ANNUAL REPORT

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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

Barbara Romanowicz, P.I., and Mark H. Murray, Co-P.I.
Berkeley Seismological Laboratory, UC Berkeley, CA 94720-4760
(510) 643-5690, x3-5811 (Fax), barbara@seismo.berkeley.edu
(510) 643-3980, x3-5811 (Fax), mhmurray@seismo.berkeley.edu
http://quake.geo.berkeley.edu/bard

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INVESTIGATIONS UNDERTAKEN

Geodetic measurements show that crustal deformation in the San Francisco Bay area varies both in space and time. Much of this deformation is due to strain accumulation and release along the San Andreas, one of the most seismically hazardous fault systems in the U.S. To better understand the distribution and rate of loading of its individual faults, and the timing and hazards posed by future earthquakes, our collaborative group installed and maintains the Bay Area Regional Deformation (BARD) network of Global Positioning System (GPS) permanent stations. This network provides continuous, near real-time monitoring of crustal deformation in the 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 40 permanent stations and will expand to about 50 stations in 2000 (Figure 1). These include 18 maintained by the BSL (including two with equipment provided by Lawrence Livermore National Laboratory (LLNL), and the Satloc Corporation), 10 by the USGS, 2 by Trimble Navigation, and one each by LLNL, Stanford University, and UC Davis. 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.

During fiscal year 1998–99, the Berkeley Seismological Laboratory (BSL) installed 3 new stations and converted 2 other stations to continuous operational mode, all located in the Bay Area. We performed significant upgrades on all existing stations, including firmware upgrades to make the receivers Y2K and GPS week rollover compliant, and installed antenna adapters and domes at most stations to provide greater protection and uniformity to the network. We have prepared many stations to transmit the data through collocated seismic dataloggers for more robust real-

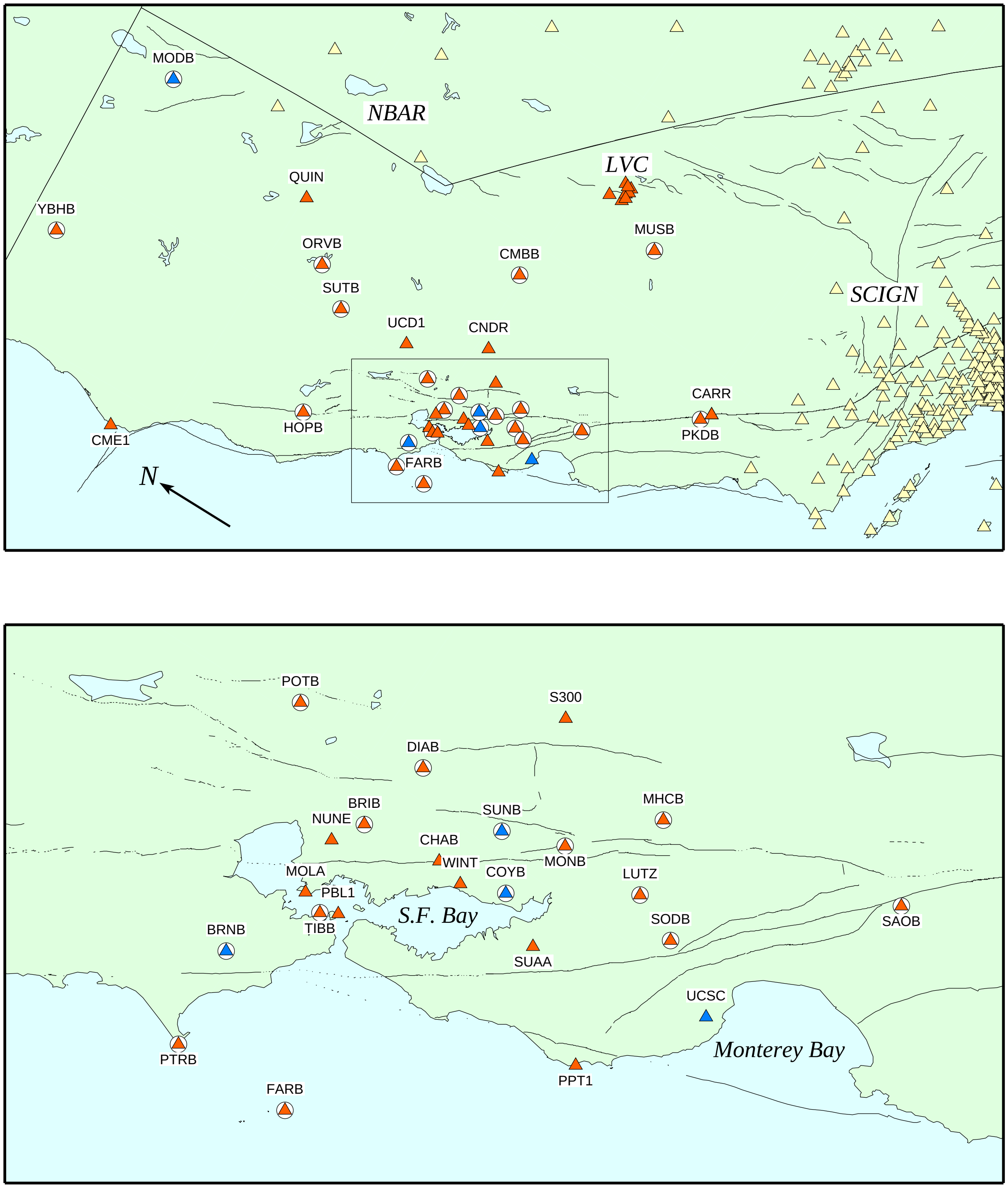

Figure 1: Operational (red triangles) and planned (blue triangles) BARD stations in northern California (top) and in the San Francisco Bay area (bottom). The oblique Mercator projection is about the NUVEL-1 Pacific–North America Euler pole so that expected relative plate motion is parallel to the horizontal. Circled stations (will) use continuous telemetry. The eight station Long Valley Caldera (LVC) network is shown with unlabelled red triangles. Other nearby networks (yellow triangles) include: Northern Basin and Range (NBAR), and Southern California Integrated GPS Network (SCIGN).

time telemetry. We have helped to develop database schema and file formats for the UNAVCO-sponsored GPS Seamless Archive Centers project, which will provide an easier, more reliable, and more uniform method to retrieve data from a distributed system of archives, including the NCEDC archive maintained by the BSL. We have tested an experimental single-frequency receiver developed by UNAVCO to improve our monitoring capability in the vicinity of hazardous faults. We determined a self-consistent deformation field 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 35 mm/yr of the Pacific-North America relative plate motion. We also detected transient deformation at one station associated with the August 1998 M=5.1 San Juan Bautista earthquake.

RESULTS

Site Installations

During fiscal year 1998–99 three new BARD stations were permitted, designed, constructed and equipped with Ashtech Z-12 receivers by the BSL staff. Station MONB is located on Monument Peak in the Mission Hills, east of San Jose, in a tectonically complicated region near the intersection of the Calaveras and southern Hayward faults where the seismicity appears to step over along the Mission fault. Station PTRB is located near the historic lighthouse in the Point Reyes National Seashore, at the westernmost point of land in the north Bay Area. Midway between the San Andreas fault (SAF) and the Farallon Islands, it will provide valuable constraints on deformation west of the SAF. Station POTB is located at the Potrero Hills-OEA Aerospace Inc. facility near Fairfield, just west of the Central Valley. The site is collocated with BDSN seismic instruments, allowing both instruments to share the same power and telemetry subsystems.

The BSL staff also performed significant modifications to two stations to convert them to continuous operations. Stations LUTZ and SODB, both in Santa Clara county in the south Bay Area, formerly used Trimble receivers operated intermittently by UC Davis depending on their availability. In early 1999, the BSL assumed responsibility for these 2 stations, installed Ashtech Z-12 receivers, and made the power and telemetry systems consistent with the standard BSL station configuration. Both sites are located in a tectonically complex region between the SAF and Calaveras fault where transient deformation has been observed in the past, particularly in the aftermath of the 1989 Loma Prieta earthquake (Bürgmann et al., 1997).

Each of these new stations conforms as much as possible to the standard station configuration developed by the BSL. They use a low-multipath choke-ring antenna, typically mounted to a reinforced concrete pillar approximately 0.5–1.0 meter above local ground level. If possible, the reinforcing steel bars of the pillar are drilled and cemented into rock outcrop to improve long-term monument stability. Low-loss antenna cables are used to minimize signal degradation on the longer cable setups that normally would require signal amplification. Continuous telemetry is provided by a combination of radio modem or frame-relay technologies. Low-voltage cutoff devices are installed to improve receiver performance following power outages. The Ashtech Z-12 receivers are programmed to record data once every 30 seconds, observing up to 12 satellites simultaneously at elevations down to the horizon.

During 1997-99 BSL staff installed a reinforced concrete monument at the Site 300 explosion testing facility (S300, Figure 1) of the Lawrence Livermore National Laboratory, and worked closely with LLNL and Trimble representatives to design a multi-purpose system, maintained by LLNL, that became fully operational in April 1999. This system also provides real-time kinematic surveying (cm-level) and differential positioning (meter-level) capabilities. Because it is located at one of the easternmost sites in the Diablo Range, it will provide valuable constraints on the total deformation accommodated between the Sierra Nevada range and the San Andreas fault system. Installations are also currently being permitted and prepared at several other sites, including Barnabe Peak (BRNB), just east of the SAF in the north Bay Area, in the Modoc plateau (MODB) in the northeast corner of California, and two stations (COYB and SUNB) that will be collocated with USGS borehole strainmeters along the southern Hayward fault.

Site Upgrades

The BSL staff performed significant modifications to nearly all the other BSL stations. The firmware on every Ashtech receiver was upgraded to a version compatible with both 4-digit year numbers, in anticipation of the year 2000 (Y2K), and with the GPS Week Rollover. The GPS satellites keep time in weeks and seconds of week, beginning on Sunday, January 6, 1980. On August 22, 1999, the week number changed from 1023 to 0000 internally on the satellites due to memory bit limitations. The receiver firmware was modified to maintain continuity of week number after the rollover. None of the BSL receivers were adversely affected by these problems.

The BSL staff also installed antenna domes at many of the stations. 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 long 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 5 stations that require the most security due to public accessibility: DIAB, MUSB, PTRB, SAOB, and YBHB. Short domes were installed at 7 less accessible stations: HOPB, LUTZ, MHCB, MONB, PKDB, POTB, and SODB.

Additional modifications were made to a number of the existing stations to make them consistent with the standard BSL station configuration. Low-voltage cutoff devices, which improve system performance following power outages, were installed at 6 stations: BRIB, MHCB, PKDB, SAOB, SUTB, and TIBB. Lightning protectors were installed on short-haul modem cables at CMBB and SAOB. The BSL staff also helped to install a direct serial connection to a UNIX workstation at the UCD1 station maintained by UC Davis. The new telemetry path allows automated ftp retrieval of the data in near-realtime, dramatically improving on the previous intermittent manual download method.

Continuous Telemetry

The BSL currently maintains and retrieves data from 18 Ashtech Z-12 receivers. Data from all stations are collected at 30-second intervals, transmitted continuously over serial connections, collected into 24-hour raw serial files and processed daily. The serial connections to 12 sites use frame relay technology, one site (TIBB) has a direct radio link to Berkeley and several sites (FARB, MUSB, PTRB, SODB, and SUTB) use a combination of radio and frame-relay technologies. We have developed software to interpret and collect the raw serial output into hourly files, which is then converted to the standard interchange RINEX format using the TEQC software developed by UNAVCO.

Ten current 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 stored on and retrieved from the Quanterra dataloggers (Perin et al., 1998). This approach preserves GPS data during telemetry outages, and will be used at all the collocated stations after a new version of the Quanterra system software is installed this Fall. In anticipation, we have established and tested serial connections between the GPS receivers and dataloggers at six sites: FARB, HOPB, MHCB, PKDB, POTB, and YBHB.

Data Archival and Distribution

Raw and RINEX data files from the 18 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 compatible with standards set by the International GPS Service (IGS) are also similarly available. Please contact Ray Baxter (510-642-3977, bard@seismo.berkeley.edu) for further information.

In the past year 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 working to implement programs that create 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.

L1 System

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 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 would tend to cancel due to similar propagation paths. We plan to deploy this self-contained system, which uses solar polar and an integrated radio modem, in the vicinity of the Hayward fault to improve the spatial density of our monitoring effort. The BSL borrowed 2 receivers and a master radio from UNAVCO to perform the evaluation. Considerable hardware and software development was required before the system became operation in June 1999. Baseline lengths estimated using the GAMIT software have cm-level precision out to 10-km lengths if ambiguity resolution is not attempted, but are several times worse if it is attempted, and are not improved by processing more than 2 stations simultaneously. These results are contrary to those typically obtained using dual-frequency data. We are currently working with MIT to assess how to improve the ambiguity resolution algorithms and with UNAVCO to investigate other analysis packages, such as Bernese, that may be better suited to this data type.

Data Analysis

The data from the BARD sites generally are of high quality and measure relative horizontal positions at the 2-4 mm level. The 24-hour RINEX data files are processed daily with an automated system using high-precision IGS orbits. Final IGS orbits, available within 7-10 days of the end of a GPS week, are used for final solutions. Preliminary solutions for network integrity checks and rapid fault monitoring are also estimated from Predicted IGS orbits (available on the same day) and from Rapid IGS orbits (available within 1 day). Data from 5 primary IGS fiducial sites located in North America and Hawaii are included in the solutions to help define a global reference frame. Average station coordinates are estimated from 24 hours of observations using the GAMIT software developed at MIT and SIO, and the solutions are output with weakly constrained station coordinates and satellite state vectors.

Processing of data from the BARD and other nearby networks is split into 6 geographical subregions: the Bay Area, northern California, Long Valley caldera, southern and northern Pacific Northwest, and the Basin and Range Province. Each subnet includes the 5 IGS stations and 3 stations in common with another subnet to help tie the subnets together. The weakly constrained solutions are combined using the GLOBK software developed at MIT, which uses Kalman filter techniques and allows tight constraints to be imposed a posteriori. This helps to ensure a self-consistent reference frame for the final combined solution. The subnet solutions for each day are combined assuming a common orbit to estimate weakly constrained coordinate-only solutions. These daily coordinate-only solutions are then combined with tight coordinate constraints to estimate day-to-day coordinate repeatabilities, temporal variations, and site velocities. The estimated relative baseline determinations typically have 2–4 mm WRMS scatter about a linear fit to changes in north and east components and the 10–20 mm WRMS scatter in the vertical component.

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.

Deformation in Northern California and Nevada

Average velocities for the longest running stations from BARD and other nearby networks are shown in Figure 2. To account for colored-noise error processes, such as monument wander, multipath, and atmospheric effects, we scaled the formal uncertainties according to the approximate expression given by Mao et al. (1999) for the total uncertainty of velocity as a function of both the white noise and flicker noise uncertainties appropriate for North American sites. This flicker noise model results in velocity uncertainties 6–12 times their formal uncertainties. The velocities are relative to stable North America, as defined by the five IGS fiducial stations.

Stations in eastern Nevada show little motion relative to North America, whereas the station on the Farallon Islands (FARB), 30 km offshore near San Francisco, is moving at 46 mm yr^{-1} N35°W. This is consistent with the motion predicted by NUVEL-1A for the Pacific plate (DeMets et al., 1994), indicating that the network spans nearly the entire deformation field associated with the plate boundary.

The San Andreas Fault system accommodates $\sim$35 mm yr^{-1} parallel to the predicted plate motion across a 100-km wide zone near the coast. The remaining $\sim$11 mm yr^{-1} of predicted plate motion is distributed across the Sierran-Great Valley, and Basin and Range province with significant velocity components normal to the predicted direction. This region can be divided into 3 relatively stable crustal blocks delimited primarily by seismicity patterns. The Sierran-Great Valley (SG) block is located between the SAF and a northwest trending seismicity belt between Lake Tahoe and Mount Shasta in eastern California. This seismicity belt is the western edge of the Basin and Range province, which we divide into eastern (EB) and western (WB) blocks about the Central Nevada Seismic Zone (CNSZ).

Our preferred kinematic model (Murray et al., in prep., 2000), assumes a single angular velocity for SG block, and a single Euler pole location, but different angular velocity rates for the EB and WB blocks. The WRMS misfits of the horizontal components of 1, 1, and 2 mm yr^{-1} for the EB, WB, and SG regions, respectively. Relative motion along the boundaries between the regions varies with position. Because EB and WB share the same Euler pole, relative motion is purely extensional across oblique longitudinal lines, which the CNSZ closely approximates. The predicted extension at 40°N, 118°W is 3 mm yr^{-1} N75°W. The relative motion between WB and SG at 40°N, 121°W is 3 mm yr^{-1} N45°W, approximately parallel to the seismicity trend, indicating the deformation is primarily right-lateral strike-slip.

Motion of stations near the San Andreas fault system is approximately parallel to the NUVEL-1A predictions (Figure 3). Velocity components normal to this direction do not differ significantly from zero west of the SAF and are less than 5 mm yr^{-1} for sites between the SAF and Great Valley. The parallel velocity components vary in magnitude almostly linearly by $\sim$35 mm yr^{-1} across a 100-km wide zone near the coast, which previous studies show is consistent with interseismic strain accumulation on faults that are freely slipping except at shallow depths (Lisowski et al., 1991).

To model the observed deformation, we assume interseismic deformation is a superposition of long-term average rigid-body motions on either side of faults, and back-slip on shallow locked portions of faults. This approach is similar to the elastic dislocation model commonly used in subduction zone studies (Savage, 1983), except we express the long-term average motion using angular velocities. Given that the westernmost stations in our study form a roughly linear profile across the SAF system and their motions are predominantly parallel to predicted motion, we model interseismic strain accumulation using two-dimensional (anti-plane strain) screw dislocations. This

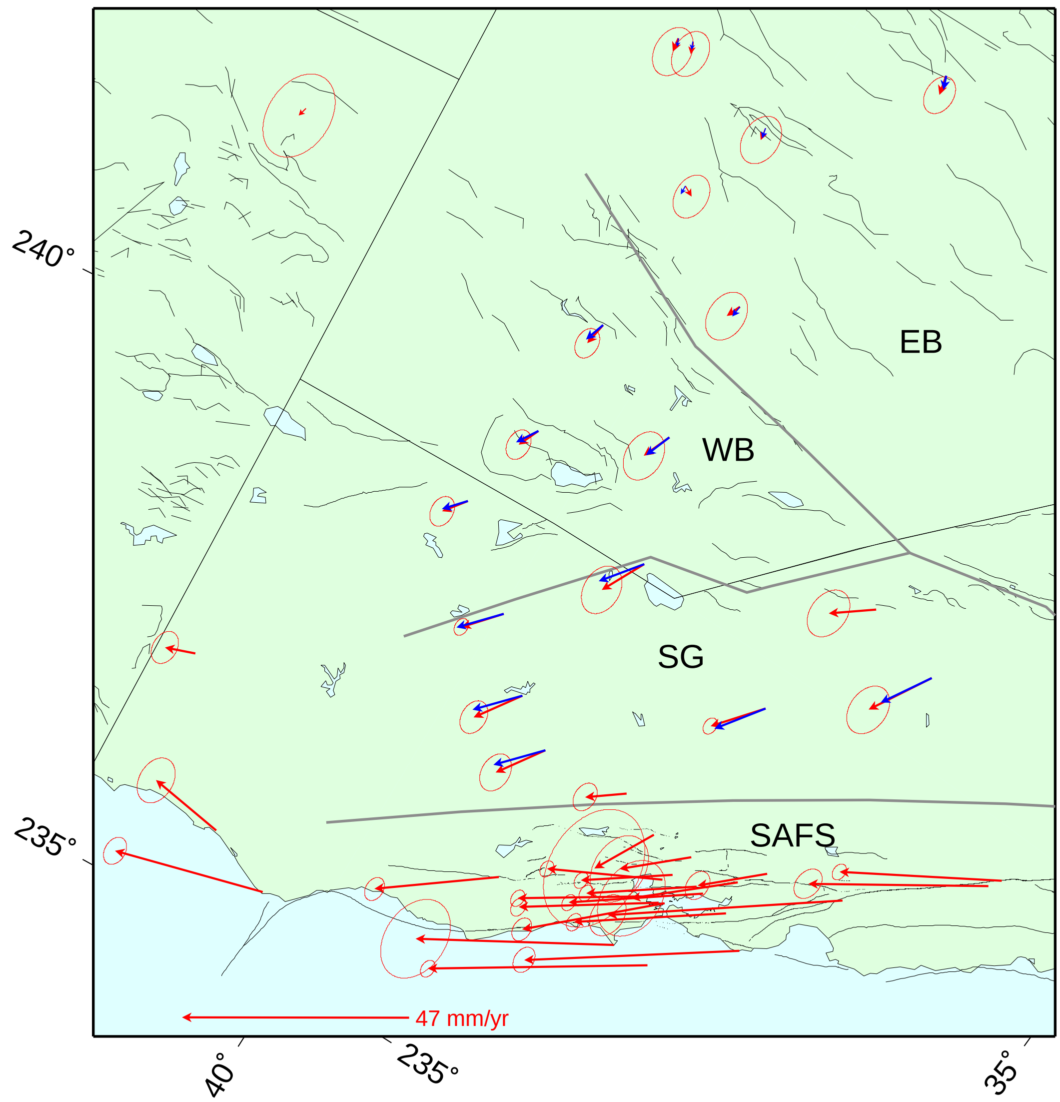

Figure 2: Observed (red) and modeled (blue) velocities relative to stable North America for stations in the BARD and nearby networks. Data from November 1993 to October 1999 was processed by the BSL using GAMIT software. Ellipses show 95% confidence regions, scaled by a white and flicker noise model, with the predicted Pacific–North America relative plate motion in central California shown for scale. The projection is the same as Figure 1. Modeled velocities are from Euler pole determinations for the Sierran-Great Valley (SG), and west (WB) and east (EB) Basin and Range blocks. Velocities within the San Andreas fault system (SAFS) are estimated using two-dimensional models.

method is described in more detail in Murray et al. (in prep, 2000).

Figure 3 shows the results using a model with 3 faults, corresponding to the San Andreas (SA), Hayward (H), and Calaveras/Concord (CC) fault strands. Given the high correlations associated with determining fault geometry and slip parameters in a parallel fault regime, we assume the fault locations are known from surface geology studies, and use locking depths derived from observed seismicity. Estimated deep slip rates on SA, H, and CC faults are 19.2, 11.3, and 7.4 mm yr^{-1}, respectively, in reasonably good agreement with neotectonics studies (17±4, 9±2, and 5±3 mm yr^{-1}, WGCEP, 1999). We are currently extending these methods to three dimensions to better characterize the complex geometry of faults in the San Francisco Bay area.

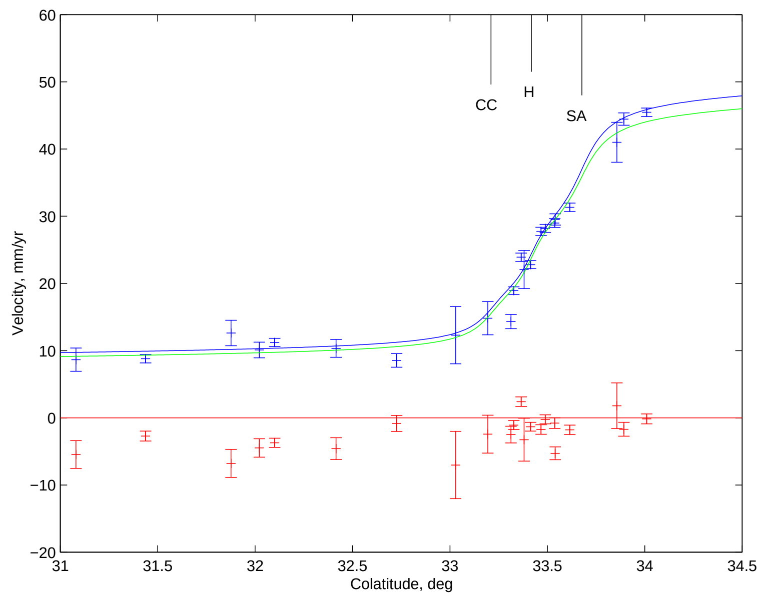

Figure 3: Velocities relative to the NUVEL-1A Pacific-North America Euler pole of stations located in a profile from eastern Nevada to the San Francisco Bay area. Observed velocities (crosses), with one standard deviation error bars, are perpendicular (red) and parallel (blue) to the predicted direction as a function of oblique colatitude from the Euler pole. The blue curve is the angular velocity and 3-fault backslip model prediction. The green curve is the same model, assuming the NUVEL-1A rate on the Pacific plate. Vertical lines at top indicate location and relative depths of the San Andreas (SA), Hayward (H), and Calaveras/Concord (CC) faults.

Transient Deformation of the 1998 San Juan Bautista Earthquake

The August 1998 Mw=5.1 San Juan Bautista earthquake produced a detectable displacement signal at the nearby SAOB GPS receiver (Uhrhammer et al., 1999). The observed transient deformation, which appears to have both coseismic and postseismic components, is similar to nearby creep and strainmeter observations. No significant vertical offset was detected and no other BARD sites were measurably displaced. Relative to the PKDB station (Figure 4), SAOB moved north 2.6±0.5 mm and west 4.3±0.6 mm. This GPS-derived displacement, which represents an average over the six-week interval following the earthquake, is more than double that inferred from the more instantaneous accelerometer measurements at the collocated seismic station SAO. Continued aseismic slip on the fault following the earthquake is one possible explanation for this difference. Measurements at the nearby SJS borehole tensor strainmeter, which show an instantaneous 0.5 microstrain coseismic offset followed by an additional 0.5 microstrain increase over the next 12 days, are consistent with this interpretation (Figure 4).

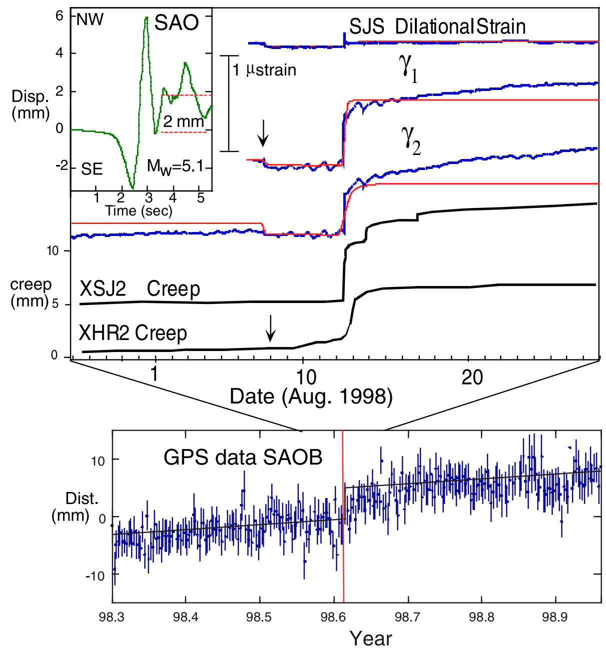

Figure 4: Transient deformation following the 1998 San Juan Bautista earthquake, as observed on strain dilatometers (top right), accelerometers (top left), surface creepmeters (middle), and GPS (bottom). Modified from Uhrhammer et al. (1999).

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 3 new stations, performed many enhancements to the existing network, estimated several crustal block motions and fault deep slip rates, and detected deformation due to a moderate-sized earthquake near one of the GPS stations.

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