at depth may also accommodate San Andreas fault system perpendicular motion (Page and Brocher, 1993; Jones et al., 1994).

The BASIX (Bay Area Seismic Imaging Experiment) seismic reflection and refraction data image a regional seismic discontinuity (the 6s reflector) underlain by an ~10-km-thick unit of higher velocity rocks (Brocher et al., 1994). The discontinuity extends from west of the San Andreas fault to east of the Hayward-Calaveras faults at ~15–18 km depth (Brocher et al., 1994). However, variability in lower crustal seismic velocity suggests that compositions may change across major fault zones (Holbrook et al., 1996; Parsons and Zoback, 1997). It has been suggested that the 6s reflector may represent an active horizontal detachment fault or may be part of a zone of pervasive, distributed shear that links the San Andreas fault with the Hayward-Calaveras faults to the east (Fig. 2A) (Brocher et al., 1994; Furlong and Verdonck, 1994; Holbrook et al., 1996) and possibly extends to the Sierra Nevada (Jones et al., 1994).

Horizontal detachment models imply that the location of the plate boundary in the lower crust and upper mantle can be significantly offset from the surface traces of major strike-slip faults. The >15 km depth of the discontinuity imaged by BASIX and low seismicity at that

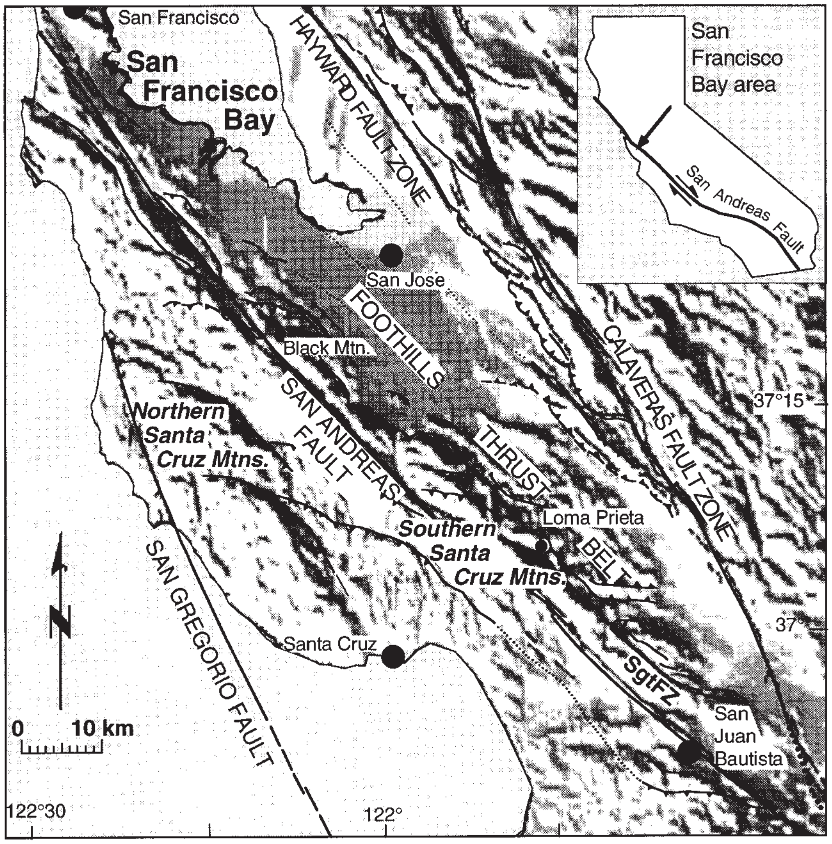


Figure 1. Fault map of San Francisco Bay area showing major fault zones and localities described in text. SgtFZ, Sargent fault zone.

Geology; December 1997; v. 25; no. 12; p. 1135–1138; 4 figures.

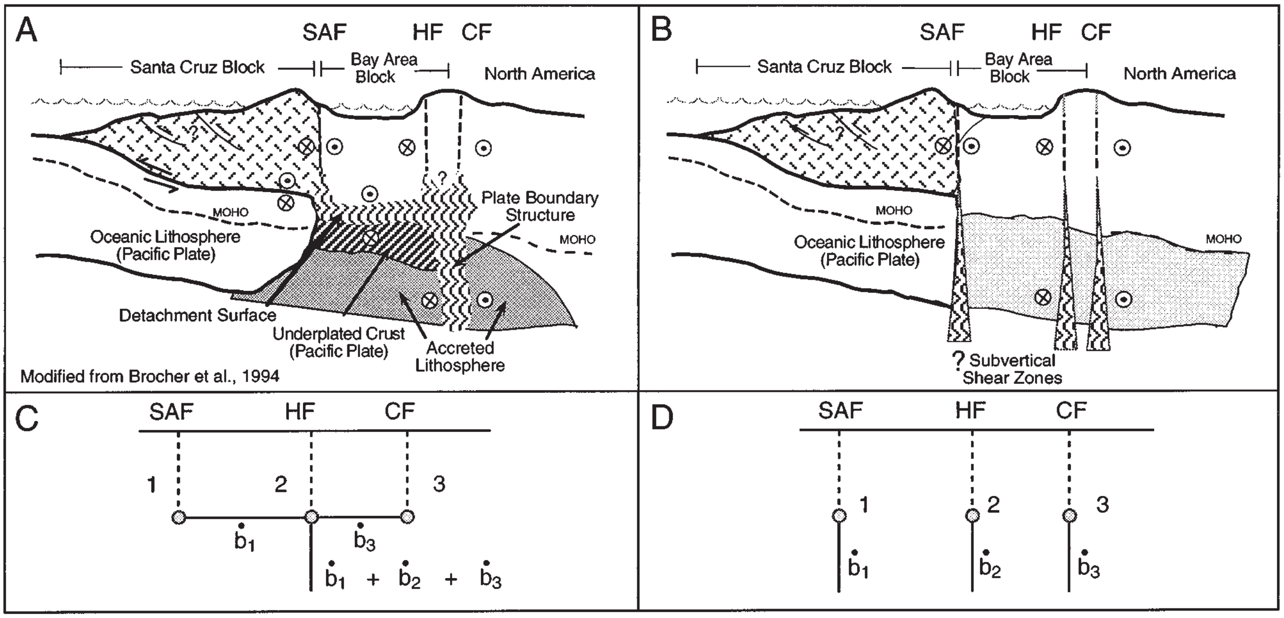


Figure 2. Schematic cross sections across San Francisco Bay area showing two end-member subsurface fault architectures. A: Subhorizontal detachment transfers displacement from shallow San Andreas fault (SAF) to Hayward-Calaveras fault (HF, CF) zone. Deep transform motion occurs predominantly below Hayward fault (modified from Brocher et al., 1994). B: Subvertical shear zones continue below all major strike-slip faults. Transform motion at depth is accommodated by mylonitic shear zones below brittle-ductile transition. C and D: Dislocation model geometries that produce identical surface displacements (based on Lisowski et al., 1991). Faults are parallel and infinitely long, and displacements are parallel to faults (plane strain).

depth suggest that deformation is accommodated by creep or ductile shearing. If a regional active detachment exists, it would play a fundamental role in the local earthquake cycle and interaction of bay area faults.

The lack of knowledge of the fundamental deep architecture and mechanics of the San Andreas fault system is an impediment to progress in understanding the mechanics of the earthquake cycle and the interaction of faults within the transform plate boundary. We test whether models involving a decoupling horizon are compatible with geodetic data spanning almost 20 yr by focusing on the branching region in the southern bay area (Fig. 1). Here, competing models of the subsurface fault architecture predict different displacement patterns. Previous interpretations of the displacement field in this region invoked only motion on vertical strike-slip faults and their lower crustal extensions (Savage et al., 1979; Thatcher, 1979; Matsu'ura et al., 1986; Bürgmann et al., 1997).

CRUSTAL DEFORMATION IN THE SOUTHERN SAN FRANCISCO BAY AREA

Precise geodetic measurements of interseismic deformation in the southern bay area have been carried out since the early 1970s (Lisowski et al., 1991). Except for the coseismic and postseismic effects of large earthquakes, the deformation rates appear to have been constant during this time (Lisowski et al., 1991; Savage et al., 1994; Bürgmann et al., 1997). Figure 3A shows the horizontal velocity field relative to a station at Loma Prieta (solid arrows with 95% confidence ellipses) in the region based on ~20 yr of trilateration data and 5 yr of Global Positioning System (GPS) data. We do not include data collected since the October 17, 1989, Loma Prieta earthquake, because the postseismic displacements are significantly different from preearthquake levels in this area (Savage et al., 1994; Bürgmann et al., 1997).

Figure 3A is plotted in an oblique Mercator projection about the Euler pole of Pacific plate to Sierra Nevada-Great Valley block motion. Structures or velocity vectors oriented parallel to the base or top of the plot are parallel to local plate motion. Also shown in Figure 3A are the velocities of the Pacific plate and the Sierra Nevada–Great Valley block determined from very long baseline interferometry (VLBI) data that measure 41.3 ± 3 mm/yr of relative motion oriented N34.5°W ± 2.5° between the San Andreas fault-bounding blocks at this latitude (D. F. Argus and R. G. Gordon, 1996, written commun.).

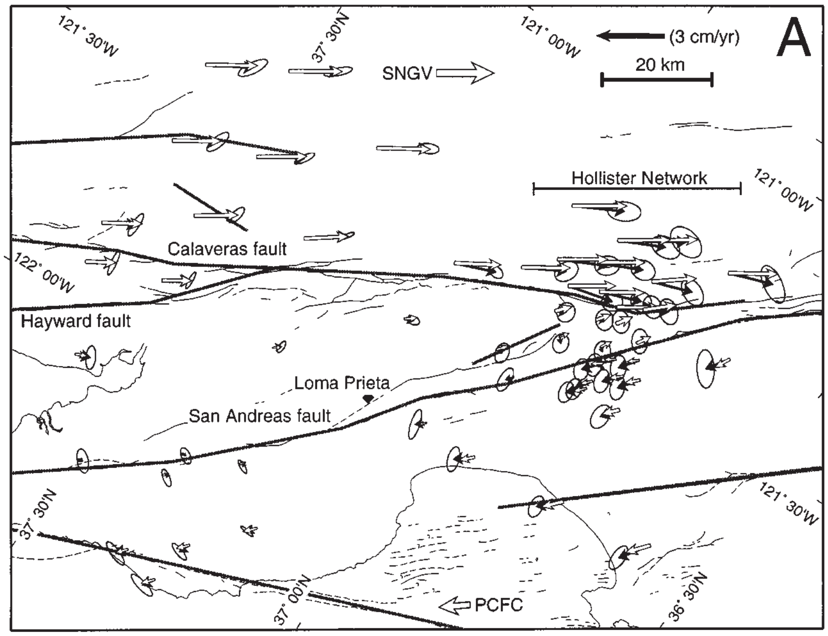
The displacement field broadens significantly from San Juan Bautista toward the northwest, where fault slip is distributed between the San Andreas, Hayward, and Calaveras fault zones. Measured velocities perpendicular to the plate motion trend are insignificant. However, stations adjacent to the splay of the southern Calaveras fault from the San Andreas fault diverge from parallelism with the regional displacement field in a zone of oblique convergence (Fig. 3A). We focus on this region, because this is the area where first-order models of vertical strike-slip shear and detachment faulting predict somewhat different patterns (Figs. 2 and 4).

MODELS OF ACTIVE FAULTING IN THE SAN FRANCISCO BAY AREA

Mechanical models allow us to interpret the surface deformation caused by active faulting and shear at depth. Unfortunately, models linking surface displacements to subsurface processes are often nonunique and depend on assumptions about the fault geometry, constitutive material behavior, and boundary conditions. Lisowski et al. (1991) illustrated that along long and parallel strike-slip faults, elastic dislocation models with subsurface fault geometry ranging from vertical to horizontal dislocation planes produce identical surface displacements, as long as the combined screw-dislocation Burgers vectors are the same (Fig. 2, C and D). That is, in the central and northern bay area, where the major strike-slip faults are subparallel, it is difficult to distinguish even such first-order models using surface displacements alone (Prescott and Yu, 1986). Therefore we focus our attention on regions of three-dimensionally complex fault geometry such as fault bends, steps, and branches, where distinguishable surface displacements may occur.

In our models, uniform-slip dislocations in an elastic, homogenous, and isotropic half-space represent the bay area faults (Okada, 1985). Interseismic shear about a locked strike-slip fault is approximated by slip on a buried vertical dislocation below the seismic zone at a rate comparable to the average geologic slip rate. Surface creep on the Hayward, Calaveras, and the central San Andreas faults is modeled by shallow dislocation elements.

To gain general intuition into the expected patterns, we first examine simplified models involv-



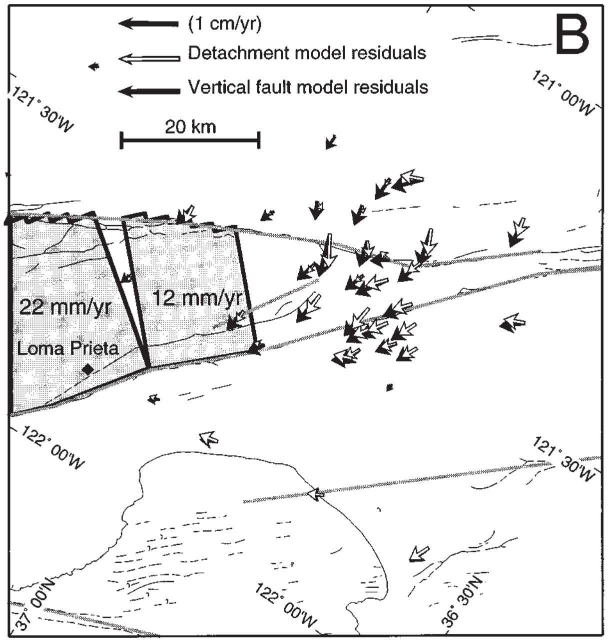


Figure 3. A: Comparison of measured velocities with 95% confidence ellipses (solid vectors) from geodetic measurements and displacements computed from elastic model derived by linear inversion of interseismic data (open vectors). Plate motions of Pacific plate (PCFC) and Sierra Nevada–Great Valley block (SNGV) show that most of relative plate motion is contained in our network and that little contraction occurs across the San Andreas fault system at this latitude. All displacements are shown relative to Loma Prieta in oblique Mercator projection about Pacific plate–SNGV block Euler pole. Shaded bold lines indicate surface projection of dislocation elements of interseismic model. B: Comparison of residual velocities (observed minus computed) from model shown in A and model in which decoupling horizon (shaded planes) is introduced between the San Andreas and Hayward faults. At depths greater than 15 km all block motion is accommodated beneath Hayward and Calaveras faults.

ing vertical strike-slip faults only and models with detachment transfer of strike-slip shear from the San Andreas fault to the Hayward fault, respectively. Figure 4 shows the geometry and differenced horizontal motions of these models; the inset table lists the model-fault slip rates. We find that model displacements away from the branching region do not differ significantly, but the detachment model produces an added component of contraction of ~3 mm/yr across the fault splay.

A more complex dislocation model of the bay area faults can explain much of the observed displacement field. We estimate fault slip rates on 78 dislocations using a linear inversion method (Du et al., 1992; Bürgmann et al., 1994, 1997) that inverts the trilateration and GPS data for slip on individual segments of the San Andreas fault system. All faults are assumed to be vertical with strike slip only. Dislocations representing deep fault slip extend to 3000 km depth to avoid effects caused by the bottom fault edge. See Bürgmann et al. (1994) for more details on the modeling procedures and model parameters.

The model velocities relative to Loma Prieta are shown in Figure 3A as open arrows. Significant deviations from the observed displacement field occur along the southern Calaveras fault in the closely spaced Hollister network (Fig. 3A). Stations just east of the Calaveras fault consistently appear to converge toward the fault, whereas the model predicts motions more parallel to the plate motion. The misfit of the model displacements and the geodetic data in Figure 3A comes primarily from motions in the splay-off region. The weighted residual sum of squares (*WRSS*) of this model is 244, and the misfit $\sqrt{WRRS/n - p}$ is 7.1, where n and p are the number of data (112 north and east velocities relative to Loma Prieta) and model parameters (78 strike-slip dislocations), respectively.

To test the hypothesis of slip transfer on horizontal detachments, we modify our model and (1) remove the San Andreas fault dislocation elements below 15 km, (2) add horizontal faults at 15 km depth that slip at 22 mm/yr in the central bay area and 12 mm/yr in the southern bay area, and (3) increase the slip on the deep Hayward and southern Calaveras faults to about 38 mm/yr (Fig. 3B). Slip on the detachment surfaces is prescribed to be parallel to the adjoining San Andreas fault segments. Figure 3B shows the shaded detachment surfaces and the residual displacements relative to Loma Prieta (observed minus model) computed from the detachment and vertical-fault models. We find that the inclusion of detachment slip improves the fit to the data. The *WRSS* and misfit in this model are 174 and 4.5, respectively, with $p = 71$ independent model parameters. More important than the better statistical fit to the data is that the detachment faulting model better predicts the fault-normal displacements in the branching region.

DISCUSSION

Active deformation and faulting in the subsurface cause geodetically measurable surface displacements that represent a window into the active architecture of the San Andreas fault system. Our results suggest that certain characteristics of the displacement field predicted by a detachment model are observed. It is possible that what we model as a discrete detachment fault at 15 km depth represents the effect of distributed pervasive shearing on subhorizontal structures, as suggested by Holbrook et al. (1996). Other physical processes could be invoked, such as complex flow patterns in a lower-crustal asthenosphere, active thrusting to the east of the Calaveras, and convergence by oblique slip on the southern Calaveras or the southern Sargent faults. We are currently densifying our GPS observations in this region (Bürgmann et al., 1997) and will carefully investigate the effects of inelastic crustal rheology.

High rates of contraction perpendicular to the San Andreas fault system are not currently measured between the Pacific plate and the Sierra Nevada–Great Valley block (Argus and Gordon, 1991) or along the San Andreas fault system (Fig. 3A), and are also not predicted by geologic plate-motion models averaged over the past 3 m.y. (DeMets et al., 1990). Active contraction

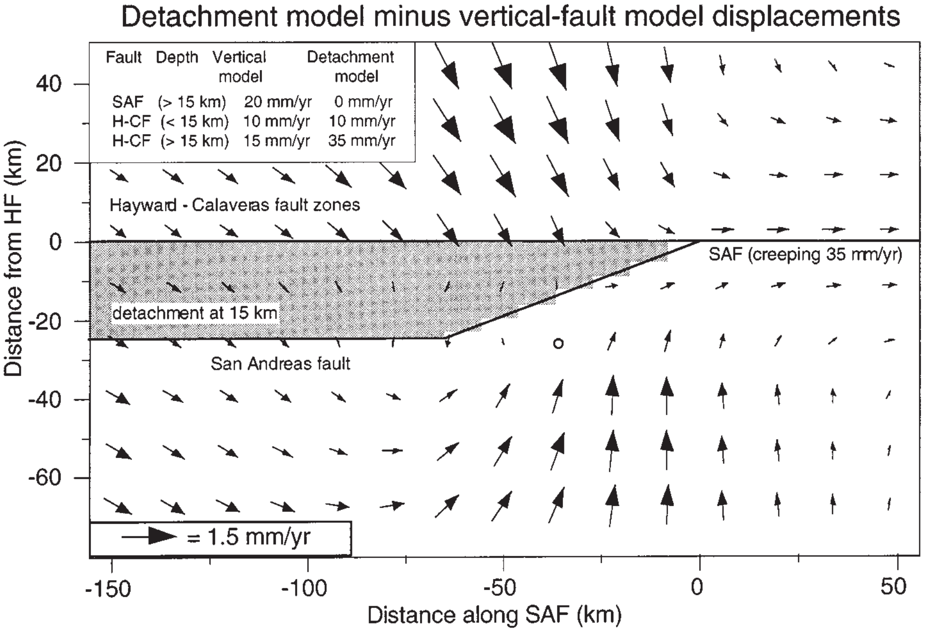


Figure 4. First-order model showing difference between vertical fault model and detachment model with transfer of deep slip from San Andreas (SAF) to Hayward-Calaveras fault zones (H-CF). Inset table gives slip magnitudes of dislocations.

across the plate boundary at this latitude does not exceed the resolution (~3 mm/yr) of the geodetic data. If we allow for dip-slip motion on the model detachment, a small decrease in the *WRSS* results from slip opposite to presumed Pacific underthrusting. The data do not allow for active underthrusting across the plate margin at the late Cenozoic rates (~50 km since 3–5 Ma) suggested by Jones et al. (1994).

CONCLUSIONS

Observed horizontal displacements in the southern San Francisco Bay area appear to be consistent with (but do not prove) a mechanical model of bay area faulting involving subhorizontal shear at depth that transfers slip from a deep central shear zone below the Hayward fault to the San Andreas fault. There is no evidence for San Andreas fault-perpendicular motion on this detachment; or for any appreciable regional contraction across the San Andreas fault system. Active contraction is localized near fault discontinuities and bends. Improving geodetic data sets and the development of more realistic fault models promise better understanding of the subsurface processes along active fault systems.

ACKNOWLEDGMENTS

I thank Tom Brocher and Fred Pollitz for comments and discussions. Mary Lou Zoback and Joann M. Stock provided valuable reviews. Supported by U.S. Geological Survey NEHRP External Program grant 1434-96-G-2744.

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Manuscript received May 5, 1997
Revised manuscript received September 19, 1997
Manuscript accepted September 26, 1997