ANNUAL PROJECT SUMMARY

AWARD NUMBER: 99HQGR0062

THE BARD PERMANENT GPS NETWORK: CONTINUOUS MONITORING OF ACTIVE DEFORMATION AND STRAIN ACCUMULATION IN THE SAN FRANCISCO BAY AREA:

Collaborative research with UC Berkeley, Stanford University,
and the U.S. Geological Survey, Menlo Park

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PROGRAM ELEMENTS: I & II

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INVESTIGATIONS UNDERTAKEN

The Bay Area Regional Deformation (BARD) network of permanent, continuously operating Global Positioning System (GPS) receivers monitors crustal deformation in the San Francisco Bay area (”Bay Area”) and northern California [Murray et al., 1998a]. It is a cooperative effort of the Berkeley Seismological Laboratory at UC Berkeley (BSL), the US Geological Survey (USGS), and several other academic, commercial, and governmental institutions. Started by the USGS in 1991 with 2 stations spanning the Hayward fault [King et al., 1995], BARD now includes 45 permanent stations and will expand to about $\sim$55 stations by July 2001 (Figure 1). The principal goals of the BARD network are: 1) to determine the distribution of deformation in northern California across the wide Pacific–North America plate boundary from the Sierras to the Farallon Islands; 2) to estimate three-dimensional interseismic strain accumulation along the San Andreas fault (SAF) system in the Bay Area to assess seismic hazards; 3) to monitor hazardous faults and volcanoes for emergency response management; and 4) to provide infrastructure for geodetic data management and processing in northern California in support of related efforts within the BARD Consortium and with surveying, meteorological, and other interested communities.

BARD presently includes 45 permanent, continuously operating stations, 8 of which monitor the Long Valley caldera near Mammoth. The remaining 37 stations include 19 maintained by the BSL (including 3 with equipment provided by Lawrence Livermore National Laboratory (LLNL), the Omnistar Corporation, and UC Santa Cruz), 6 by the USGS, 2 by Trimble Navigation, and one each by LLNL, Stanford University, UC Davis, and East Bay Municipal Utilities District. Other stations are maintained by institutions outside of northern California, such as the National Geodetic Survey, the Jet Propulsion Laboratory, and the Scripps Institution of Oceanography, as part of larger networks devoted to real-time navigation, orbit determination, and crustal deformation. The network includes several profiles between the Farallon Islands and the Sierra Nevada in order to better characterize the larger scale deformation field in northern California (Figure 1). Three

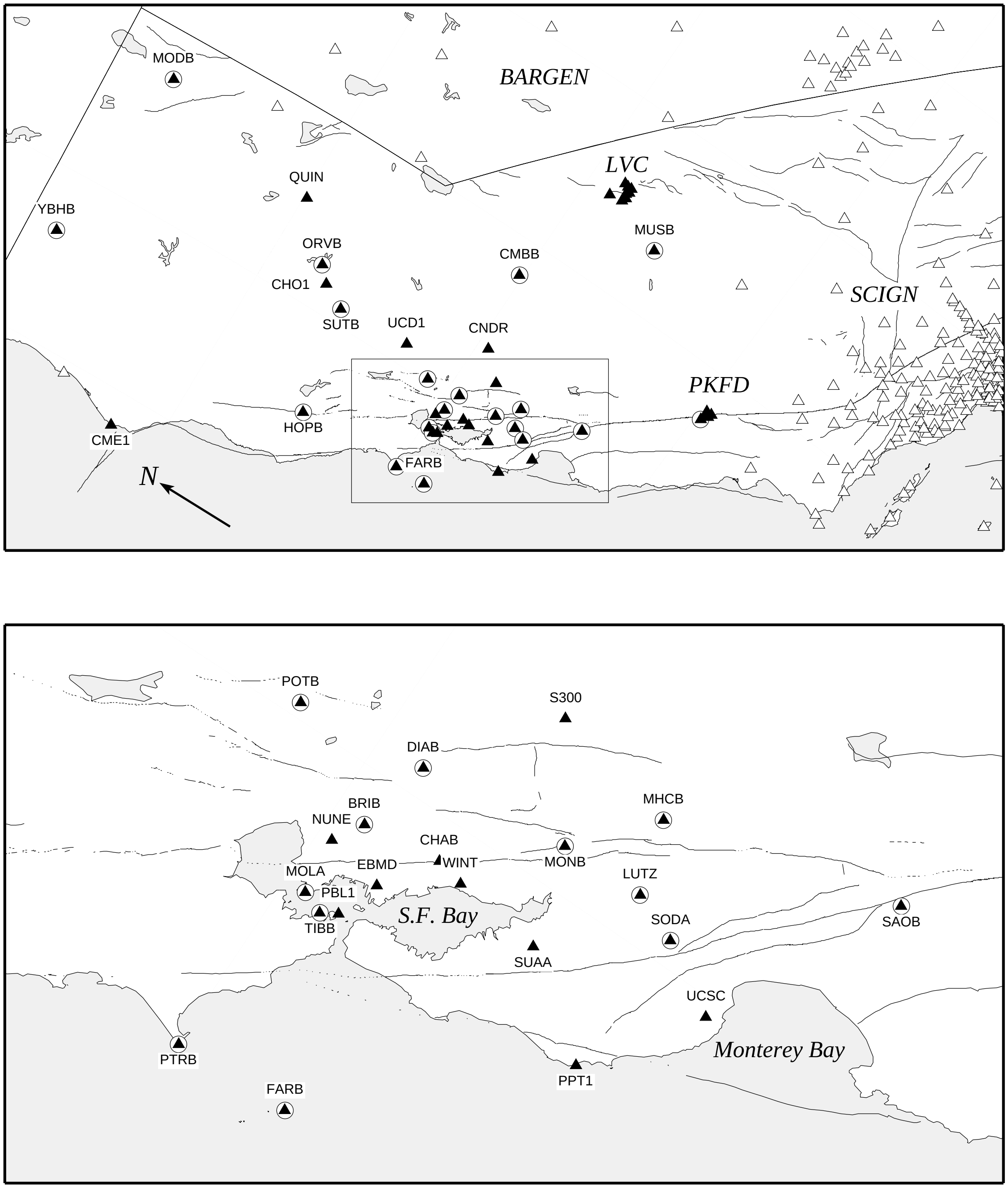

Figure 1: Operational BARD stations (solid triangles) in northern California (top) and in the San Francisco Bay area (bottom). The oblique Mercator projection is about the NUVEL-1 Pacific–North America Euler pole so that expected relative plate motion is parallel to the horizontal. Circled stations use continuous telemetry. The eight station Long Valley Caldera (LVC) network and eight station Parkfield (PKFD) networks are also part of BARD. Other nearby networks (open triangles) include: Basin and Range (BARGEN), and Southern California Integrated GPS Network (SCIGN).

more of the BSL receivers will be installed next year, and 7 additional receivers will installed during 2000–2002 as part of the NSF-funded mini-PBO project, which will establish collocated GPS/seismometer/borehole strainmeter observatories in the Bay Area.

During fiscal year 1999–2000, the BSL installed one new station, remonumentated and performed upgrades to existing stations, continued assessment of an experimental single-frequency receiver, improved data archive and processing methods, and analyzed the data to estimate daily changes in relative site positions. We determined a deformation field from these site positions consistent with plate motions and the effects of strain accumulation on locked faults for northern California and Nevada that shows extension across the Basin and Range Province, a relatively stable Sierran-Great Valley block, and right-lateral shear across the San Andreas fault system accommodating about 37 mm/yr of the Pacific-North America relative plate motion.

RESULTS

Site Installations, Upgrades, and Telemetry

During last year, one new BARD station (MODB) was installed near Alturas in Modoc county in the northeast corner of California. It is collocated with the new broadband seismic station MOD. This station should provide important kinematic constraints on the poorly understood tectonics of the region, which is roughly where the Basin and Range extensional province in Nevada transitions into the backarc of the Cascadia subduction zone in southern Oregon. This region may also accommodate deformation associated with the eastern California shear zone as it extends north from Owens Valley.

The design of MODB GPS station is similar to other BSL permanent stations. It uses a low-multipath choke-ring antenna mounted to a reinforced concrete pillar approximately 0.5 meter above local ground level. The reinforcing steel bars of the pillar are drilled and cemented into rock outcrop to improve long-term monument stability. It uses a low-loss antenna cable to minimize signal degradation on the longer cable setups that normally would require signal amplification. Low-voltage cutoff devices are installed to improve receiver performance following power outages. The Ashtech Z-12 receiver is programmed to record data once every 30 seconds, observing up to 12 satellites simultaneously at elevations down to the horizon.

Unlike most other stations, which use a combination of radio modem or frame-relay technologies to provide continuous telemetry, MODB uses the collocated Quanterra seismic data logger to package the GPS data into blockettes, which are then sent using VSAT satellite telemetry to Berkeley via Golden, Colorado. Initial problems with this telemetry method, primarily caused by long forwarding times of the data packets, have recently been resolved and we are preparing to make the data publicly available.

New monuments were installed at the existing stations BRIB and CMBB during early 2000. These sites were the first GPS installations performed by the BSL staff, and the antennas were mounted directly to bedrock near the ground surface, which was considered an optimal configuration at that time (late 1993). However, subsequent tests performed by UNAVCO on low antenna mounts revealed that estimates of tropospheric water vapor from the GPS data are strongly correlated with signal multipath errors, which can degrade the precision of the vertical position estimates. The new concrete pier monuments at BRIB and CMBB, similar to most of the other BSL GPS stations, elevate the antennas 0.5–1.0 m above the ground surface, which helps to minimize the correlations between multipath and tropospheric parameters. At the same time, a low-multipath choke-ring antenna was installed at BRIB, and SCIGN-designed adapters and protective domes were installed at both stations to improve their security and make them more consistent with the other BSL GPS stations that were upgraded during 1999.

The BSL staff helped to improve data retrieval from the UCD1 antenna located on the roof of the UC Davis Geology Building. Data had previously been downloaded manually at weekly intervals. We helped to configure a new telemetry path using a serial connection to a computer where data is continuously made available via ftp. We also helped UC Santa Cruz install the same system for a new BARD station (UCSC) that was established on the roof of the Earth Sciences Building on the UC Santa Cruz campus. This station uses a permanently installed Trimble antenna, but will operate in semi-permanent mode depending on receiver availability, primarily when they are not in use on survey-mode projects.

Significant disruptions were experienced at several stations. The NUNE station ceased operation in December 1999 due to water damage sustained during a winter storm. This station has repeatedly experienced problems due to landsliding of the near surface during severe storms that displace the receiver and antenna enclosure relative to the more deeply anchored antenna. We have decided to abandon this site in favor of a new site on nearby Pt. Wilson to be installed as part of the mini-PBO project.

The MOLA station, located at a former US Navy fuel supply depot, has experienced significant power and telemetry disruption during the last 2 years as the site undergoes hazard waste cleanup. We established radio telemetry to the station via Yerba Buena Island to replace the phone line that had been became permanently inoperable in 1998, and installed a temporary power line to replace the previous line that been cut in mid-2000. We are also considering moving this station if a suitable site on nearby Pt. San Pablo can be established as part of the mini-PBO project.

The BSL staff completed the antenna dome upgrade project begun last year. We purchased SCIGN-designed hemispherical domes using federal (USGS) funding. Domes cover the antennas to provide security and protection from the weather and other natural phenomenon. Previously the BSL stations had a mixture of dome types or none at all, adding a potential non-uniformity to signal delays and antenna phase patterns. The new SCIGN dome is designed for the Dorne-Margolin antennas and minimizes differential radio propagation delays by being hemispherical about the phase center and uniform in thickness at the 0.1 mm level. It is also very resistant to damage and, in its tall form in combination with the SCIGN-designed antenna adapter, can completely cover the dome and cable connections for added protection. Tall domes and adapters were installed at the new and upgraded stations, as well as 6 stations that require the most security due to public accessibility: BRIB, CMBB, DIAB, MODB, MUSB, PTRB, SAOB, TIBB, and YBHB. Short domes were installed at 8 less accessible stations: HOPB, LUTZ, MHCB, MONB, ORVB, PKDB, POTB, and SODB.

Data from all BSL-maintained stations are collected at 30-second intervals and transmitted continuously over serial connections. Two sites (MOLA and TIBB) have direct radio links to Berkeley, and MODB uses VSAT satellite telemetry. The remaining 17 sites use frame relay technology, either alone or in combination with radio telemetry. Twelve GPS stations are collocated with broadband seismometers and Quanterra data collectors. With the support of IRIS we have developed software that will allow continuous GPS data to be converted to miniSEED opaque blockettes, which can be stored and retrieved from the Quanterra dataloggers [Perin et al., 1998]. This approach preserves GPS data during telemetry outages. During the past year, we installed a new version of the Quanterra system software that recognizes the new MiniSEED blockettes, established generally reliable connections at 10 of the 12 collocated sites, and worked to resolve problems at the remaining 2 stations (BRIB and POTB). We are currently developing procedures to preferentially use the miniSEED data where available, based on our experiences with data from MODB, which is only available using that method.

Data Archival and Availability

Raw and Rinex data files from the BSL stations and the other stations run by BARD collaborators are archived at the BSL/USGS Northern California Earthquake Data Center (NCEDC) data archive maintained at the BSL [Romanowicz et al., 1994]. The data are checked to verify their integrity, quality, completeness, and conformance to the RINEX standard, and are then made accessible, usually within 2 hours of collection, to all BARD participants and other members of the GPS community through Internet, both by anonymous ftp and by the World Wide Web (http://quake.geo.berkeley.edu/bard).

Data and ancillary information about BARD stations are also made compatible with standards set by the International GPS Service (IGS), which administers the global tracking network used to estimate precise orbits and has been instrumental in coordinating the efforts of other regional tracking networks. The NCEDC also retrieves data from other GPS archives, such as at SIO, JPL, and NGS, in order to provide a complete archive of all high-precision continuous GPS measurements collected in northern California.

In the past 2 years the BARD Project and the NCEDC have collaborated with UNAVCO and other members of the GPS community to define database schema and file formats for the GPS Seamless Archive Centers (GSAC) project. When completed this project will allow a user to access the most current version of GPS data and metadata from distributed GSAC locations. The NCEDC will participate at several levels in the GSAC project: as a primary provider of data collected from BSL-maintained stations, as a wholesale collection point for other data collected in northern California, and as a retail provider for the global distribution of all data archived within the GSAC system. We have produced monumentation files describing the data sets that are produced by the BARD project or archived at the NCEDC, and are during the last year began creating incremental files describing changes to the holdings of the NCEDC so that other members of the GSAC community can provide up-to-date information about our holdings.

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 2). 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. 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.

We use continuous GPS data from the (BARD network, 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 2).

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 s on each of F faults. 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].

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 2). 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 (Figure 3): 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.

The preferred model is one constraining $\hat{\mathbf{\Omega}}_{WB}$ = $\hat{\mathbf{\Omega}}_{EB}$, which 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

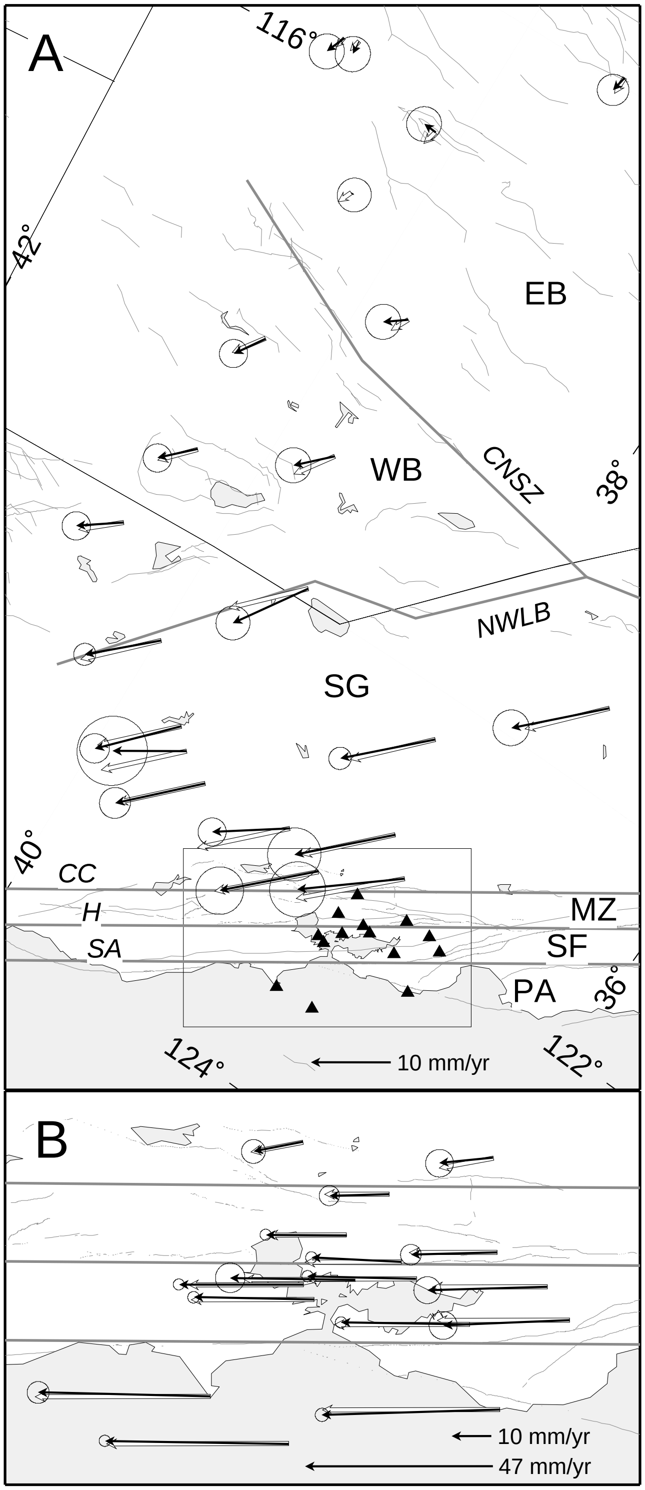

Figure 2: Predicted (open) and observed (solid) site velocities, with 95% confidence regions, relative to NA. Projection, oblique mercator about $\hat{\mathbf{\Omega}}^{NU}_{PA}$. A) northern California and Nevada (see box in Figure 3), with velocities of sites in box (triangles) omitted for clarity. 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.

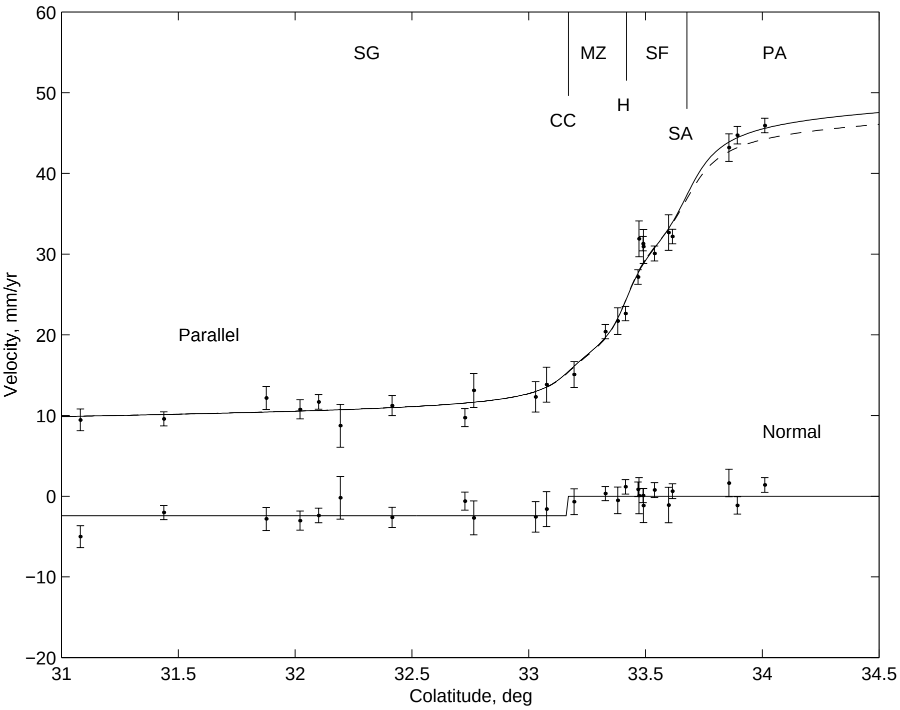

Figure 3: Velocities relative to NA versus colatitude from $\hat{\mathbf{\Omega}}_{PA}^{NU}$. Velocities, with one standard error bars, are parallel (top) and normal (bottom) to small circles about $\hat{\mathbf{\Omega}}_{PA}^{NU}$. Solid line, preferred model. Dashed line, model with ω_{PA} = ω_{PA}^{NU}, which has significantly greater misfit (95% confidence) than preferred model. Plate regions and San Andreas faults, with proportional depths, are shown schematically at top.

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. 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 4). $\hat{\mathbf{\Omega}}_{SG}$ 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, according to an F-ratio test.

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

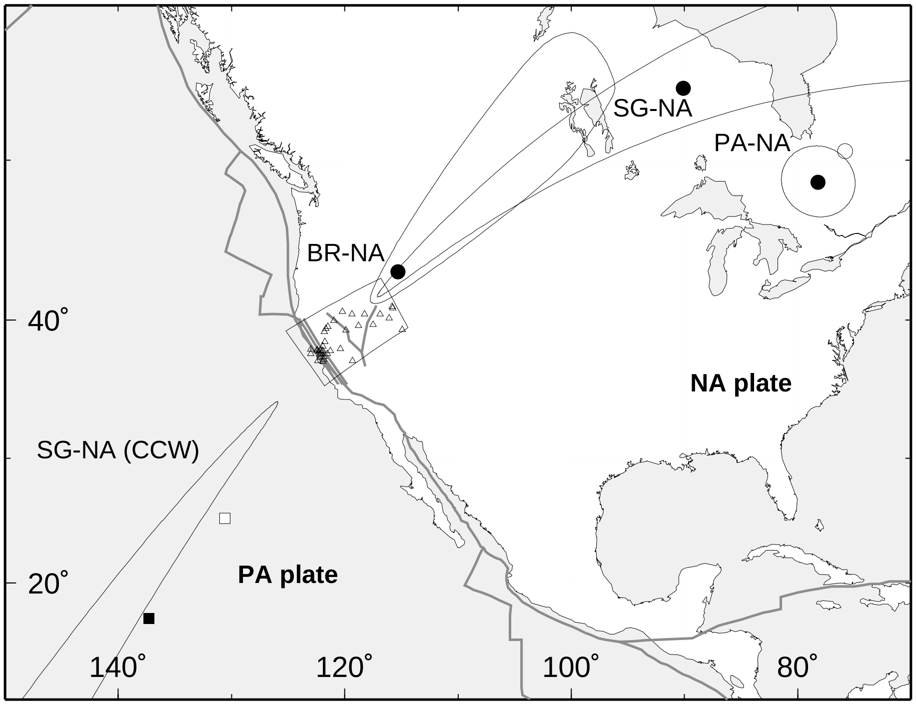

Figure 4: Estimated $\hat{\boldsymbol{\Omega}}$ (solid circles) with 95% confidence bootstrap regions. PA-NA is from NUVEL-1A. Open circle, alternative $\hat{\boldsymbol{\Omega}}_{PA}$ [*DeMets and Dixon*, 1999]. BR-NA is combined $\hat{\boldsymbol{\Omega}}_{WB}$ = $\hat{\boldsymbol{\Omega}}_{EB}$. The SG-NA region, which spans nearly 180°, is split into clockwise (top) and counterclockwise (bottom) rotation regions. Squares, alternative $\hat{\boldsymbol{\Omega}}_{SG}$: open, [*Argus and Gordon*, 2000]; solid, [*Dixon et al.*, 2000]. Box encloses stations and plate boundaries shown in Figure 1.

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 4) with other geodetic studies suggesting this [Dixon et al., 2000, Argus and Gordon, 2000]. A clockwise-consistent $\hat{\boldsymbol{\Omega}}_{SG}$, located between $\hat{\boldsymbol{\Omega}}_{BR}$ and $\hat{\boldsymbol{\Omega}}_{PA}^{NU}$, 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 2). This suggests convergence may be accommodated over a fairly narrow (<15 km) zone (Figure 3), 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].

Other Projects

These BARD results are being combined with older VLBI and spatially dense Geodolite EDM and survey GPS measurements collected by the USGS, Stanford University, and UC Berkeley [Murray et al., 1998b]. The combined velocity map will provide significantly improved constraints on three-dimensional locking depth and deep-slip models of strain accumulation, which will be used for seismic hazard assessment along the SAF system.

We are also developing real-time analysis techniques that will enable rapid determinations (∼minutes) of deformation following major earthquakes to complement seismological information and aid determinations of earthquake location, magnitude, geometry, and strong motion [Murray et al., 1998c]. We currently process data available within 1 hour of measurement from the 18 continuous telemetry BSL stations, and several other stations that make their data available on an hourly basis. The data are binned into 1 hour files and processed simultaneously. The scatter of these hourly solutions is much higher than the 24-hour solutions: 10 mm in the horizontal and 30–50 mm in the vertical. Our simulations suggest that displacements 3–5 times these levels should be reliably detected, and that the current network should be able to resolve the finite dimensions and slip magnitude of a M=7 earthquake on the Hayward fault. We are currently investigating other analysis techniques that should improve upon these results, such as using a Kalman filter that can combine the most recent data with previous data in near real-time. The August 1998 M=5.1 San Juan Bautista earthquake [Uhrhammer et al., 1999] is the only event to have produced a detectable earthquake displacement signal at a BARD GPS receiver.

The BSL staff is evaluating the performance of the UNAVCO-designed L1 system in an urban setting. This single-frequency receiver is relatively inexpensive but is less accurate than dual-frequency receiver systems that can completely eliminate first-order ionospheric effects. Hence we expect the L1 system to be most useful for short baseline measurements where ionospheric effects tend to cancel due to similar propagation paths. The systems are self-contained, using solar polars and an integrated radio modems. In summer 2000, we received equipment and software for 4 systems and a master radio. We are currently working closely with UNAVCO engineers to finishing testing and securing land permits in order to deploy the systems on a 10-km profile extending normal to the Hayward fault between the UC Berkeley campus and the permanent BRIB site. We currently achieve 2–4 mm repeatability in horizontal components on 1.5-km long baselines, and 3–5 mm repeatability on 10-km long baselines. These results are similar to those obtained using Bernese processing by UNAVCO, and may be improved by incorporating ionospheric models using data from the nearby dual-frequency permanent receivers. We expect that these systems will provide useful constraints on relative displacements near the Hayward fault in 3–5 years, and should help to resolve variations in creeping and locked portions of the fault [e.g., Bürgmann et al, 2000].

NON-TECHNICAL ABSTRACT

We maintain the Bay Area Regional Deformation (BARD) network of permanent Global Positioning System (GPS) stations to better understand crustal deformation in northern California and the timing and hazards posed by future earthquakes caused by strain accumulation along the San Andreas fault system in the San Francisco Bay area. During the past year, we added one new station, performed enhancements to the existing network and operation procedures, and estimated horizontal interseismic deformation in northern California and Nevada using the angular velocities of 6 rigid plates and strain accumulation on 3 faults in the San Andreas system that requires no distributed deformation.

REPORTS PUBLISHED

Bürgmann, R. D. Schmidt, R. M. Nadeau, M. d'Alessio, E. Fielding, D. Manaker, T. V. McEvilly, and M. H. Murray, Earthquake potential along the northern Hayward fault, California, *Science, 289,* 1178–1182, 2000.

Murray, M. H., R. Bürgmann, W. H. Prescott, B. Romanowicz, S. Schwartz, P. Segall, and E. Silver, The Bay Area Regional Deformation (BARD) permanent GPS network in northern California, *EOS Trans. AGU, 79(45),* Fall Meeting Suppl., F206, 1998a.

Murray, M. H., W. H. Prescott, R. Bürgmann, J. T. Freymueller, P. Segall, J. Svarc, S. D. J. Williams, M. Lisowski, and B. Romanowicz, The deformation field of the Pacific-North America plate boundary zone in northern California from geodetic data, 1973-1989, *EOS Trans. AGU, 79(45),* Fall Meeting Suppl., F192, 1998b.

Murray, M. H., D. S. Dreger, D. S. Neuhauser, D. R. Baxter, L. S. Gee, and B. Romanowicz, Real-time earthquake geodesy, *Seismol. Res. Lett., 69,* 145, 1998c.

Murray, M. H., and P. Segall, Modeling broadscale deformation in northern California and Nevada from plate motions and elastic strain accumulation, *Geophys. Res. Lett.,* in review, 2000.

Perin, B. J., C. M. Meertens, D. S. Neuhauser, D. R. Baxter, M. H. Murray, and R. Butler, Institutional collaborations for joint seismic and GPS measurements, *Seismol. Res. Lett., 69,* 159, 1998.

Romanowicz, B., B. Bogaert, D. Neuhauser, and D. Oppenheimer, Accessing northern California earthquake data via Internet, *EOS Trans. AGU, 75,* 257–260, 1994.

Uhrhammer, R., L. S. Gee, M. Murray, D. Dreger, and B. Romanowicz, The M_w 5.1 San Juan Bautista, California earthquake of 12 August 1998, *Seismol. Res. Lett., 70,* 10–18, 1999.

OTHER REFERENCES

Argus, D. F., and R. G. Gordon, Present tectonic motion across the Coast Ranges and San Andreas fault system in central California, *Geol. Soc. Am. Bull., in press*, 2000.

Bennett, R. A., B. P. Wernicke, and J. Davis, Continuous GPS measurements of contemporary deformation across the northern Basin and Range province, *J. Geophys. Res., 25*, 563–566, 1998.

DeMets, C., Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, *Geophys. Res. Lett.*, *21*, 2191–2194, 1994.

DeMets, C., and T. H. Dixon, New kinematic models for Pacific-North America motion from 3 ma to present, I: Evidence for steady motion and biases in the NUVEL-1A model, *Geophys. Res. Lett.*, *26*, 1921–1924, 1999.

Dixon, T. H., M. Miller, F. Farina, H. Z. Wang, and D. Johnson, Present-day motion of the Sierra Nevada block and some tectonic implications for the Basin and Range province, North American cordillera, *Tectonics*, *19*, 1–24, 2000.

Freymueller, J. T., M. H. Murray, P. Segall, and D. Castillo, Kinematics of the Pacific-North American Plate Boundary Zone, northern California, *J. Geophys. Res., 104,* 7419–7441, 1999.

King, N. E., J. L. Svarc, E. B. Fogleman, W. K. Gross, K. W. Clark, G. D. Hamilton, C. H. Stiffler, and J. M. Sutton, Continuous GPS observations across the Hayward fault, California, 1991-1994, *J. Geophys. Res., 100,* 20,271–20,283, 1995.

Kogan, M. G., G. M. Steblov, R. W. King, T. A. Herring, D. I. Frolov, S. G. Erorov, V. Y. Levin, A. Lerner-Lam, and A. Jones, Geodetic constraints on the rigidity and relative motion of Eurasia and North America, *Geophys. Res. Lett.*, *27*, 2041–2044, 2000.

Lisowski, M., J. C. Savage, and W. H. Prescott, The velocity field along the San Andreas fault in central and southern California, *J. Geophys. Res.*, *96*, 8369–8389, 1991.

Martinez, L. J., C. M. Meertens, and R. B. Smith, Rapid deformation rates along the Wasatch fault zone, Utah, from first GPS measurements with implications for earthquake hazards, *Geophys. Res. Lett.*, *25*, 567–570, 1998.

McClusky, S., et al., Global Positioning System constraints on plate kinematics in the eastern Mediterranean and Caucasus, *J. Geophys. Res.*, *105*, 5695–5719, 2000.

Savage, J. C., and R. O. Burford, Geodetic determination of relative plate motion in central california, *J. Geophys. Res.*, *78*, 832–845, 1973.

Savage, J. C., M. Lisowski, J. L. Svarc, and W. K. Gross, Strain accumulation across the central Nevada seismic zone, 1973-1994, *J. Geophys. Res.*, *100*, 20,257–20,269, 1995.

Thatcher, W., G. R. Foulger, B. R. Julian, J. Svarc, E. Quilty, and G. W. Bawden, Present-day deformation across the Basin and Range province, western United States, *Science*, *283*, 1714–1718, 1999.

WG99, Earthquake probabilities in the San Francisco Bay region: 2000 to 2030–A summary of findings, *USGS Open File Rpt.*, *99-417*, 1999.