FINAL TECHNICAL REPORT

- AWARD NUMBER: 01HQAG0035
- RECIPIENT: Regents of the University of California
- PRINCIPAL INVESTIGATOR: Barbara Romanowicz and Mark H. Murray
- TITLE: 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
- PROGRAM ELEMENTS: I & II

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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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1. TECHNICAL ABSTRACT

The Bay Area Regional Deformation (BARD) network of continuously operating Global Positioning System (GPS) receivers monitors crustal deformation in the San Francisco Bay area and northern California . It is a cooperative effort of the BSL, the USGS, and several other academic, commercial, and governmental institutions. The BARD network expanded during the three years of this project (April 1, 2001 to March 31, 2004) from 50 to over 70 permanent stations. The BARD network is designed to study the distribution of deformation in northern California across the Pacific–North America plate boundary and interseismic strain accumulation along the San Andreas fault system in the Bay Area for seismic hazard assessment, and to monitor hazardous faults and volcanoes for emergency response management.

During this reporting period, the BSL upgraded existing stations, installed 4 new stations in an experimental single-frequency receiver profile, and four new dual-frequency stations collocated with borehole strainmeters and seismometers. Procedures were improved for analyzing BARD data, both in near real-time and for long-term deformation analysis. Results from this analysis were used to study the M_w 6.5 2003 San Simeon earthquake, which significantly displaced the BARD continuous stations in the Parkfield region. A preliminary inversion of continuous and survey-mode coseismic displacements and velocity waveform data shows that the fault slip was shallow and ruptured unilaterally 25 km to the southeast producing a pronounced directivity effect in that direction.

Analysis of data from BARD and other continuous stations in northern California and Nevada show that the horizontal interseismic deformation is consistent with a simple 10-parameter model using 6 rigid plates and 3 locked San Andreas system faults. Deformation 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 Central Nevada Seismic Zone, 3.6 mm yr^{-1} primarily right-lateral strike-slip on the Northern Walker Lane Belt and 37.2$\pm$1.0 mm yr^{-1} slip rate across the San Andreas system in the Bay Area. The Sierran-Great Valley block 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, which may contribute to uplift of the Coast Ranges.

2. CURRENT NETWORK

The Bay Area Regional Deformation (BARD) network of continuously operating Global Positioning System (GPS) receivers monitors crustal deformation in the San Francisco Bay area ("Bay Area") and northern California (*Murray et al.,* 1998). It is a cooperative effort of the BSL, the 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), by April 2004, the BARD network included over 70 continuously operating stations in the Bay Area and northern California, including 14 near Parkfield along the central San Andreas fault, and 17 near the Long Valley caldera near Mammoth. The BSL maintains 23 of these stations (including 2 with equipment provided by Lawrence Livermore National Laboratory (LLNL) and UC Santa Cruz). Other stations are maintained by the USGS (Menlo Park and Cascade Volcano Observatory), LLNL, Stanford University, UC Davis, UC Santa Cruz, Hat Creek Radio Observatory, U. Wisconsin, Haselbach Surveying Instruments, East Bay Municipal Utilities District, the City of Modesto, the National Geodetic Survey, Thales, Inc., and the Jet Propulsion Laboratory. Many of these stations are part of larger networks devoted to real-time navigation, orbit determination, and crustal deformation.

Recent additions to the BARD network in the Parkfield and San Francisco Bay area were supported under a complementary project called the Integrated Instrumentation Program for Broadband Observations of Plate Boundary Deformation or "Mini-PBO". This collaborative project of the BSL, the Department of Terrestrial Magnetism at Carnegie Institution of Washington (CIW), the IGPP at UC San Diego (UCSD), and the U.S. Geological Survey (USGS) at Menlo Park, Calif was partially funded through the EAR NSF/IF program with matching funds from the participating institutions and the Southern California Integrated Geodetic Network (SCIGN).The goal of Mini-PBO was to augment 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. Nine new GPS stations were installed in the Parkfield region and 5 broadband deformation stations with collocated borehole strainmeters and seismometers and GPS instrumentation were installed in the Bay Area.

The number of continuous GPS stations in northern California will dramatically increase over the next 5 years, with over 250 new site installations planned as part of the Plate Boundary Observatory (PBO) component of the NSF-funded Earthscope project. In addition, UNAVCO and researchers from BARD and the other regional networks, such as SCIGN, BARGEN, and PANGA, have been funded by NSF to fold operation and maintenance of portions of the existing networks into the PBO array at the end of the 5 years. Due to incompatible management plans for real-time telemetry and site maintenance procedures between the BSL and UNAVCO, only two BSL-maintained stations (SUTB and MUSB), out of a total of 25 BARD stations, will become PBO stations. The other BSL stations are either collocated with seismic instrumentation or are located near the San Andreas fault where real-time processing of the GPS data for earthquake notification is a high priority. We are working closely with UNAVCO to facilitate the transition of the 25 stations, including most of the Parkfield network, and are acting in an advisory role on siting issues for the planned new installations.

Today, 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 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/`).

Many of the BARD sites are classified as CORS stations by the NGS, and are used as reference stations by the surveying community. We coordinate efforts with surveying community at meetings of the Northern California GPS Users Group and the California Spatial Reference Center, and are currently developing plans to use the existing infrastructure at the NCEDC to provide a hub for a high-frequency real-time surveying network in the Bay Area. 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.

2.1 BARD Station Configuration

Each BSL BARD station uses a low-multipath choke-ring antenna, most of which are mounted to a reinforced concrete pillar approximately 0.5–1.0 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. A low-loss antenna cable is used 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. Most use Ashtech Z-12 receivers that are programmed to record data once every 30 seconds and observe up to 12 satellites simultaneously at elevations down to the horizon. The antennas are equipped with SCIGN antenna adapters and hemispherical domes, designed to provide security and protection from weather and other natural phenomena, and to minimize differential radio propagation delays. The BSL acquired 7 Ashtech MicroZ-CGRS (uZ) receivers with NSF funding for the Mini-PBO project. These receivers, designed for continuous station applications, use less power (5.6 W) than the Z-12 receivers due to the lack of an interactive screen, provide better remote receiver control, and can support serial telemetry in both native raw format and the receiver independent BINEX format.

Data from most BSL-maintained stations are collected at 30-second intervals and transmitted continuously over serial connections. Station TIBB uses a direct radio link to Berkeley, and MODB uses VSAT satellite telemetry. Most stations use frame relay technology, either alone or in combination with radio telemetry. Fourteen GPS stations are collocated with broadband seismometers and Quanterra data loggers. With the support of IRIS we developed software that converts continuous GPS data to MiniSEED opaque blockettes that are stored and retrieved from the Quanterra data loggers (*Perin et al.,* 1998), providing more robust data recovery from onsite disks following telemetry outages.

Data from DIAB, MONB, POTB, and TIBB in the Bay Area, the 4 Mini-PBO stations, and 13 stations in the Parkfield regional (all but PKDB), are now being collected at 1-second intervals. Collecting at such high-frequency (for GPS) allows dynamic displacements due to large earthquakes to be better measured, such as was demonstrated by several studies following the 2002 Denali fault earthquake. However, this 30-fold increase in data pose telemetry bandwidth limitations. Data from the Parkfield stations are collected on an on-site computer, written to removable disk once per month, and sent to SOPAC for long-term archiving (decimated 30-sec data is acquired daily via the BSL frame relay circuit). In the Bay Area, we have converted stations that have sufficient bandwidth and are currently assessing bandwidth issues at other stations. We are planning to convert to 1-second sampling where possible during the next year.

The BSL also acquired several Wi-Lan VIP 110-24 VINES Ethernet bridge radios. These 2.4 GHz spread spectrum radios use a tree structure to create a distributed Ethernet backbone with speeds up to 11 Mbps. Each system uses a directional antenna to talk to its “parent” in the tree, and an omni-directional antenna to talk to its children, if multiple, or a directional antenna if it has only 1 child. These radios offer several advantages over the Freewave radios used at other sites, including TCP/IP Ethernet control, higher bandwidth, and greater flexibility for setting up networks. We installed a set of Wi-Lan radios at the SVIN Mini-PBO station to transmit data from the site to the frame relay circuit, and are assisting EBMUD in converting their continuous station to real-time telemetry using Wi-Lan radios.

3. 2001-2004 DEVELOPMENTS

Here we recap some of the important developments of the BARD network during the contract period.

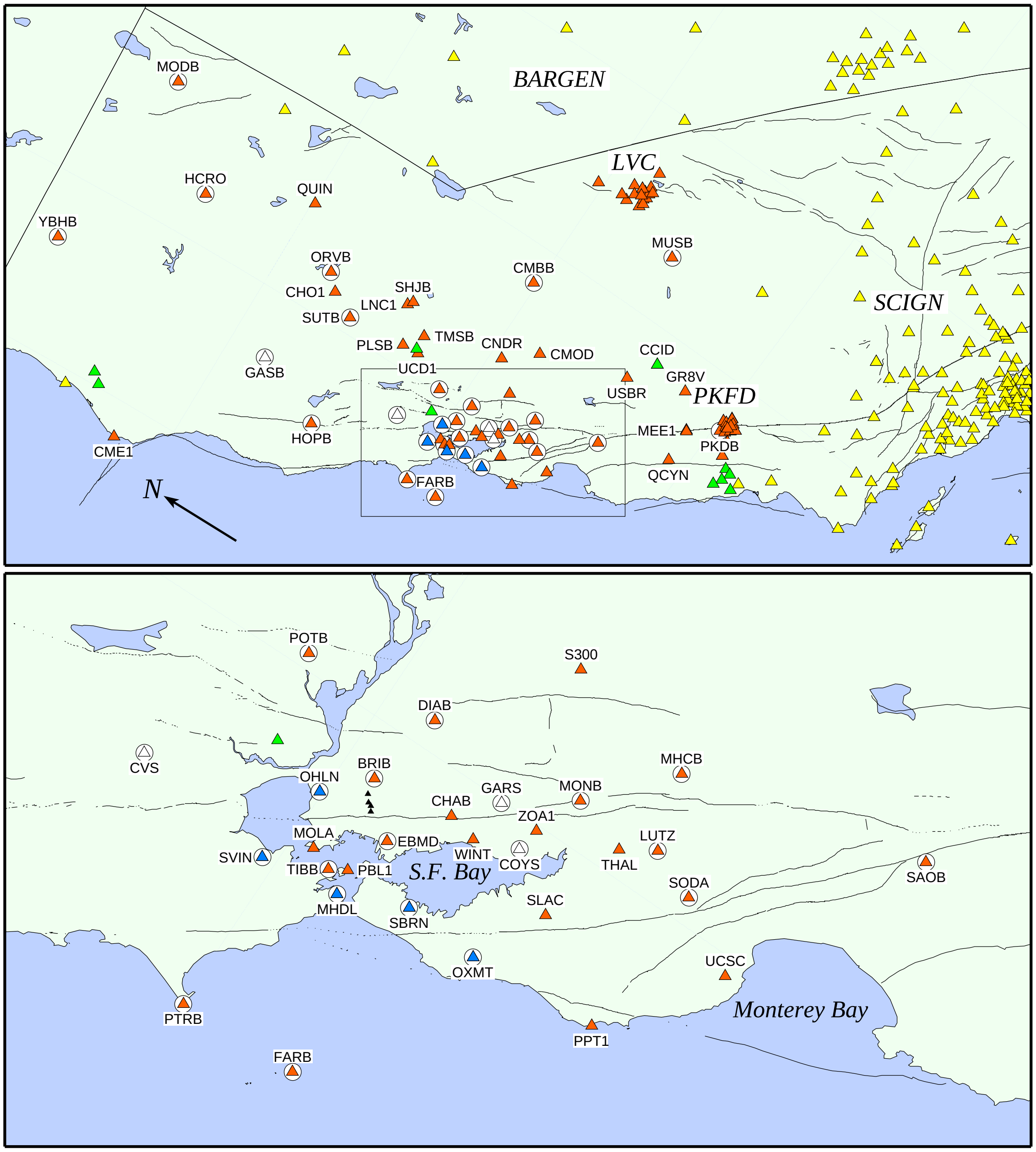

Figure 1: Operational (red) and planned (blue) BARD stations in northern California (top) and in the San Francisco Bay area (bottom). In the oblique Mercator projection expected Pacific–North America relative plate motion is parallel to the horizontal. Circled stations use continuous real-time telemetry. The 18-station Long Valley Caldera (LVC) network and 15-station Parkfield (PKFD) networks are also part of BARD. The small black triangles near BRIB are the experimental L1 stations. Mini-PBO stations are OHLN and SBRN (existing), and MHDL, OXMT, and SVIN (planned), all located along the northern Hayward and San Andreas fault. We plan to install 3 other stations at CVS, GARS, and COYS. The 2 Central Valley sites (USBR and CCID) are being installed in cooperation with the CSRC. Other nearby networks (open triangles) include: Basin and Range (BARGEN), and Southern California Integrated GPS Network (SCIGN).

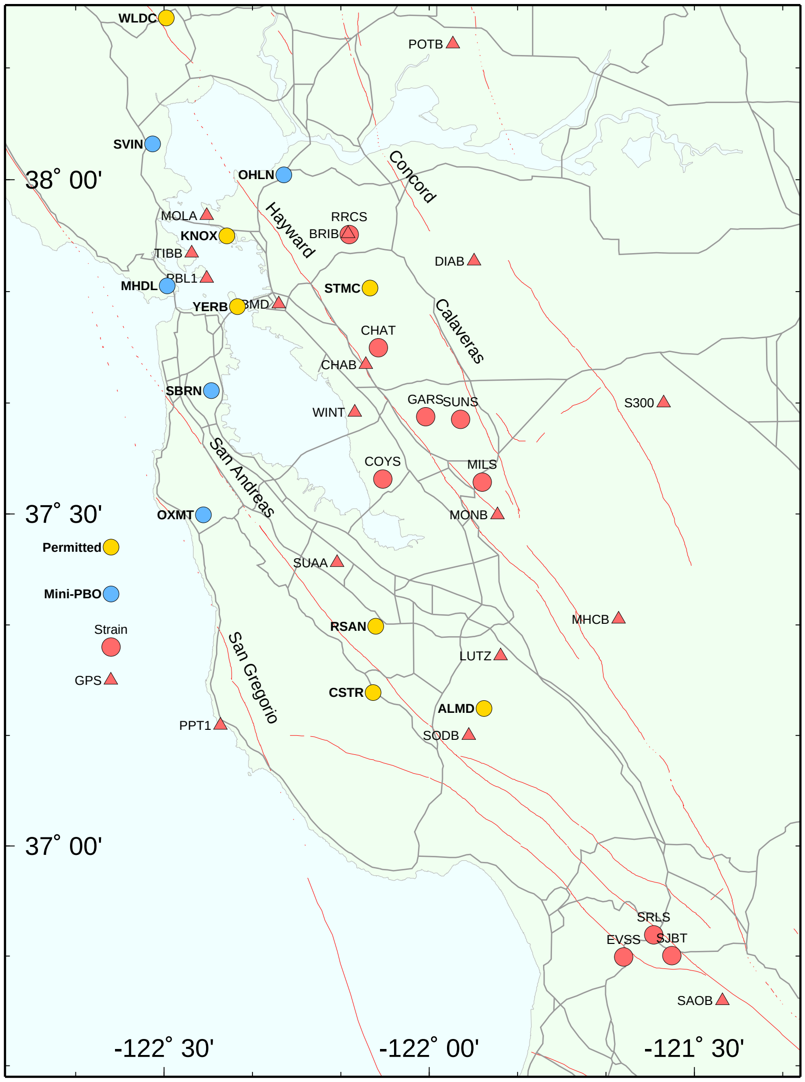

Figure 2: Location of existing (red), in preparation (yellow), and pending (blue) Mini-PBO sites in the San Francisco Bay area. Shown also (red) are currently operating strainmeter (circles) and BARD (triangles) stations. Blue triangles are other pending BARD stations. Black triangles are L1-system profile sites near the Hayward fault and the UC Berkeley campus.

3.1 Mini-PBO Station Installations

The Mini-PBO program supported the installation of stations along the Hayward and San Andreas faults in the San Francisco Bay area to complement existing instrumentation (Figure 2). From July 2001 to August 2002, five boreholes were drilled and equipped with tensor strainmeters and 3-component L22 (velocity) seismometers. The strainmeters were recently developed by CIW and use 3 sensing volumes placed in an annulus with 120 degree angular separation, which allows the 3-component horizontal strain tensor to be determined. Installation of pore pressure sensors and 2-component tiltmeters was completed at all the stations by the USGS in Spring 2003. GPS instrumentation now included in the BARD network are installed at 4 of the stations: Ohlone (OHLN), San Bruno/Brisbane (SBRN), St Vincents (SVIN), and Ox Mountain (OXMT) near Half Moon Bay.

The BSL developed an experimental GPS mount for the top of the borehole casings to create a stable, compact monument. The antennas, using standard SCIGN adapters and domes for protection, are 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. The current design, which has been adopted by PBO for use at their borehole strainmeter stations, uses a flange that is permanently attached to the top of the casing, which allows access to the borehole for instrument maintenance, and a top plate with the vertical pipe and antenna adapter that is bolted to the flange. Several dowels between the flange and top plate ensure that the top plate can be removed and reattached with better than 0.1 mm repeatability. Preliminary analysis of 100 days of the GPS observations at OHLN shows that the short-term daily repeatabilities in the horizontal components are about 0.5-1 mm. These values are similar to those obtained with more typical monuments, such as concrete piers or braced monuments, but it is too early to assess the long-term stability of the borehole casing monument, which might also be affected by annual thermal expansion effects on the casing.

3.2 Parkfield Network

The second component of this project is to link the BARD network in central and northern California to the SCIGN network in southern California. The distribution of these sites allows measurement of both near-field deformation from fault slip on the San Andreas and regional strain accumulation from far-field stations. During Summer 2001, nine new continuous GPS sites were installed in the Parkfield area spanning about 25 km on either side of the San Andreas fault. One of the receivers was contributed by the USGS and the other eight were contributed by SCIGN, while the braced monuments for all the sites were constructed using Mini-PBO funding. The new array augments the considerable geophysical instrumentation already deployed in the area and contributes to the deep borehole drilling on the San Andreas fault (SAFOD) component of Earthscope. Although data are currently downloaded daily by SCIGN and archived by SOPAC, the NCEDC will assume the responsibility for retrieving the data from these sites over their existing frame relay circuit at Parkfield. We are currently readying a Linux computer to control the data download at Carr Hill. A subset of the GPS sites will eventually be upgraded to real-time streaming and analyzed in instantaneous positioning mode.

3.3 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.

In April 2002, we installed 4 sites in a 10-km profile extending normal to the Hayward fault between the UC Berkeley campus and BARD station BRIB (Figure 3). Due to the topography of the East Bay hills, each site acts as a repeater for other sites. Data from WLDC passes 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 the master radio on the roof of McCone Hall where the BSL is located on campus. 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).

Between April 2002 and January 2003, the L1 system operated reasonably well, although problems with faulty batteries solar power regulators caused some loss of data. The Freewave radio at the repeater site SPSC was replaced with an Intuicom system. The original radio was sent in for routine maintenance and was found to have a frequency crystal that was beyond its normal operating range. In mid-January 2003, the solar panel at GRIZ was stolen, which resulted in damage

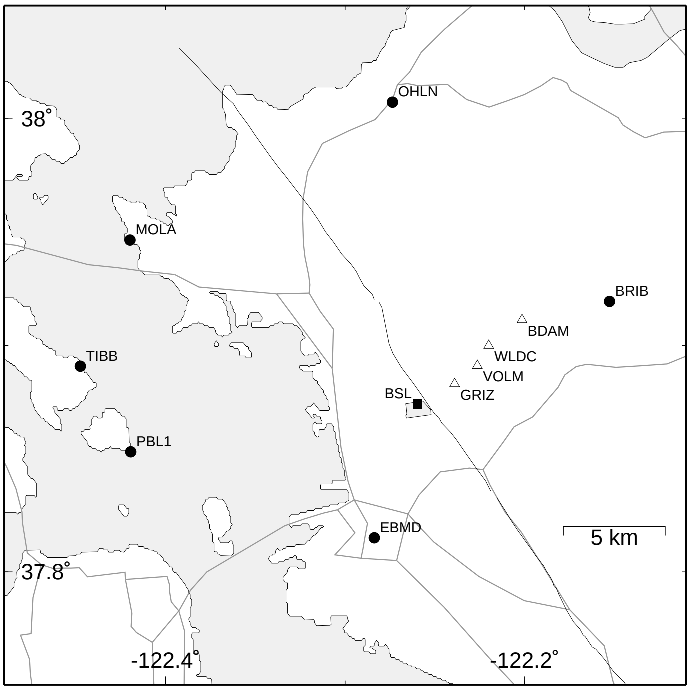

Figure 3: Location of L1-system (open triangles) and BARD (closed circles) stations. BSL, just southwest of the Hayward fault, is the location of the Berkeley Seismological Laboratory, where data from the 4 L1-system receivers northeast of the Hayward are telemetered.

to the cables located outside of the protective metal enclosure. The replacement solar panel was installed in a steel channel frame welded to the vertical steel post that forms the monument base. A 0.5”-thick Plexiglas layer was inserted to protect the surface of the solar panel. Acquisition of all data failed not long after this repair. Initial tests suggested a problem at the repeater site SPSC, but subsequent efforts failed to resolve the problem. In August 2003 we isolated the problem to bad cable connections at the GRIZ sites and re-established operations of the network.

We are processing the data using the GAMIT/GLOBK analysis package, which required modifications to handle L1-only observations. We corrected software provided by UNAVCO to synchronize the phase, pseudorange, and clock offset observables, which allows the data to be cleaned in an automatic fashion. Preliminary results suggest that repeatabilities of 1–2 mm in daily horizontal relative positions and 5 mm in the vertical on the shortest (several km) baselines can be achieved (Figure 4), but these degrade to 3–4 mm on the longer (10 km) baselines. We are investigating ways to simultaneously process the dual-frequency data from nearby BARD stations (e.g., BRIB, OHLN), with the single-frequency L1 data to improve these results. Currently data from second frequency on the BARD stations is not used, which degrades the definition of the local reference frame and repeatability of the baselines.

3.4 Station Upgrades and Maintenance

During the contract period, we upgraded and performed routine maintenance on a number of the GPS stations in the BARD network. Some of the highlights include:

During 2001, 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

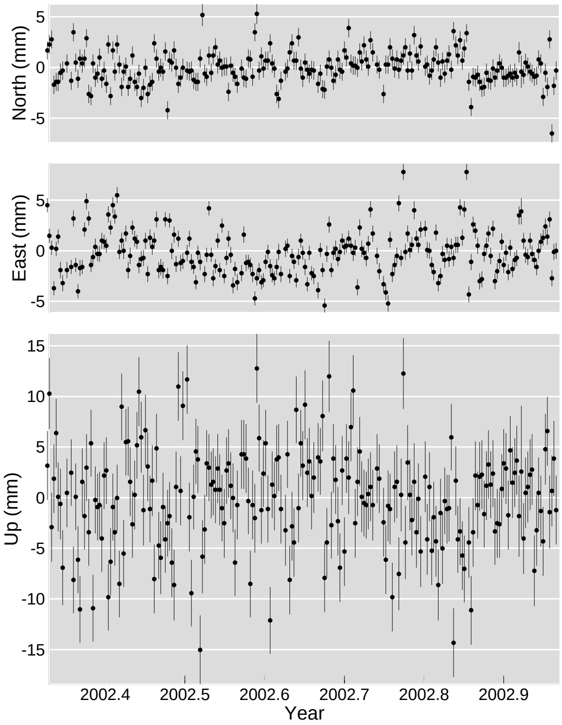

Figure 4: Daily estimates of the north, east, and vertical components of the BRIB to BDAM 3-km baseline. Daily repeatabilities are about 1, 2, and 5 mm, respectively.

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.

In March 2002, “copper-miners” took advantage of of the poor security at the decommissioned Point Molates naval facility to fell the power poles and remove high tension copper power lines that were used by the MOLA station. The property has been put aside for environmental cleanup before the ownership is transferred from the Navy to the City of Richmond. Due to the status of the property, the high costs to reestablish power, and the unsecured nature of the area, the station was removed from continuous GPS service. The monument and enclosure were left intact and the site is being be periodically reoccupied, approximately 2–3 days per month, in a semi-permanent mode.

In May 2002, forced entry in the building housing the GPS equipment at SAOB resulted in theft of GPS receiver and damage to building and telemetry system. We reinforced the plywood building walls with a layer of wire mesh followed by a surface layer of plywood secured with screws and liquid adhesive. Inside the building, the GPS receiver and short-haul modems where replaced and stored within a double locked large metal “Hoffman” box.

In February 2003, telemetry flow of GPS data stopped at MUSB. Access to the site was initially limited by the winter snowpack, and then by the need to coordinate the visit with Southern California Edison engineers. During a visit to the site in August 2003 continuity tests revealed that the hardline antenna cable had apparently failed. This 70 m cable may have been damaged by repeated water freezing in the PVC conduit that houses it. The antenna cable was replaced and drainage of the conduit was improved in October 2003.

We assisted Hat Creek Radio Observatory (HCRO), located in northeastern California near Mt Lassen (Figure 1), in designing and installing a continuous GPS station. The HCRO is installing the new Allen Telescope Array (ATA), which will consist of approximately 350 6.1-meter radio telescope dishes arrayed at the site, for both astrophysical and Search for Extraterrestrial Intelligence (SETI) studies. In June 2003, we assisted with the construction of a 12”-diameter concrete pier that is anchored to a reasonably competent section of lava flow outcrop that surrounds HCRO.

3.5 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 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.

Since 1997, the NCEDC has collaborated with UNAVCO and other members of the GPS community on the development of 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 archive locations. The NCEDC is participating at several levels in the GSAC project: as a primary provider of data collected from core BARD stations and USGS MP surveys, 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 helped to define database schema and file formats for the GSAC project, and for several years have produced complete and incremental monumentation and data holdings files describing the data sets that are produced by the BARD project or archived at the NCEDC so that other members of the GSAC community can provide up-to-date information about our holdings. Currently, the NCEDC is the primary provider for over 74,000 data files from over 1400 continuous and survey-mode monuments. The data holdings records for these data have been incorporated into a preliminary version of the retailer system currently undergoing testing, which should become publicly available in late 2002.

4. 2001-2004 DEFORMATION MONITORING

4.1 Data Analysis and Quality

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

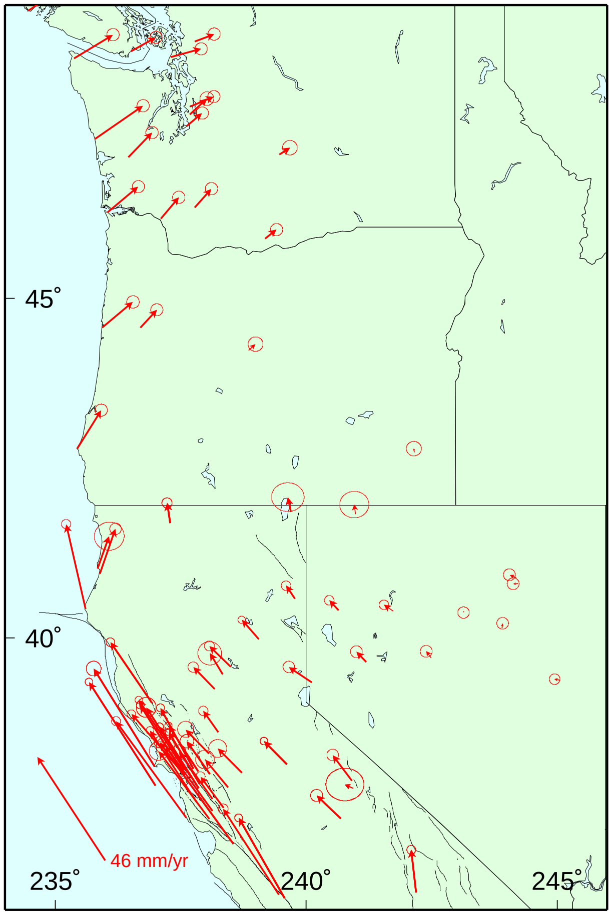

Figure 5: Velocities relative to stable North America for the BARD stations and other stations operated in nearby networks. Data from November 1993 to July 2000 was processed by the BSL using GAMIT software. Ellipses show 95% confidence regions, assuming white noise and 1 mm $yr^{-1/2}$ random-walk noise, with the predicted Pacific–North America relative plate motion in central California shown for scale.

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 5, 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

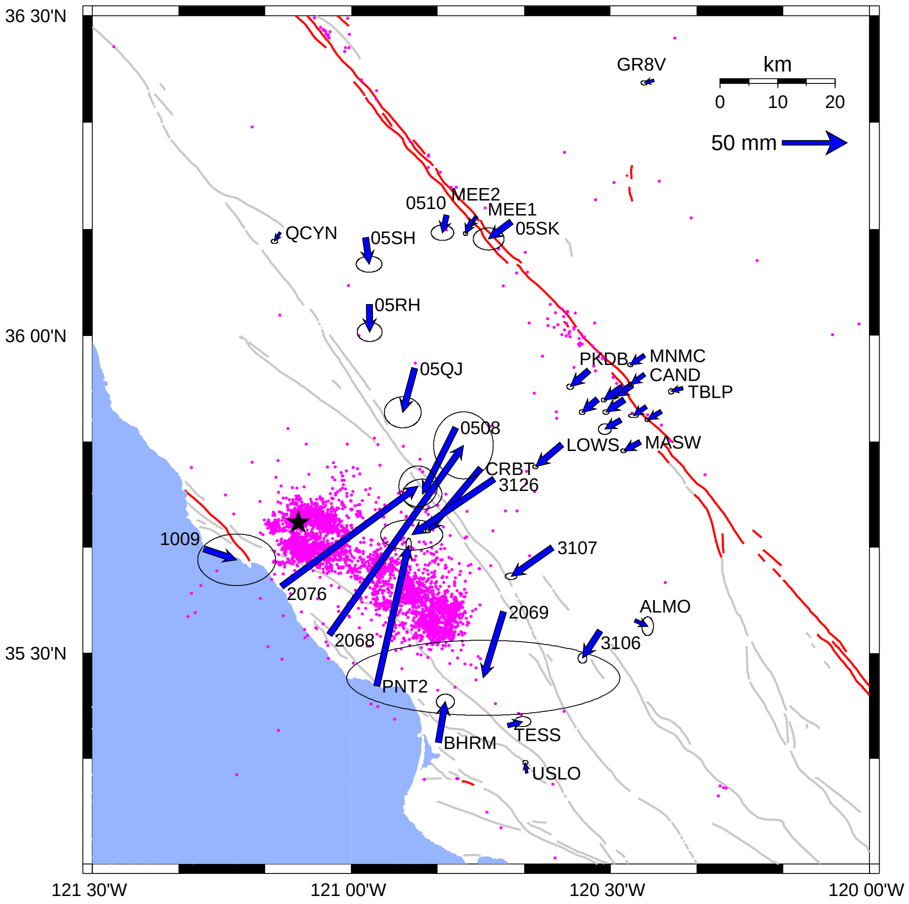

Figure 6: GPS sites and and preliminary coseismic displacements from the M_w 6.5 San Simeon earthquake with 95% confidence ellipses. The black star shows the epicenter, the pink dots show relocated aftershocks . Surface fault traces are shown as red and grey lines.

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).

4.2 Coseismic Slip Distribution of the 22 December 2003 San Simeon Earthquake

The M_w 6.5 San Simeon earthquake struck the central California coast on December 22 2003, 50 km west of the San Andreas fault. The San Simeon earthquake is one of several destructive blind-thrust earthquakes to have hit the central California Coast Range during the past two decades. This thrust earthquake accommodates a compressional component of the Pacific-North America plate motion. The mainshock nucleated at a depth of 8 km and was followed by a vigorous aftershock sequence primarily southeast of the hypocenter, consistent with the mainshock directivity. The strong directivity of the rupture resulted in a concentration of damage to the southeast, with high levels of damage in Paso Robles. The San Simeon earthquake produced static displacements at 14 continuously operating GPS stations located within 70 km of the epicentral region. These stations are located northeast of the rupture near the Parkfield segment. The cluster of BARD stations near Parkfield were displaced southwest by about 15 mm. One station 35 km northwest of the rupture moved about 60 mm southwest. In addition, one continuous station south of the rupture and 4 continuous stations north of it (operated by the University of Wisconsin since January 2003) recorded small (less than 12 mm) displacements.

Together with Frederique Rolandone and Douglas Dreger at the BSL, we are preparing a paper combining displacement and velocity waveform data from 9, three-component BDSN/CISN strong motion stations with 36 observations of GPS deformation (Figure 6), including survey-mode observations, to simultaneously invert for the distribution of fault slip. Preliminary results of the inversions indicate that the slip is shallow in depth (1.3 to 8 km) and extends approximately 25 km to the southeast of the epicenter. This unusual aspect ratio for reverse fault rupture is consistent with the results of separate GPS and seismic waveform inversions, and leads to a moderate horizontal directivity effect as compared to a more typical updip directivity as was observed in the 1994 Northridge, California earthquake. The spatially concentrated peak slip was found to be 5.5 m, which is unusually high for a Mw6.5 event, and it does depend on the applied smoothing. Over much of the fault, however the slip is between 1 to 3 m. The extension of slip to the southeast of the epicenter indicates that this event ruptured unilaterally to the southeast producing a pronounced directivity effect in that direction. Elevated ground motions in the Paso Robles region, about 35 km to the southeast, resulted in two deaths from collapsed unreinforced masonry (URM) buildings, and numerous damaged red-tagged URM buildings in Paso Robles.

4.3 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 ~2.4±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. The inferred ~37.2±1.0 mm yr^{-1} slip rate across the San Andreas system is consistent with geologic estimates. The ~14.2±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.

4.4 Real-Time Processing

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). In northern California, rapid earthquake notification is a collaborative effort of the USGS Menlo Park and the UC Berkeley Seismological Laboratory (BSL). Notification is performed in stages as data and results become available. The USGS use data from their short-period vertical seismic network to provide preliminary locations within seconds, and final locations and preliminary coda magnitudes within 2-4 minutes. This information is used by BSL to drive the Rapid Earthquake Data Integration (REDI) processing system (*Gee et al.*, 1996; 2002). If the coda magnitude is 3.0 or greater, waveforms from the BSL broadband seismic network are analyzed to estimate local magnitude, and peak ground motions and moment tensors are estimated at higher magnitudes.

Because the point source approximation made in the moment tensor codes may break down at regional distances from $M > 7.5$ events, we have extended the seismic methodologies to estimate finite fault parameters. However, seismic data alone have difficulty determining the geometry of finite faults. Geodetic networks provide a complementary data source that can be used to independently estimate rupture parameters of $M > 6$ events, particularly for shallow events located near stations in the network. Geodetic measurements of coseismic displacements provide important constraints on earthquake faulting, including the location and extent of the rupture plane, unambiguous resolution of the nodal plane, and the distribution of slip on the fault unbiased by rupture velocity assumptions (e.g., *Murray et al.,* 1996).

We currently process data available within 1 hour of measurement from the 20 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. Prior to the earthquake, the station locations can be constrained at the cm-level to well-known locations, which improves resolution of carrier phase integer ambiguities. The scatter of these hourly solutions is similar to the 24-hour solutions: 2-4 mm in the horizontal and 10 mm in the vertical. After an earthquake the station locations cannot be assumed as precisely, so the uncertainties become much larger. Using 30 minutes of data, our simulations suggest that displacements 10 cm-level 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 both the rapidity and precision of the postseismic position estimates using a Kalman filter techniques 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.

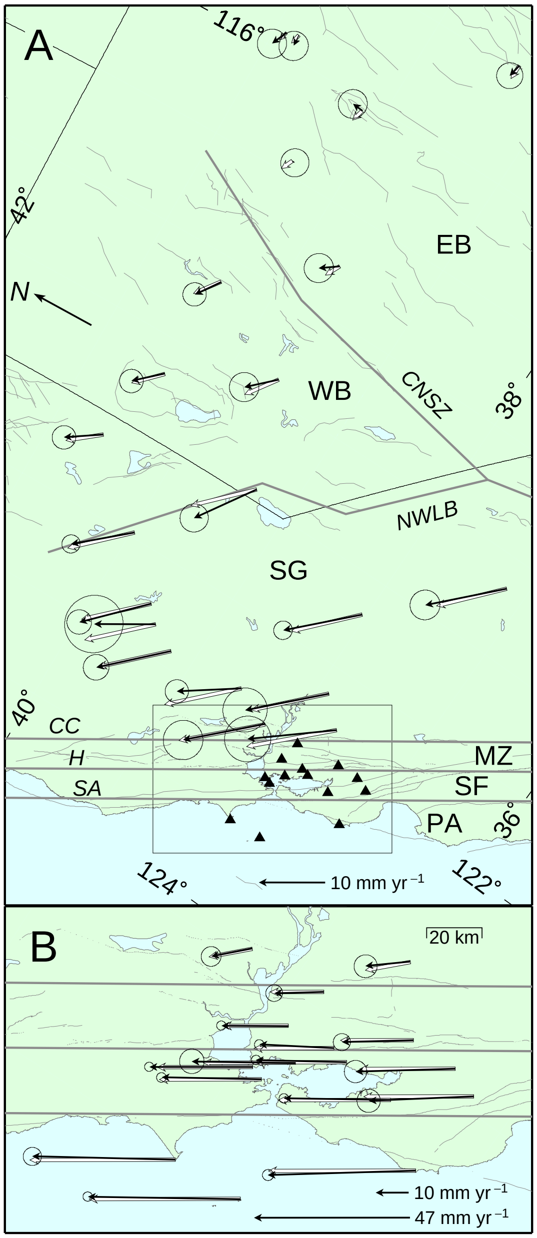

Figure 7: Predicted (open) and observed (solid) site velocities, with 95% confidence regions, relative to NA. Projection, oblique Mercator about $\hat{\Omega}^{NU}_{PA}$. A) northern California and Nevada (see box in Fig. 9), with velocities of sites in box (triangles) omitted for clarity. B) San Francisco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

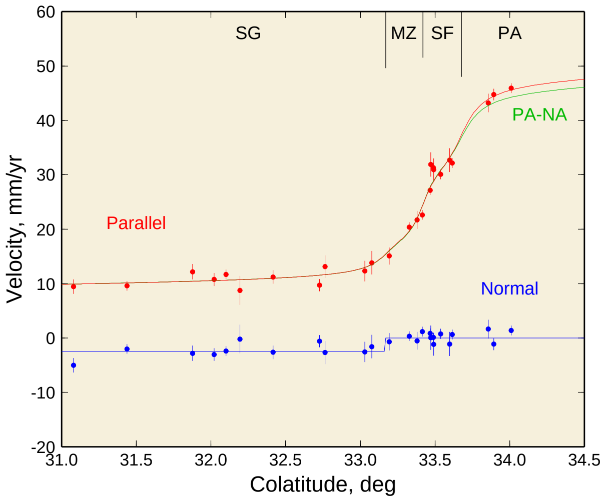

Figure 8: Velocities relative to NA, with one standard error bars, parallel and normal to small circles about $\hat{\Omega}^{NU}_{PA}$ versus angular distance from $\hat{\Omega}^{NU}_{PA}$. Red line, preferred model. Green line, model with Pacific angular rate constrained to NUVEL-1A, which has significantly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

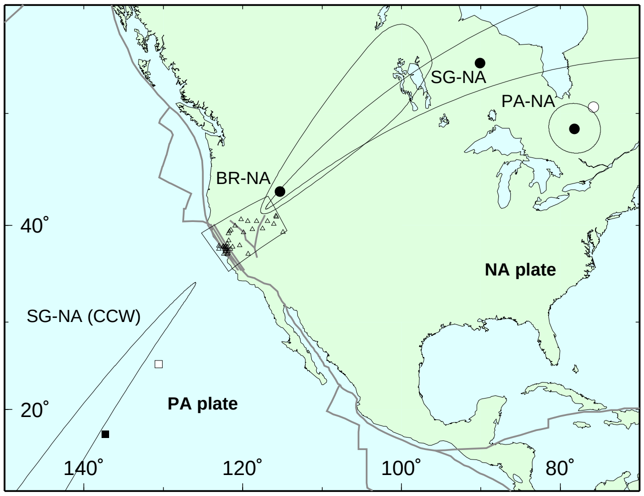

Figure 9: Estimated $\hat{\Omega}$ (solid circles) with 95% confidence bootstrap regions. PA-NA is $\hat{\Omega}^{NU}_{PA}$. Open circle, alternative $\hat{\Omega}_{PA}$ (*DeMets and Dixon*, 1999). BR-NA applies to both WB and EB. The SG-NA uncertainty, which spans nearly 180deg, has both clockwise (top)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

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8. DATA AVAILABILITY

Data and results from the BARD project are available at the Northern California Earthquake Data Center (*//www.quake.geo.berkeley.edu*) For additional information on the BARD network, contact Mark Murray at 510-642-2601 or mhmurray@seismo.berkeley.edu.

FINAL TECHNICAL REPORT

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

KEY WORDS: GPS-Continuous, Surface Deformation, Fault Stress Interactions

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 this 3-year project period, we performed enhancements to the existing network and operation procedures, installed several new stations, included new broadband deformation stations equipped with GPS and borehole strainmeters and seismometers and measured deformation due to the 2003 San Simeon earthquake.