ANNUAL PROJECT SUMMARY

AWARD NUMBER: 01HQAG0035

THE BARD CONTINUOUS GPS NETWORK: MONITORING ACTIVE DEFORMATION AND STRAIN ACCUMULATION IN NORTHERN CALIFORNIA AND THE SAN FRANCISCO BAY AREA: Collaborative research with UC Berkeley, and 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 U.S. 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 60 permanent stations and will expand to about $\sim$70 stations by 2003 (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.

During the past year, the BSL performed maintenance to existing stations, prepared to install an experimental single-frequency receiver profile and several broadband deformation stations that include GPS, improved data archiving and processing methods, and analyzed of GPS data to estimate deformation signals monitored by the network. 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

Continuous GPS Measurements in Northern California

BARD presently includes 60 permanent, continuously operating stations, 14 of which monitor the Long Valley caldera near Mammoth. The remaining 46 stations include 19 maintained by the BSL (including 2 with equipment provided by Lawrence Livermore National Laboratory (LLNL) and UC Santa Cruz), 8 by the USGS, and one each by LLNL, Stanford University, UC Davis, UC Santa Cruz, Trimble Navigation, 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 (SIO), 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).

In the last year, the SIO and USGS installed 9 new GPS stations near the Parkfield segment of the San Andreas fault. Fifteen continuous stations now monitor this region that is expected to rupture in a long-anticipated M6 earthquake. Part of the funding for these installations was provided by an NSF-funded project. The BSL is participating in another component of this project, in collaboration with the USGS and Carnegie Institute of Washington to install 8 collocated GPS/seismometer/borehole strainmeter observatories during 2001–2002 in the Bay Area. Our efforts on this project (commonly referred to as “Mini-PBO”), which will enhance GPS monitoring by the BARD network of the northern Hayward and peninsular San Andreas faults, is described in more detail in a later section.

Station Maintenance

In late June 2000, the estimated position of one of the BSL stations (MODB) began to change at a significantly high rate, resulting in an apparent displacement of over 30 mm to the northeast over a one month period (Figure 2). MODB, one of the newest BARD stations, was installed in November 1999 in the remote northeasternmost corner of California. Although the tectonics of this region, located in backarc of the Cascadia subduction near the Basin and Range province, are poorly understood, the apparent displacement of the antenna was much larger than could be reasonably expected from geophysical causes. Visual inspection of the concrete pier did not reveal any obvious signs of monument instability. The signal-to-noise ratios (SNR) of the raw phase measurements significantly decreased after the anomaly began, particularly for observations at high satellite elevation angles (Figure 3). We performed antenna and receiver swap tests to show that the antenna had malfunctioned, and repair of the antenna dipole element by Ashtech restored the observations to their original signal levels. We intend to incorporate the SNR analysis into our automated data quality control procedures to improve hardware failure detection.

During the past year, we converted telemetry at the 12 sites equipped with seismic Quanterra dataloggers to take advantage of the methods we developed to store data packets in MiniSEED blockettes. Originally these stations used direct serial connections that would result in loss of data during frame relay outages. The MiniSEED approach provides more robust data recovery from onsite backup on the Quanterra disks following telemetry outages. Our comparisons also show the loss of individual records is fewer when using the Quanterra MiniSEED rather than direct serial method due to the superior short-term data buffer in the Quanterra.

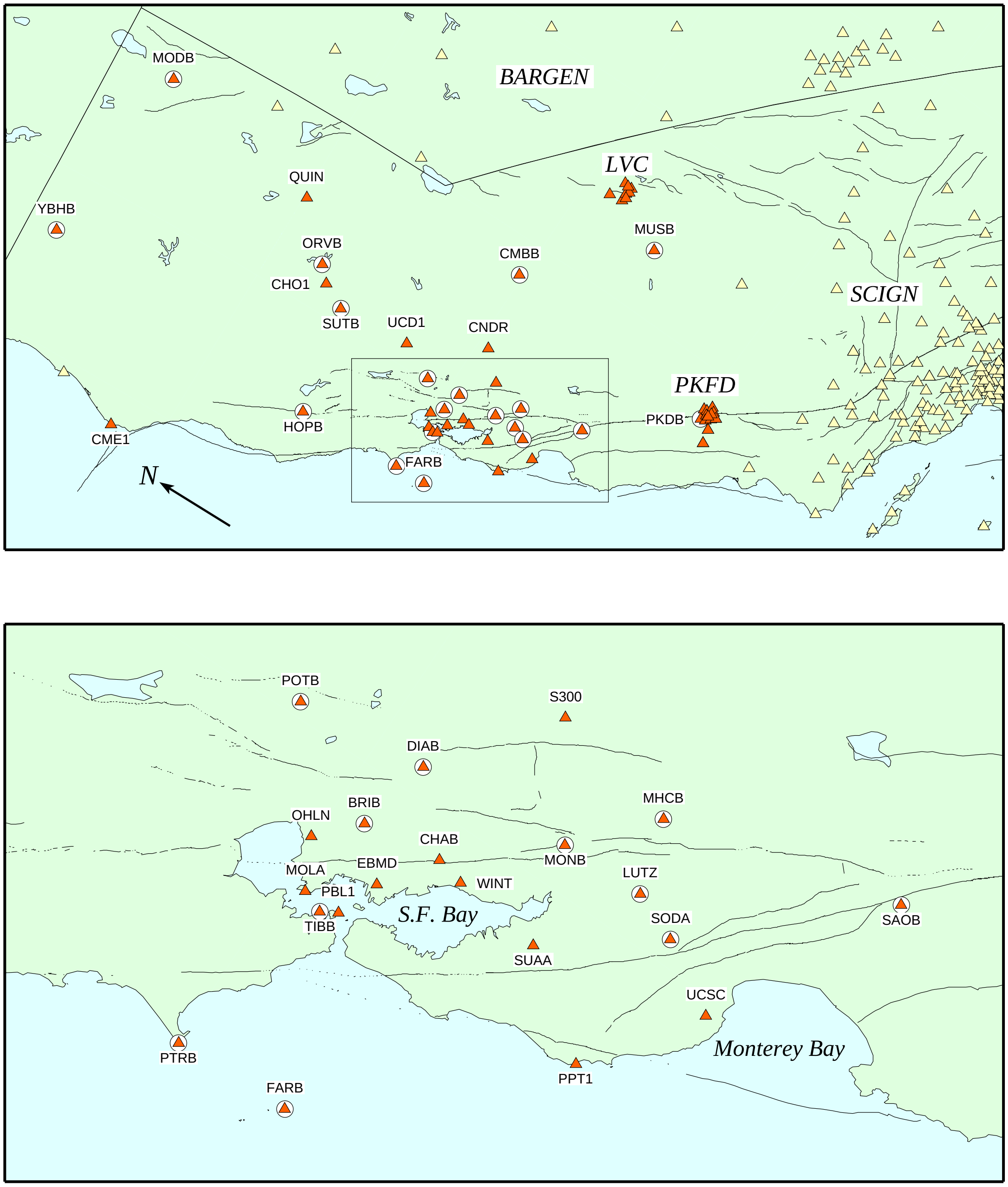

Figure 1: Operational BARD stations (solid triangles) in northern California (top) and in the San Francisco Bay area (bottom). The oblique Mercator projection is about the NUVEL-1 Pacific–North America Euler pole so that expected relative plate motion is parallel to the horizontal. Circled stations use continuous telemetry. The eight station Long Valley Caldera (LVC) network and 15 station Parkfield (PKFD) networks are also part of BARD. Other nearby networks (yellow triangles) include: Basin and Range (BARGEN), and Southern California Integrated GPS Network (SCIGN).

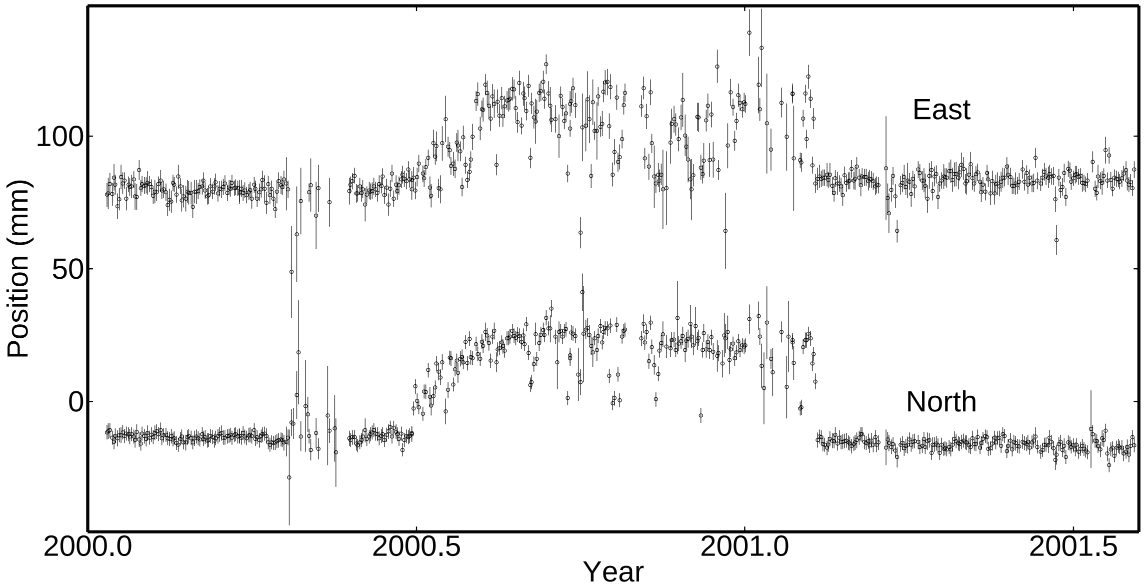

Figure 2: Daily variation in relative position of MODB antenna. The east and north components are arbitrarily offset for clarity. The antenna began to malfunction around 2000.5 and was replaced around 2001.1. The station telemetry was poor around 2000.3.

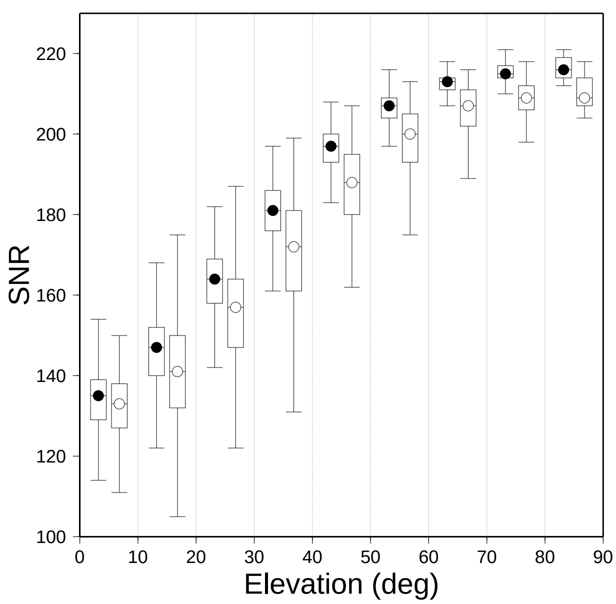

Figure 3: L1 phase signal strength for properly operating (solid circles) and malfunctioning (open circles) antennas by angle of elevation above the horizon. The signal-to-noise ratio (SNR) values are in arbitrary units defined by the receiver manufacturer. Observations are binned in 10 degree intervals. The circles show the median value and the box-and-whisker symbols show the 25% and 75% quantile, and the minimum and maximum values. The malfunctioning antenna has significantly smaller SNR values at high elevation angles.

L1-system Profile

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 power and integrated radio modems (Fig. 4). During 1999, the BSL borrowed 2 receivers and a master radio from UNAVCO to perform the evaluation, but persistent hardware and software problems limited progress on this project. UNAVCO subsequently resolved many of the problems and in summer 2000, we received new, improved equipment and software for 4 systems and a master radio. We are currently preparing 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 (Fig. 5).

We have completed permitting at two of the sites (Fig. 5), both located on East Bay Municipal Utilities District (EBMUD) property. BDAM is located just east of the Briones Dam (BDAM) site, a few km west from the Briones (BRIB) continuous BARD station. VOLM is located on the ridge of the East Bay Hills close to Volmer Peak. Permitting is nearly complete at the other two stations, Wildcat (WLDC), also on EBMUD property near San Pablo Reservoir, and Grizzly Peak (GRIZ) on East Bay Regional Park property. Finding suitable stations with line-of-sight telemetry across the East Bay Hills proved challenging. Data from WLDC must pass through all the other stations, with its relay path being (in order) BDAM, VOLM, GRIZ, a repeater on the UC Berkeley Space Sciences Building, and then finally BSL in McCone Hall. We expect to install the stations with assistance from UNAVCO in Fall 2001. This profile, complemented by BRIB and EBMD to the west of the fault, will be most sensitive to variations in locking at 2-8 km depth. 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).

Data Archival and Distribution

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.

Many of the BARD sites are classified as CORS stations by the NGS, which are used as reference stations by the surveying community. All continuous stations operating in July 1998 were included in a statewide adjustment of WGS84 coordinates for this purpose; a more recent adjustment is

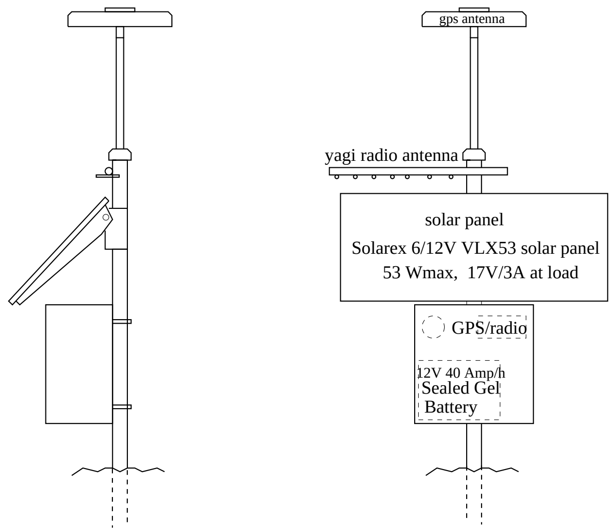

Figure 4: Schematic of the L1-system instrumentation and monument.

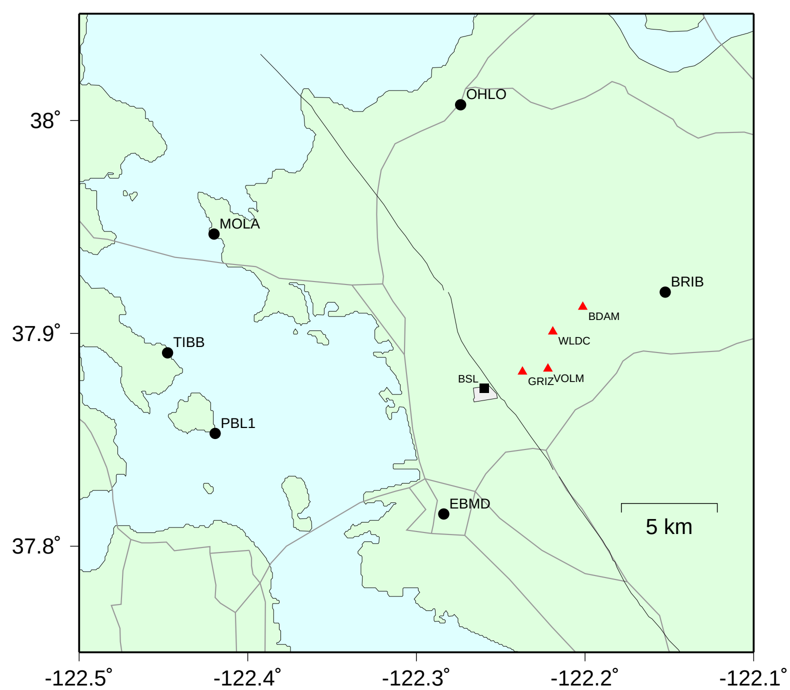

Figure 5: Location of L1-system (red triangles) and BARD (black circles) stations. BSL, just southwest of the Hayward fault, is the location of the Berkeley Seismological Laboratory, where data from the 4 L1-system receivers northeast of the Hayward will be telemetered.

currently underway. Members of the BARD project regularly discuss these and other common issues with the surveying community at meetings of the Northern California GPS Users Group.

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.

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 7 geographical subregions: the Bay Area, northern California, Long Valley caldera, Parkfield, 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. Average velocities for the longest running BARD stations during 1993–2000 are shown in Figure 6, with 95% confidence regions. We have allowed 1 mm $yr^{-1/2}$ random-walk variations in the site positions in order to more accurately characterize the long-term stability of the site monuments and day-to-day correlations in position. The velocities are relative to stable North America, as defined by the IGS fiducial stations, which we assume have relative motions given by *Kogan et al.* (2000).

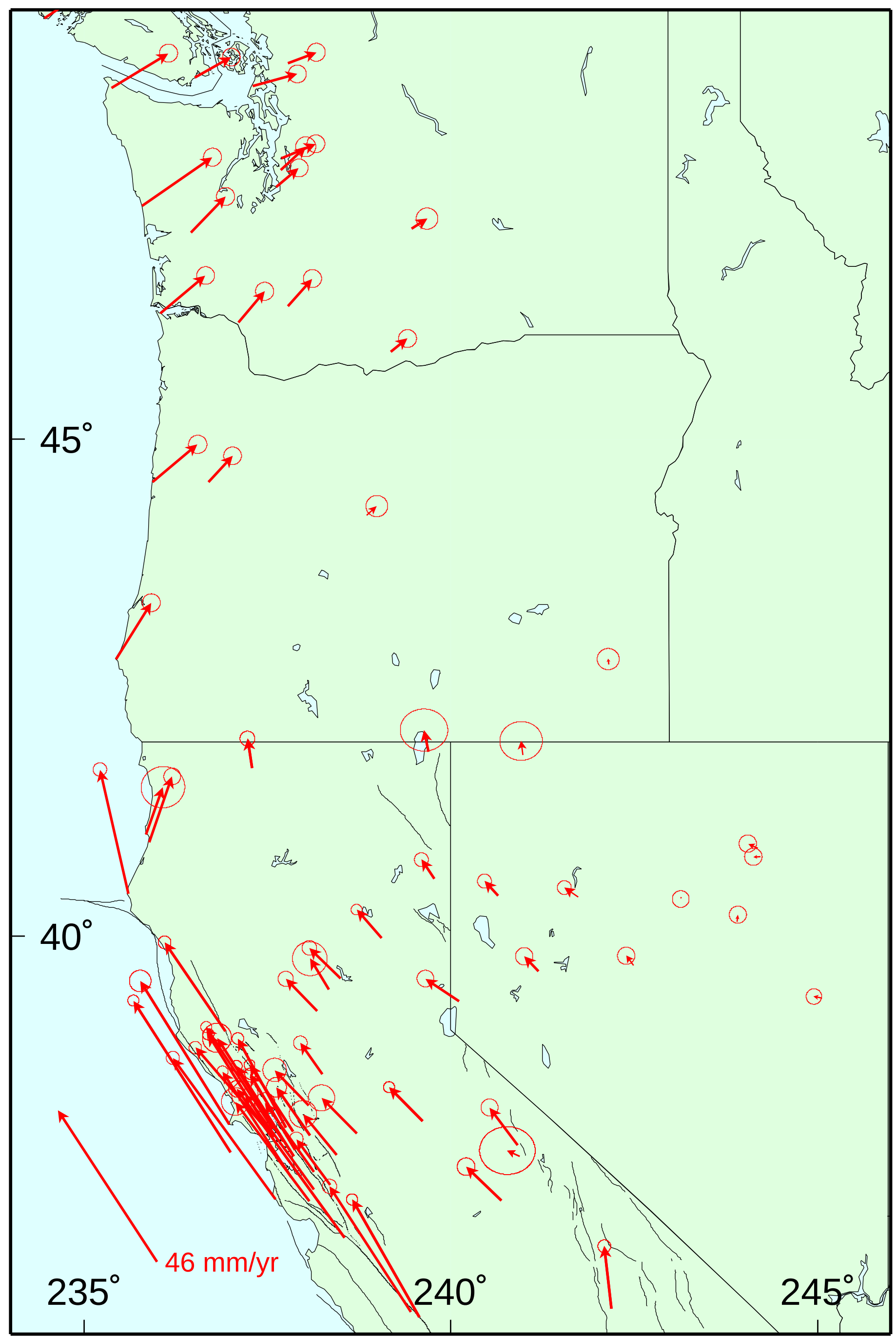

Figure 6: Velocities relative to stable North America for the BARD stations and other stations operated in nearby networks. Data from November 1993 to July 2000 was processed by the BSL using GAMIT software. Ellipses show 95% confidence regions, assuming white noise and 1 mm yr$^{-1/2}$ random-walk noise, with the predicted Pacific–North America relative plate motion in central California shown for scale.

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

In *Murray and Segall* (2001), we present a simple method for modeling crustal deformation as a combination of plate tectonic motions and interseismic elastic strain accumulation on faults. We assume the crust is composed of spherical caps, such as the major tectonic plates and microplates, that behave over many earthquake cycles as rigid bodies with angular velocity relative motions. Transient strain accumulation effects are accommodated by adding slip opposite the long-term rates (backslip) on the shallow seismogenic (locked) parts of the plate-boundary faults. Strain effects due to shallow backslip become negligible in the stable plate interiors where angular velocity motions predominate. This method provides a better kinematic description of broadscale deformation than models using forward slip on semi-infinite deep faults or other backslip dislocation models that assume block motions on planar surfaces, which do not approach angular velocities far from the plate boundaries.

We analyzed continuous GPS data collected from November 1993 to July 2000 by 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 other agencies (Fig. 7). Based on seismic, geologic, and previous geodetic studies we divided the study area into 6 plates (Fig. 7). In addition to the North America (NA) and Pacific (PA) plates, the San Andreas system in the San Francisco Bay area is represented by three strike-slip faults with assumed locking depths that bound the San Francisco (SF) and Martinez (MZ) plates. Station motions in the Bay Area are nearly parallel to the motion of PA relative to NA (denoted PA-NA) predicted by the NUVEL-1A Euler pole, denoted $\hat{\mathbf{\Omega}}_{PA}^{NU}$ (*DeMets*, 1994) (Figs. 7B and 8), so we used 2D anti-plane strain screw dislocations on small circles about $\hat{\mathbf{\Omega}}_{PA}^{NU}$ and estimated only angular rates of rotation for each plate. The Sierran-Great Valley plate (SG) is bounded by the San Andreas system and the northern Walker Lane Belt (NWLB). The Central Nevada Seismic Zone (CNSZ) divides the Basin and Range province (BR) into eastern (EB) and western (WB) plates.

Horizontal station motions predicted by the preferred 10-parameter model (angular rates for 6 plates and Euler pole latitude and longitude for the SG and BR plates) have a total wrms misfit of 1.1 mm yr^{-1}. Misfits within each plate are comparable to the data uncertainties and consistent with plate rigidity. We assessed model uncertainties using bootstrap methods (*Freymueller et al.*, 1999) due to the nonlinear pole location constraints. The 2D-confidence regions of BR and SG pole locations are elongated due to the limited station distribution (Fig. 9).

These results suggest that the horizontal interseismic deformation is consistent, within the 1 mm yr^{-1} uncertainties of the estimated site velocities, with a simple 10-parameter model using 6 rigid plates and 3 locked San Andreas system faults. Predicted relative motions on the plate boundaries suggest that deformation across the Basin and Range can be partitioned into 2.4 mm yr^{-1} east-west extension across the Wasatch fault, 2.3 mm yr^{-1} east-west extension across the CNSZ, and 3.6 mm yr^{-1} primarily right-lateral strike-slip on the NWLB. The SG moves obliquely to the San Andreas system, with $\sim$2.4$\pm$0.4 mm yr^{-1} of fault-normal convergence being accommodated over a narrow ($<$15 km) zone (Figs. 7 and 8). This convergence may contribute to uplift of the Coast Ranges (*Argus and Gordon*, 2001). The inferred $\sim$37.2$\pm$1.0 mm yr^{-1} slip rate across the San Andreas system is consistent with geologic estimates. The $\sim$14.2$\pm$2.0 mm yr^{-1} slip rate on the Hayward fault is higher than the geologic estimate, although models with rates lower on the Hayward and higher on the other faults are also acceptable due to high correlations between these parameters.

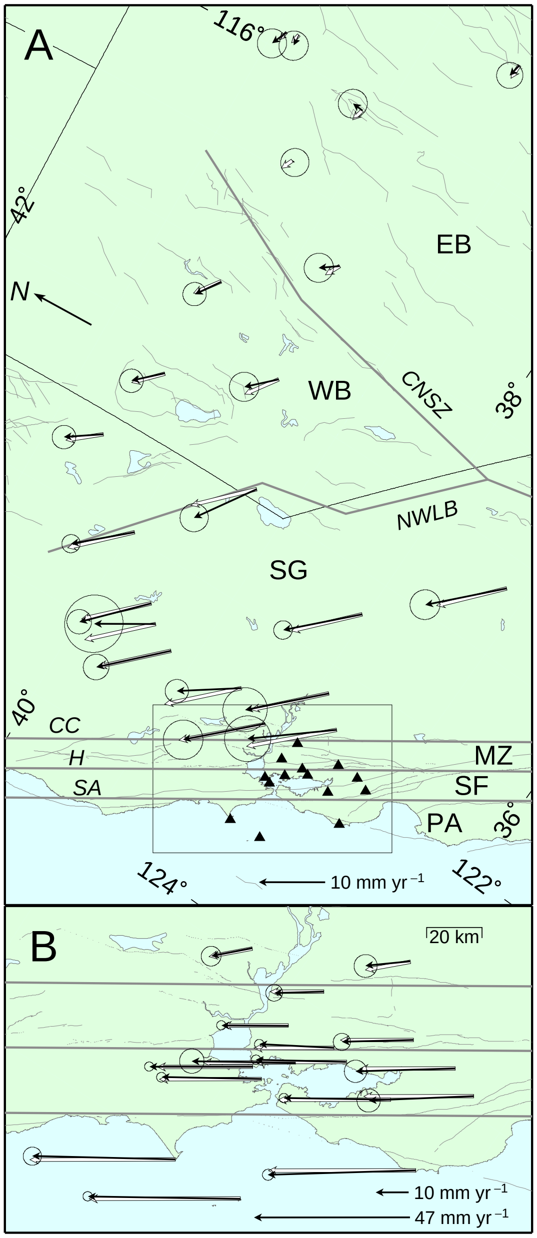

Figure 7: Predicted (open) and observed (solid) site velocities, with 95% confidence regions, relative to NA. Projection, oblique Mercator about $\hat{\mathbf{\Omega}}_{PA}^{NU}$. A) northern California and Nevada (see box in Fig. 9), with velocities of sites in box (triangles) omitted for clarity. B) San Francisco Bay area. Faults: SA = San Andreas, H = Hayward, CC = Concord/Calaveras, NWLB = northern Walker Lane Belt, CNSZ = Central Nevada Seismic Zone.

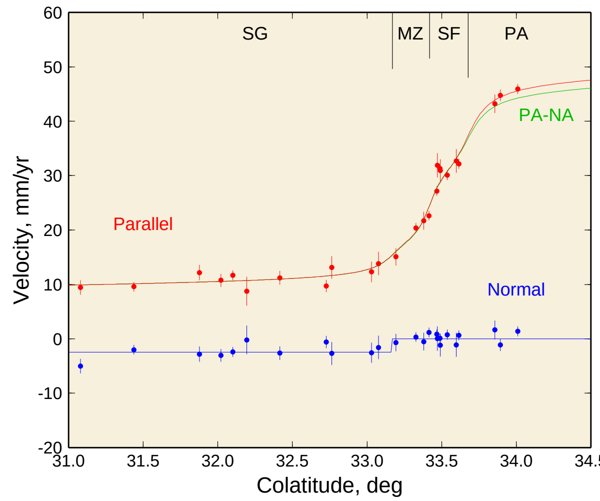

Figure 8: Velocities relative to NA, with one standard error bars, parallel and normal to small circles about $\hat{\mathbf{\Omega}}_{PA}^{NU}$ versus angular distance from $\hat{\mathbf{\Omega}}_{PA}^{NU}$. Red line, preferred model. Green line, model with Pacific angular rate constrained to NUVEL-1A, which has significantly greater misfit (95% confidence) than preferred model. Plate regions and San Andreas faults are shown schematically at top.

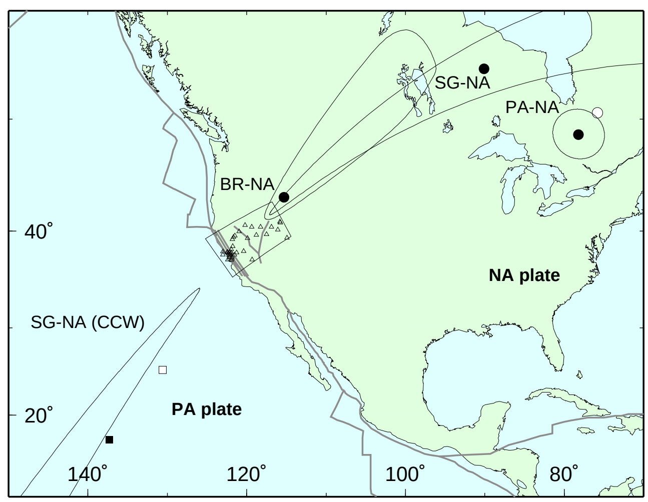

Figure 9: Estimated $\hat{\mathbf{\Omega}}$ (solid circles) with 95% confidence bootstrap regions. PA-NA is $\hat{\mathbf{\Omega}}_{PA}^{NU}$. Open circle, alternative $\hat{\mathbf{\Omega}}_{PA}$ (*DeMets and Dixon*, 1999). BR-NA applies to both WB and EB. The SG-NA uncertainty, which spans nearly 180deg, has both clockwise (top) and counterclockwise (bottom) rotation regions, and includes pure translation (Euler pole at 90deg distance from SG). Squares, alternative $\hat{\mathbf{\Omega}}_{SG}$: open, (*Argus and Gordon*, 2001); solid, (*Dixon et al.*, 2000). Box encloses stations and plate boundaries shown in Fig. 7.

Mini-Plate Boundary Deformation Project

The Integrated Instrumentation Program for Broadband Observations of Plate Boundary Deformation, commonly referred to as "Mini-PBO", is a joint project of the BSL, the Department of Terrestrial Magnetism at Carnegie Institution of Washington (CIW), the IGPP at U.C. San Diego (UCSD), and the U.S. Geological Survey (USGS) at Menlo Park, Calif. It augments existing infrastructure in central California to form an integrated pilot system of instrumentation for the study of plate boundary deformation, with special emphasis on its relation to earthquakes. This project is partially funded through the EAR NSF/IF program with matching funds from the participating institutions and the Southern California Integrated Geodetic Network (SCIGN).

Because the time scales for plate boundary deformation range over at least 8 orders of magnitude, from seconds to decades, no single technique is adequate. We have proposed an integrated approach that makes use of three complementary and mature geodetic technologies: continuous GPS, borehole tensor strainmeters, and interferometric synthetic aperture radar (InSAR), to provide a broadband characterization of surface deformation. In addition, ultrasensitive borehole seismometers will monitor microearthquake activity related to subsurface deformation.

This year, the BSL has focused primarily on site selection for the integrated network in the Bay Area, in cooperation with the USGS. Figure 10 shows the planned configuration. Two borehole sites were drilled during the summer of 2001, at Ohlone Park (OHLN) in Hercules and on San Bruno mountain (SBRN) near Brisbane. These holes are equipped with newly fabricated borehole tensor strainmeters and seismometers, and downhole pore pressure and tilt sensors will be added in the near future. One site in the Marin Headlands (MHDL) is scheduled to be drilled before the end of September 2001, and two additional sites will be drilled by the end of 2001, at the Knox/Miller Park (KNOX) near Richmond and on Ox Mountain (OXMT) near Half Moon Bay. The first two instrumented sites are also awaiting installation of power, telemetry, electronics, GPS receivers, and Quanterra 330 recording systems.

Permitting of five additional sites for 2002 installations are in the preliminary stages. These include: sites on U.S. Coast Guard property on Yerba Buena Island in the San Francisco Bay (YERB) and near the former Hamilton Field military base in Marin (HAML), a site at St. Marys College in the East Bay (STMC), and two sites in the south Bay in the Rancho San Antonio Open Space Preserve (RSAN) and Castle Rock State Park (CSTR). Site evaluation of geologic properties, sky visibility, ease of permitting, and power and telemetry, have been performed at most of the sites. We are continuing to evaluate the Yerba Buena site where a location suitable for both GPS and strainmeters has proven difficult to find.

After careful review and testing of several current generation GPS receivers, we have decided to purchase Ashtech MicroZ receivers, which use about half the power of the Ashtech Z-12 receivers currently used in the BARD network. We are also designing an experimental GPS mount for the top of the borehole casings to create a stable, compact monument (Figure 12). The antennas, using standard SCIGN adapters and domes for protection, will be attached to the top of the 6-inch metal casing, which will be mechanically isolated from the upper few meters of the ground. The casing below this level will be cemented fully to the surrounding rock. Although this design takes advantage of the deep anchoring of the casing, we will need to assess in the future whether other effects, such as daily or annual thermal expansion of the upper few meters of the casing, limit the long-term stability of the monument.

The GPS stations will complement 18 existing Bay Area stations of the Bay Area Regional

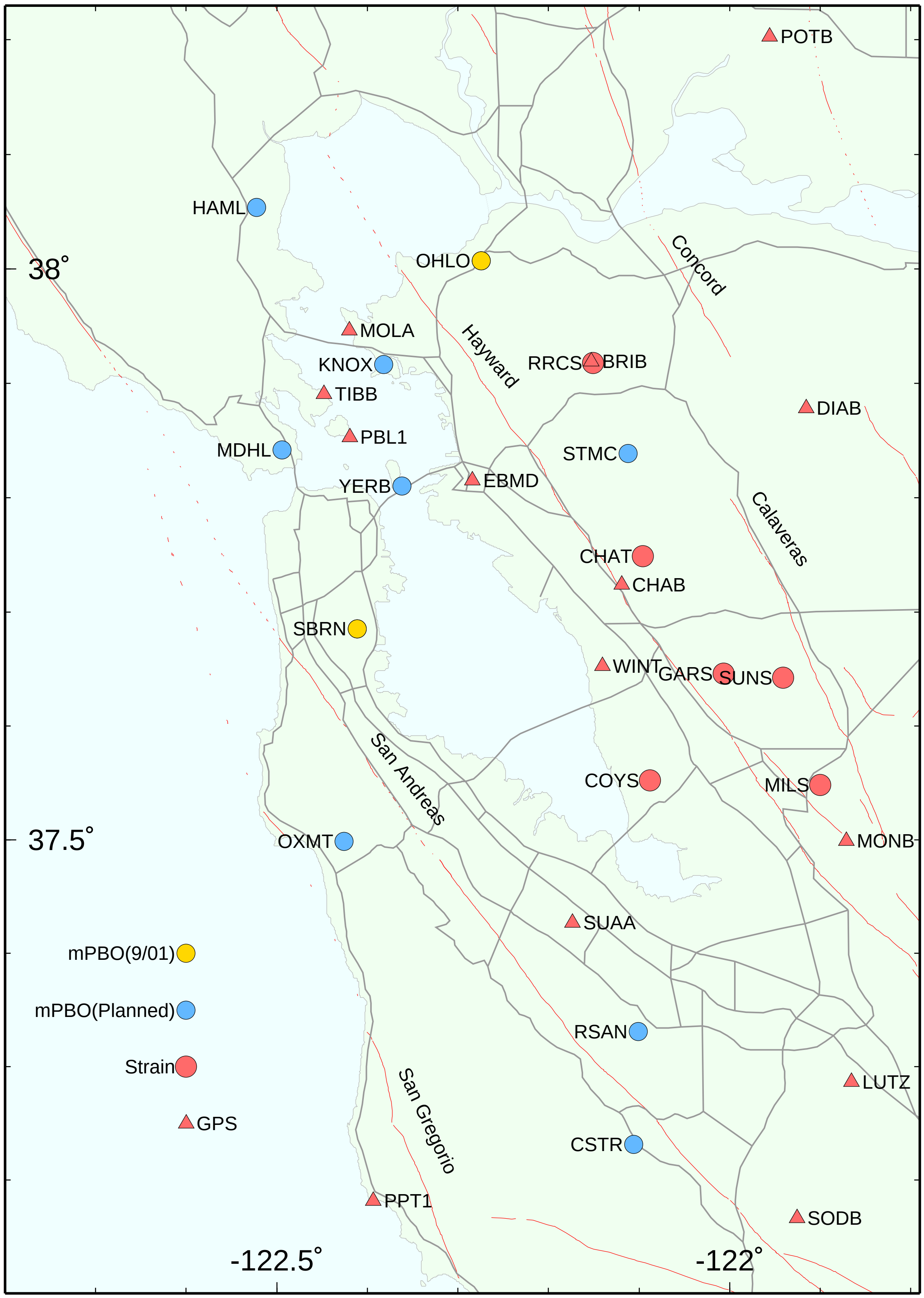

Figure 10: Location of existing (yellow) and planned (blue) Mini-PBO sites in the San Francisco Bay area. Shown also (red) are currently operating strainmeter (circles) and BARD (triangles) stations in the area.

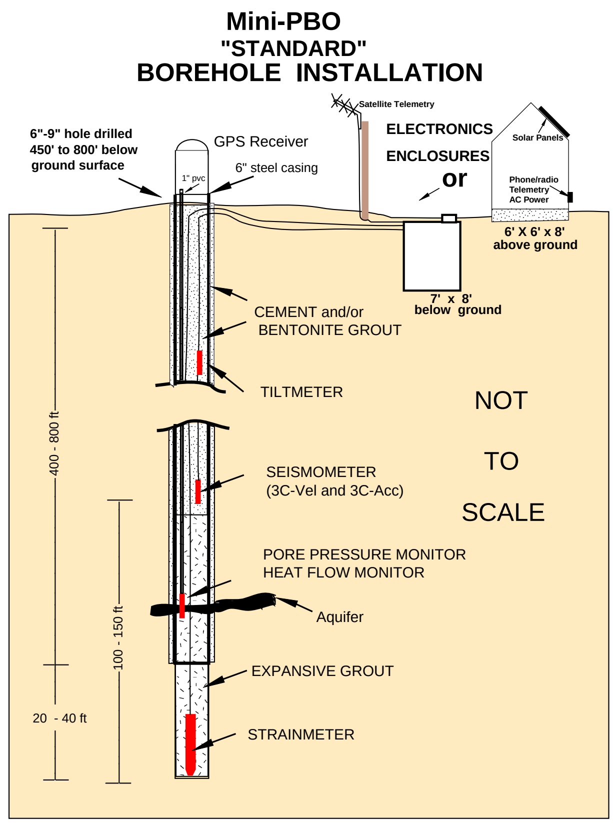

Figure 11: Design of the Mini-PBO borehole installation, showing the emplacement of the instruments downhole and the GPS receiver on the top.

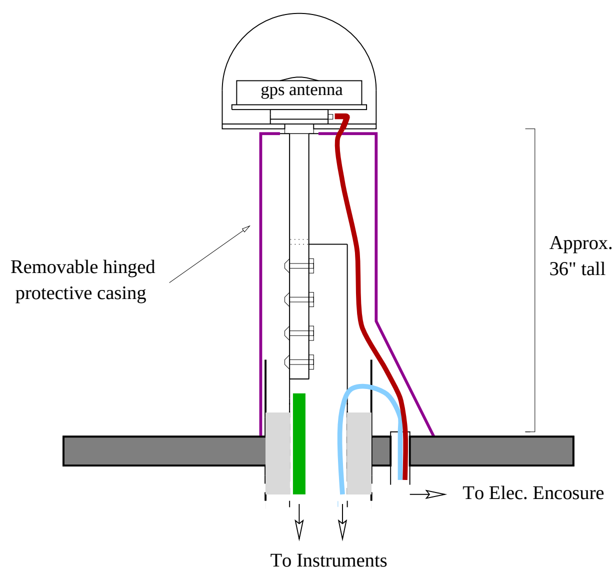

Figure 12: Design of the Mini-PBO GPS antenna mount on top of casing.

Deformation (BARD) continuous GPS network, which includes more than 50 stations in northern California. The data from the GPS, strainmeters, and seismometers will be acquired on Quanterra dataloggers and continuously telemetered over frame relay to U.C. Berkeley, while data from other low frequency sensors will be telemetered using the GOES system to the USGS. Sampling rates are 100 Hz for strainmeters and seismometers, 1 Hz atmospheric, and 30 second GPS through the Quanterra dataloggers, and 600 second for low frequency data (including strainmeters, for redundancy) over the GOES system.

All data will be made available to the community through the Northern California Earthquake Data Center (NCEDC). In preparation for this, the BSL and USGS have worked out procedures to archive data from 139 sites of the USGS ultra-low-frequency (UL) geophysical network, including data from strainmeters, tiltmeters, creep meters, magnetometers, and water well levels. These data are available in SEED format and set the stage for the archiving and distribution of data from the Mini-PBO stations.

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ANNUAL PROJECT SUMMARY

AWARD NUMBER: 01HQAG0035

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

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

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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 performed enhancements to the existing network and operation procedures, prepared for the installation of several new stations, and estimated horizontal interseismic deformation in northern California and Nevada using 6 rigid plates and strain accumulation on 3 San Andreas system faults that requires no distributed deformation.