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CRUSTAL DEFORMATION IN THE SAN FRANCISCO BAY AREA

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INVESTIGATIONS UNDERTAKEN

The primary goal of this project is to synthesize the deformation field in northern California, with emphasis on the populated San Francisco Bay region. We are combining Global Positioning System (GPS), Geodolite trilateration, and very-long-baseline interferometry observations collected primarily from U. S. Geological Survey (USGS) and Stanford University field campaigns, and the Bay Area Regional Deformation (BARD) permanent GPS network in northern California. Combining these data will enable us to clarify the rates of interseismic strain accumulation on the principal Bay area faults: the San Andreas, Hayward, and Calaveras faults, and their extensions north of the San Francisco Bay. We have analyzed deformation following the 1906 San Francisco and 1989 Loma Prieta earthquakes to better understand postseismic relaxation and stress transfer, and have performed time-dependent inversions and finite-element calculations to improve our understanding of the structure and rheology of the sub-seismogenic crust in the San Francisco Bay area.

During the past year, we have developed a first-order method for describing broadscale deformation patterns that is consistent with both plate tectonics and elastic strain accumulation on plate boundary faults. We assume interseismic deformation is a superposition of long-term rigid-body motions between faults, defined by angular velocities of spherical plates, and backslip on shallow locked portions of faults in an elastic half-space. We have applied this method to continuous GPS measurements collected during 1993–2000 at 35 sites in a profile extending from the San Francisco Bay area across northern California to eastern Nevada. Horizontal interseismic deformation observed at these sites is consistent with a simple 10-parameter model using 6 plates and 3 locked faults in the San Andreas system within the 1 mm yr^{-1} uncertainties of the observations. The data do not require zones of distributed deformation, and deformation on the boundaries between the plates is consistent with seismic, geologic, and other geodetic observations.

RESULTS

Modeling broadscale deformation in northern California and Nevada from plate motions and elastic strain accumulation

In Murray and Segall [2000], we report on measurements acquired from continuously operating Global Positioning System (GPS) networks that constrain Pacific-North America plate boundary deformation across northern California and Nevada (Figure 1). The observed deformation can be modeled as a combination of plate tectonic motions and interseismic elastic strain accumulation on faults. Strain accumulation effects are represented by backslip on shallow locked portions of faults superposed on long-term rigid-plate motions between faults. Similar dislocation models have been used in studies of subduction [Savage, 1983] and strike-slip zones [Matsuura et al., 1986], except we express the long-term motions using angular velocities of spherical plates rather than linear velocities of Cartesian blocks. Unlike deep-slip block fault models, motions far from plate boundary faults are consistent with those predicted by Euler poles, and elastic strains due to shallow backslip remain localized to the crust adjacent to the faults and to fault ends at triple junctions.

Data Analysis

We use continuous GPS data from the Bay Area Regional Deformation (BARD) network in northern California [Murray et al., 1998a], the northern Basin and Range (NBAR) network in Nevada and eastern California [Bennett et al., 1998], and stations operated by the U.S. Coast Guard, the Jet Propulsion Laboratory, and other agencies. We analyzed data collected on 2443 days at 35 stations that have been operating for at least 0.9 years from November 1993 to July 2000 using GAMIT/GLOBK software and distributed processing methods [e.g., Kogan et al., 2000; McClusky et al., 2000].

For each day, we estimated weakly constrained station positions assuming satellite orbits and Earth orientation parameters tightly constrained to globally derived values. Station velocities are estimated after tightly constraining the positions and velocities of several fiducial stations (ALGO, DRAO, FAIR) determined with respect to a stable North America plate (NA) reference frame [Kogan et al., 2000]. The daily station coordinate covariances were scaled to make the uncertainties consistent with the residual scatter about a linear rate, and we assumed 1 mm yr$^{-1/2}$ random walk variation in site position, following the approach of McClusky et al. [2000], to account for colored-noise error processes, such as monument wander. The estimated velocities have uncertainties ranging 0.9–2.7 mm yr^{-1} (Figure 1).

Deformation Model

We define station velocity at geocentric position $\mathbf{r}$ as

$$\mathbf{v}(\mathbf{r}) = \omega(\mathbf{r})\hat{\mathbf{\Omega}}(\mathbf{r}) \times \mathbf{r} - \sum_{f=1}^{F} (\mathbf{G} * \mathbf{s})_f \tag{1}$$

where the angular velocity vector is given by unit vector $\hat{\mathbf{\Omega}}$ (Euler pole latitude and longitude) and scalar magnitude ω (rate), and the effect of interseismic strain accumulation is given by an elastic Green's function $\mathbf{G}$ response to backslip distribution $\mathbf{s}$ on each of F faults.

Rigid-plate tectonics assume $\omega\hat{\mathbf{\Omega}}$ is constant within a plate. Allowing both $\hat{\mathbf{\Omega}}$ and ω to vary with $\mathbf{r}$ provides a completely general representation of distributed horizontal deformation. However, estimates of angular velocity for small regions are often poorly resolved. A useful intermediate representation is the polar deformation field [Minster and Jordan, 1984], which assumes $\hat{\mathbf{\Omega}}$ is constant within a region. Variations in ω with respect to oblique colatitude ϕ (relative to $\hat{\mathbf{\Omega}}$) then correspond to shear parallel to small circles, with velocities at the Earth's surface (radius a) given by $v = a\omega(\phi)\sin\phi$. The San Andreas system near the San Francisco Bay Area, where station motions are parallel to Pacific plate (PA) motion relative to NA (hereafter denoted PA-NA) predicted by NUVEL-1A [DeMets et al., 1994] but vary with distance from the Euler pole (Figure 2), can be modeled as a polar deformation field.

To first order, observed strain accumulation in the Bay Area can be modeled using 2D (anti-plane strain) screw dislocations, assuming a superposition of long-term block motions and backslip on the locked portions of the faults. Fault-parallel velocity at distance x from the fault, located at x=0 and locked from the surface to depth d, has the form $v = sgn(x)s/2 - (s/\pi)tan^{-1}(d/x)$, where s is the deep-slip rate on the fault, following [Savage and Burford, 1973]. When screw dislocations lie on small circles about a fixed $\hat{\mathbf{\Omega}}$, station motions are fault-parallel and Equation 1 becomes

$$v = a\omega(\phi)\sin\phi - \frac{a}{\pi}\sum_{f=1}^{F}\Delta\omega_f \sin\phi_f tan^{-1}\frac{d_f}{a(\phi-\phi_f)} \qquad (2)$$

Distance from each fault located at ϕ_f is $a(\phi-\phi_f)$. Each fault has deep-slip rate $s_f = a\Delta\omega_f\sin\phi_f$, where $\Delta\omega_f$ is the difference in angular velocity rates on either side of the fault. To fit the observed deformation field, we estimate angular velocity vectors assuming rigid plates while accounting for strain accumulation effects due to 2D screw dislocations.

Results

Based on seismic, geologic, and previous geodetic studies [e.g., Lisowski et al., 1991; Thatcher et al., 1999], we divide our study area into 6 plates (Figure 1). Adjacent to the Pacific plate (PA), 3 locked faults representing the San Andreas system bound two plates (SF and MZ). The faults lie on small circles about the NUVEL-1A PA-NA Euler pole location (48.7°N, 78.2°W), hereafter denoted $\hat{\mathbf{\Omega}}_{PA}^{NU}$. Given the high correlations associated with determining fault geometry and slip parameters in a parallel fault regime [Freymueller et al., 1999], we assume the fault locations (given in oblique colatitude) are known from surface geology studies and use locking depths derived from observed seismicity: San Andreas (33.6772°, 12.0 km), Hayward (33.4180°, 8.5 km), and Calaveras/Concord (33.2104°, 10.4 km).

The Sierran-Great Valley plate (SG) lies between the San Andreas system and the northern Walker Lane Belt (NWLB), and the Basin and Range province (BR) is divided into eastern (EB) and western (WB) plates about the Central Nevada Seismic Zone (CNSZ). We assume $d_f = 0$ on the NWLB and CNSZ because the station distribution is insufficient to reliably estimate strain accumulation. We use the component of oblique SG motion parallel to San Andreas motion in the Bay Area to determine $\Delta\omega_f$ across their boundary.

We simultaneously estimate $\hat{\mathbf{\Omega}}$ and ω for the SG, WB, and EB plates, and ω for the PA, SF, and MZ plates, assuming their pole locations equal $\hat{\mathbf{\Omega}}_{PA}^{NU}$. The misfit of 35 station horizontal velocities used to estimate 12 model parameters has a weighted residual χ^2=52.73. The estimated $\hat{\mathbf{\Omega}}_{WB}$ (42.9°N, 115.8°W) is near $\hat{\mathbf{\Omega}}_{EB}$ (42.9°N, 115.2°W). We find χ^2=52.79 when constraining $\hat{\mathbf{\Omega}}_{WB}$

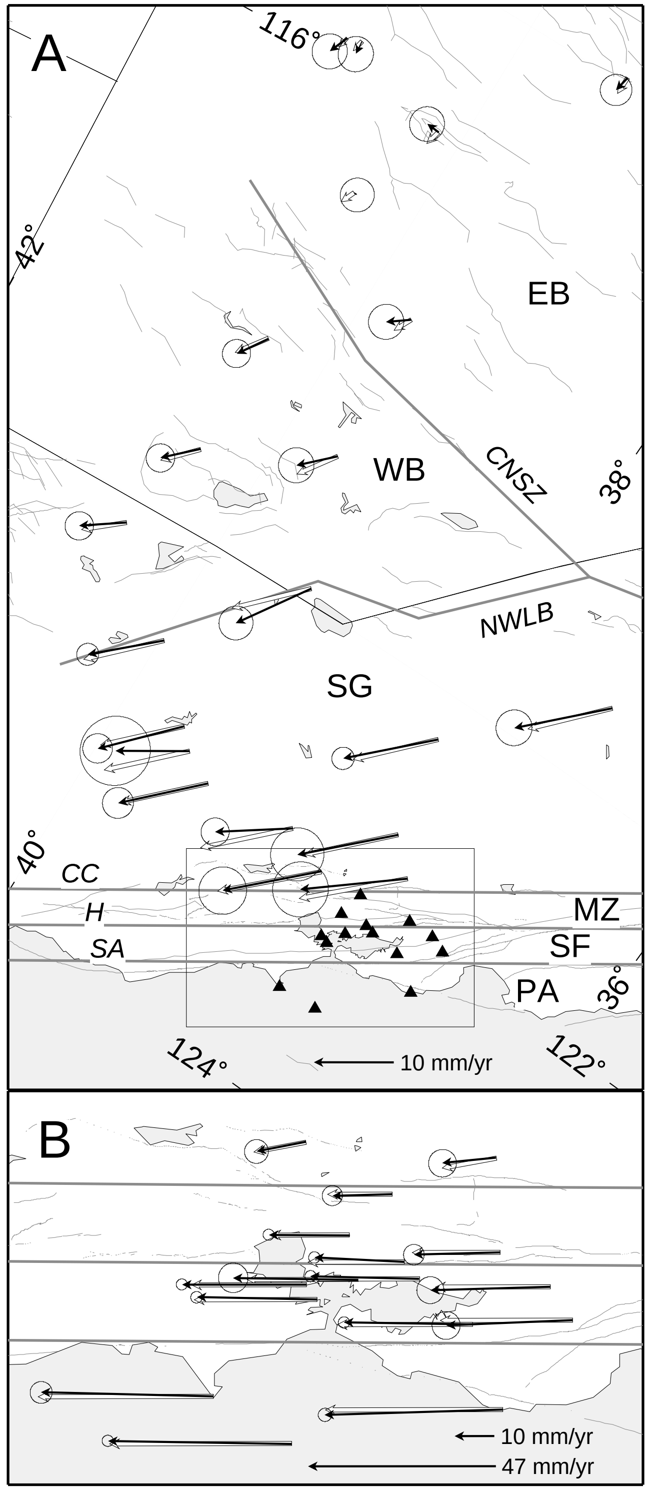

Figure 1: Predicted (open) and observed (solid) site velocities, with 95% confidence regions, relative to NA. Projection, oblique mercator about $\hat{\mathbf{\Omega}}_{PA}^{NU}$. A) northern California and Nevada (see box in Figure 3), with velocities of sites in box (triangles) omitted for clarity. B) San Francisco Bay area. Plates: PA = Pacific, SF = San Francisco, MZ = Martinez, SG = Sierran-Great Valley, WB = western Basin and Range, EB = eastern Basin and Range. Faults: SA = San Andreas, H = Hayward, CC = Concord/Calaveras, NWLB = northern Walker Lane Belt, CNSZ = central Nevada seismic zone.

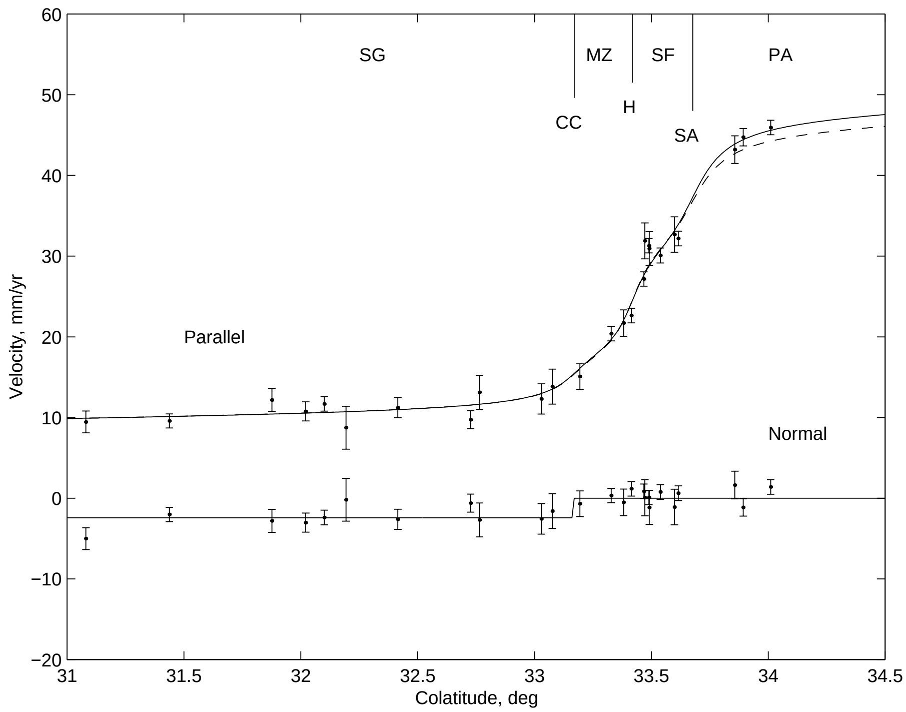

Figure 2: Velocities relative to NA versus colatitude from $\hat{\mathbf{\Omega}}_{PA}^{NU}$. Velocities, with one standard error bars, are parallel (top) and normal (bottom) to small circles about $\hat{\mathbf{\Omega}}_{PA}^{NU}$. Solid line, preferred model. Dashed line, model with ω_{PA} = ω_{PA}^{NU}, which has significantly greater misfit (95% confidence) than preferred model. Plate regions and San Andreas faults, with proportional depths, are shown schematically at top.

= $\hat{\mathbf{\Omega}}_{EB}$, an increase in misfit significant at only the 3.2% confidence level according to an F-ratio test. This suggests the data do not strongly require independent BR poles. Thus, the BR also can be described as a polar deformation field, with ω varying primarily in oblique longitude.

The preferred $\hat{\mathbf{\Omega}}_{WB}$ = $\hat{\mathbf{\Omega}}_{EB}$ model has χ^2 per degrees of freedom of 0.88, with an expected value of 1.0, suggesting that our colored-noise model used to estimate the velocity uncertainties may be slightly conservative. Horizontal station motions have an overall wrms misfit of 1.1 mm yr^{-1} and the misfit within each plate is 0.3–1.4 mm yr^{-1}, comparable to the data uncertainties.

We estimate parameter uncertainties using bootstrap methods [Freymueller et al., 1999] due to nonlinearities introduced by the $\hat{\mathbf{\Omega}}$ constraints. All ω are significantly greater than 0 at 95% confidence. The 2D-confidence regions of $\hat{\mathbf{\Omega}}_{BR}$ and $\hat{\mathbf{\Omega}}_{SG}$ are elongated in oblique latitude due to the limited distribution of stations in that direction (Figure 3). $\hat{\mathbf{\Omega}}_{SG}$ spans nearly 180° in oblique latitude, indicating that both clockwise (preferred) and counterclockwise rotation of SG are permissible. $\hat{\mathbf{\Omega}}_{SG}$ differs significantly from $\hat{\mathbf{\Omega}}_{PA}^{NU}$, but is marginally consistent with $\hat{\mathbf{\Omega}}_{BR}$. Other models combining one or more of the SG and BR Euler poles have significantly greater misfits at the 60–70% confidence.

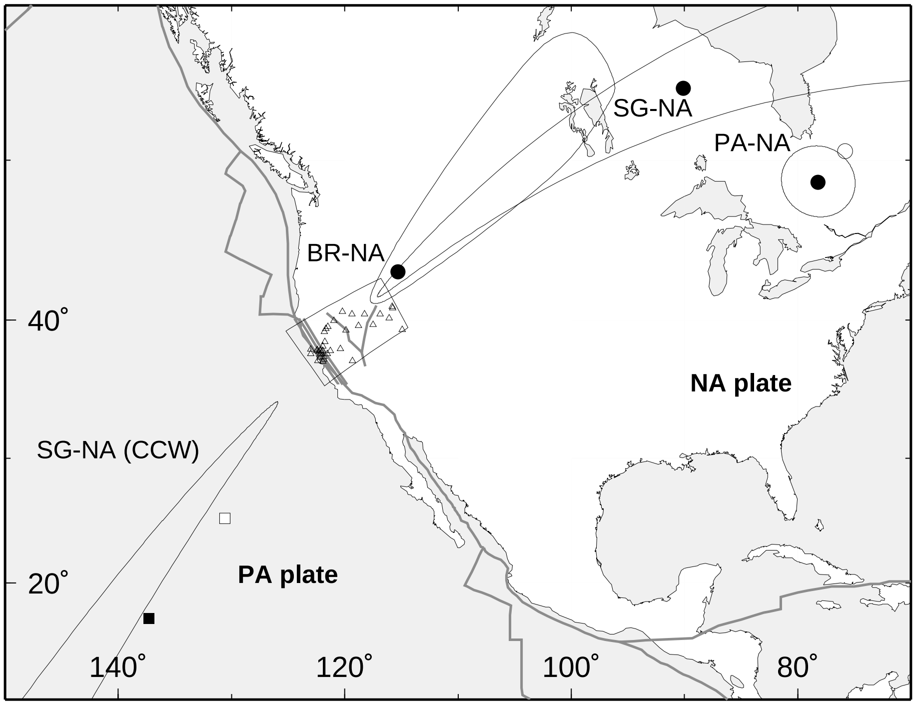

Figure 3: Estimated $\hat{\mathbf{\Omega}}$ (solid circles) with 95% confidence bootstrap regions. PA-NA is from NUVEL-1A. Open circle, alternative $\hat{\mathbf{\Omega}}_{PA}$ [*DeMets and Dixon*, 1999]. BR-NA is combined $\hat{\mathbf{\Omega}}_{WB}$ = $\hat{\mathbf{\Omega}}_{EB}$. The SG-NA region, which spans nearly 180°, is split into clockwise (top) and counterclockwise (bottom) rotation regions. Squares, alternative $\hat{\mathbf{\Omega}}_{SG}$: open, [*Argus and Gordon*, 2000]; solid, [*Dixon et al.*, 2000]. Box encloses stations and plate boundaries shown in Figure 1.

Discussion

We find that horizontal interseismic deformation in a profile extending from the San Francisco Bay area across northern California to eastern Nevada can be described by a simple 10-parameter model incorporating the angular velocities of 6 rigid plates and strain accumulation on 3 faults in the San Andreas system. The data do not require zones of distributed deformation, although more complex (e.g., viscoelastic) models are not precluded.

Plate boundary deformation predicted by this model is in good agreement with seismic, geologic, and other geodetic observations. If all EB-NA relative motion is accommodated on the Wasatch front in Utah, extension across it is about 2.4±1.2 mm yr^{-1} (all errors are given at 95% confidence), in good agreement with survey-mode GPS studies [Martinez et al., 1998]. Extension across the CNSZ is about 2.3±1.2 mm yr^{-1}, in agreement with previous strain estimates [Savage et al., 1995], although our model is more consistent with pure extension across the NE-trending normal faults within the zone. Relative motion of about 3.6±1.1 mm yr^{-1} between WB and SG is primarily right-lateral strike-slip along the NWLB, a northwest-trending diffuse zone of conjugate strike-slip and normal faults between Lake Tahoe and Mount Shasta. These results are consistent with the northern continuation of the eastern California shear zone [Savage et al., 1995] deformation being partitioned onto both the CNSZ and NWLB [Thatcher et al., 1999].

Motion of the northern SG is 10.2±0.5 N45°W mm yr^{-1}, and is rotating clockwise. Counterclockwise rotation is also permissible, although our results are marginally inconsistent at 95% confidence (Figure 3) with other geodetic studies suggesting this [Dixon et al., 2000, Argus and Gordon, 2000]. A clockwise-consistent $\hat{\mathbf{\Omega}}_{SG}$, located between $\hat{\mathbf{\Omega}}_{BR}$ and $\hat{\mathbf{\Omega}}_{PA}^{NU}$, predicts less plate boundary normal deformation than a counterclockwise-consistent pole, and so is perhaps more physically reasonable. The SG motion is oblique to the San Andreas system, causing 2.4±0.4 mm yr^{-1} fault-normal convergence, which we do not explicitly model. The oblique motion is fully evident in the SG near the San Andreas system, but disappears within it (Figure 1). This suggests convergence may be accommodated over a fairly narrow (<15 km) zone (Figure 2), possibly contributing to uplift of the Coast Ranges [Argus and Gordon, 2000].

The predicted deep-slip rates on the San Andreas, Hayward, and Concord/Calaveras faults ($17.5^{+5.4}_{-2.8}$, $14.2^{+3.6}_{-8.4}$, and $5.5^{+5.3}_{-2.7}$ mm yr^{-1}, respectively), agree with with geologic estimates (17±4, 9±2, and 6±2, respectively)[WG99, 1999]. Models with lower rates on the Hayward and higher rates on the other faults are also acceptable due to high correlations between the rates. Our simple fault model does not explore the trade-off between locking depth and deep-slip rate, and does not account for observed surface creep along the Hayward fault. The total deep-slip rate across the San Andreas system is well resolved (37.2±0.1 mm yr^{-1}), and is consistent with a geologic estimate (41±6) that includes other active Holocene faults, such as the San Gregorio and Greenville (7±4, 2±1 mm yr^{-1}, respectively) [WG99, 1999].

The estimated ω_{PA} ($0.774^{+0.007\circ}_{-0.043}$ Ma^{-1} is significantly higher than the 0.749±0.012 predicted by NUVEL-1A (Figure 2), in agreement with evidence from globally distributed GPS stations for a higher ω_{PA} [Demets and Dixon, 1999]. However, faults within the San Andreas system are not as well aligned with small circles about this alternative $\hat{\mathbf{\Omega}}_{PA}$ (Figure 3), significantly increasing the model misfit.

Including more globally distributed data to allow direct estimation of $\hat{\mathbf{\Omega}}_{PA}$, and survey-mode GPS to allow finer spatial resolution of the deformation field, would enable us to better address whether the orientation of faults in the San Andreas system is consistent with present-day PA-NA relative motion, and whether the WB is a zone of distributed deformation [Bennett et al., 1998, 1999; Thatcher et al., 1999], which is not required by our preferred model.

The angular velocity-fault backslip model provides a self-consistent description of far-field plate motions and interseismic strain accumulation. It allows for simultaneous estimation of both angular velocity and fault slip parameters, and for incorporating geologic and seismological constraints. The simple 2D method described here can be extended to more complex, 3D fault systems (including subduction zones and extensional provinces) by summing backslip on rectangular dislocations, and thus provides a general framework for estimating long-term plate motions over regional and global scales from geodetic measurements subject to short-term earthquake-cycle effects.

DATA AVAILABILITY

Raw and Rinex data files for BARD continuous GPS stations are archived at the BSL/USGS Northern California Earthquake Data Center (NCEDC) data archive maintained at the BSL [Romanowicz et al., 1994], and are publicly available through Internet, both by anonymous ftp and by the World Wide Web (http://quake.geo.berkeley.edu/bard). Data from other continuous GPS stations are available at other archive centers, including the Scripps Orbit and Permanent Array Center (http://lox.ucsd.edu), and the University NAVSTAR Consortium (http://www.unavco.ucar.edu).

NON-TECHNICAL SUMMARY

This project focuses on integration and modeling of geodetic measurements in the San Francisco Bay area. We combine previously collected Geodolite (precise laser distance measurements), Global Positioning System (GPS), and Very Long Baseline Interferometry (VLBI) measurements to determine the deformation field in the Bay area and to study how seismic stain accumulates on the principal faults. We also study deformation following the 1906 San Francisco and 1989 Loma Prieta earthquakes to study postseismic relaxation and stress transfer, and perform time-dependent inversions and finite element calculations to study the fault geometry in the lower crust and stressing-rates on Bay area faults.

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