FINAL TECHNICAL REPORT

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THE BARD CONTINUOUS GPS NETWORK: MONITORING EARTHQUAKE HAZARDS IN NORTHERN CALIFORNIA AND THE SAN FRANCISCO BAY AREA: A collaboration between UC Berkeley and the USGS Menlo Park

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1. PROJECT SUMMARY

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 Berkeley Seismological Laboratory (BSL), the United States Geological Survey (USGS), and several other academic, commercial, and governmental institutions. 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, we have completed the conversion of nearly all BARD stations to 1 Hz data sampling frequency. This was helped by upgrades at 11 sites to Trimble NetRS receivers. Collecting high-rate data is an important step toward integrating GPS data into post-event response and early warning systems. High-rate GPS analysis and modeling methods were tested by *Houlié et al*. (2007), using the 2004 Parkfield earthquake. *Houlié et al.* found that the inferred slip matched a model from strong motion and geodetic data well.

Two new sites were installed on the rooftops of UC Berkeley and UC San Francisco buildings. These will provide important densification in urban area where finding open space for a GPS monument can be difficult. Both high-rate raw and RINEX and decimated low-rate RINEX data files for all BARD stations are available through the NCEDC (http://www.ncedc.org). Among the scientific investigations undertaken using BARD data was a study by *Jolivet et al.* (2009) to use BARD and other geodetic data to model the effect of having materials with contrasting rigidity across a fault and constrain the amount of contrast and slip rates on the San Andreas fault near Point Reyes.

2. CURRENT NETWORK

2.1 Focus of Operations

The Bay Area Regional Deformation (BARD) network of continuously operating Global Positioning System (CGPS) stations monitors crustal deformation in the San Francisco Bay Area (SF Bay Area) and northern California (*Murray et al.*, 1998, *Murray and Segall*, 2001, *Houlie and Romanowicz*, 2006). It is a cooperative effort of the Berkeley Seismological Laboratory (BSL), the USGS, and several other academic, commercial, and governmental institutions. The BARD network was started in 1991 the following goals: 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 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 geodetic infrastructure in northern California in support of related efforts within the surveying and other interested communities. At its peak in 2007, the BARD network included data from over 60 permanent stations in northern California, of which about half was operated by the BSL. Many of the BSL-operated BARD stations are collocated with broadband seismic stations of the Berkeley Digital Seismic Network (BDSN), allowing the acquisition of GPS data in real time through shared frame relay telemetry (*Romanowicz et al*., 1994)

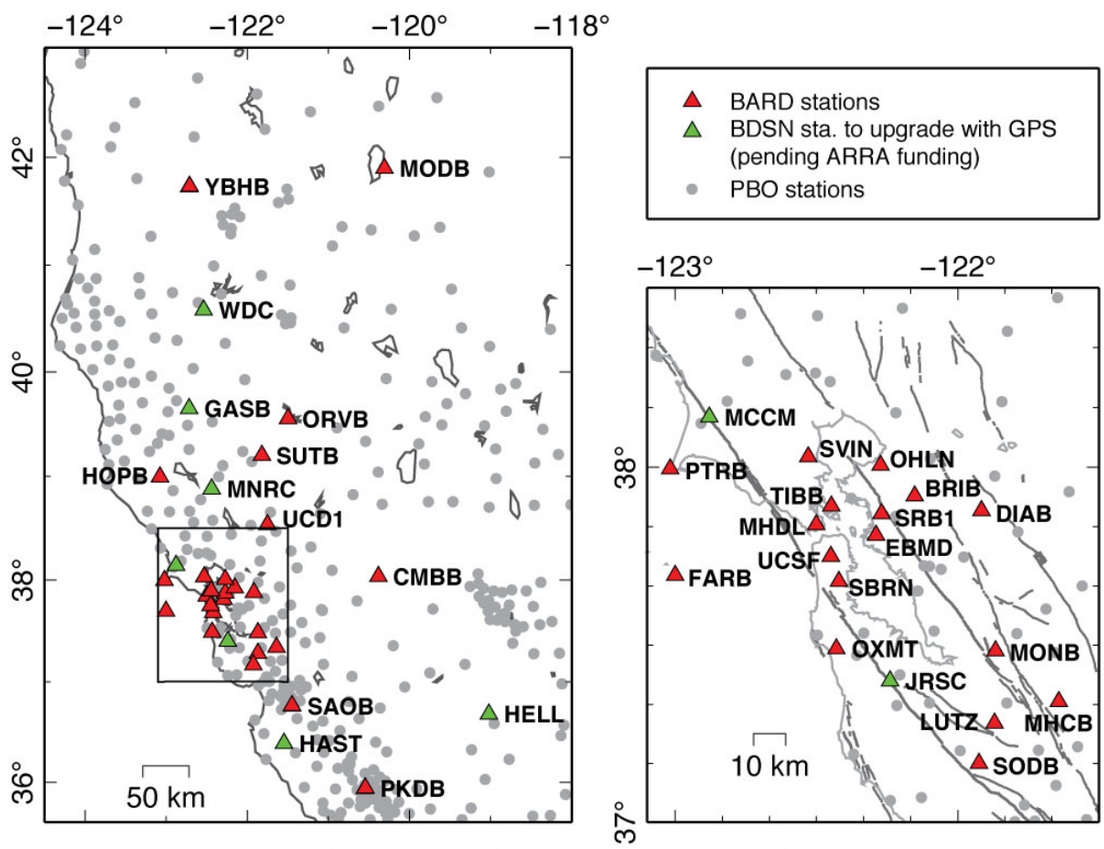

Figure 1: Overview map of Northern California showing locations of BSL-operated BARD CGPS stations(red triangles) and the locations of seven stations to be installed with ARRA funding (green triangles).

With the completion of major construction on the PBO portion of EarthScope, the number of GPS stations in Northern California has expanded to over 250 and a number of BARD

stations have been folded into the PBO network. PBO and BARD stations together provide valuable information on the spatial complexity of deformation in the SFBA and Northern California, while the BARD network has the infrastructure and flexibility to additionally provide information on its temporal complexity over a wide range of time scales and in real time. Many of the GPS stations in the BARD network are co-located with BDSN seismic instrumentation or are close to active faults where reliable access to real-time information could be critical following an earthquake. For these reasons, we have maintained operation of the majority of BSL's BARD stations.

Raw and RINEX data files from the BSL stations and the other stations run by BARD collaborators are archived at the Northern California Earthquake Data Center (NCEDC). 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 the end of the UTC day, to all BARD participants and other members of the GPS community through the internet, both by anonymous FTP and through the World Wide Web (http://ncedc.org/bard).

2.2 BARD Station Configuration

BARD station monumentations broadly fall into three types. Most are anchored into bedrock, either directly or via a steel-reinforced concrete cylinder. The five "mini-PBO" stations that are still operated by the BSL are collocated with USGS strainmeters and the GPS antennas are bolted onto the borehole casing. Four sites (UCD1, SRB1, UCSF, SBRB) are located on the roofs of buildings. Most of the last type have been installed in the past three years and their stability over long periods of time is yet to be evaluated.

For the five mini-PBO stations co-located with borehole strainmeters, 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 is mechanically isolated from the upper few meters of the ground. The casing below this level is 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.

Most BARD stations use a radome-equipped, low-multipath choke-ring antenna, designed to provide security and protection from weather and other natural phenomena, and to minimize differential radio propagation delays. Four stations are equipped with Trimble Zephyr Geodetic antenna, though we hope to upgrade these when possible. 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. During the funding period, 11 stations were upgraded to Trimble NetRS receivers, others stations have Ashtech Z12 or Micro-Z receivers. 24 of the 26 are now programmed to record data once every second (1 Hz) and all transmit data continuously to the BSL. 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 rate creates telemetry bandwidth limitations. One advantage of the NetRS receiver is that it has a more compact data stream, allowing robust high rate transmission, and allowing us to increase the sampling rate at sites where the bandwidth is limited.

All BARD stations are continuously telemetered to the BSL. Many use frame relay technology, either alone or in combination with radio telemetry. Other methods include a direct radio link to Berkeley (TIBB, EBMD) and VSAT satellite telemetry (MODB). 11 GPS

stations are collocated with broadband seismometers and Quanterra data loggers. With the support of IRIS, the BSL 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. The telemetry structure also includes 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.

	Site	Latitude (deg)	Longitude (deg)	Receiver	Antenna	Telemetry	Samp. Rate	Install Date
1	BRIB	37.91940	-122.15255	NETRS	CR	T1	1Hz	8/6/1993
2	CMBB	38.03418	-120.38604	A-UZ12	CR	FR	1Hz	12/9/1993
3	DIAB	37.87858	-121.91563	NETRS	CR	FR	1Hz	5/21/1998
4	FARB	37.69721	-123.00076	NETRS	CR	R-FR/R	1Hz	1/27/1994
5	HOPB	38.99518	-123.07472	A-Z12	CR	FR	1Hz	8/26/1995
6	LUTZ	37.28685	-121.86522	A-Z12	CR	FR	30s	5/18/1996
7	MHCB	37.34153	-121.64258	A-Z12	CR	FR	1Hz	6/14/1996
8	MHDL	37.84232	-122.49433	NETRS	ZG	FR	1Hz	9/12/2006
9	MODB	41.90233	-120.30283	NETRS	CR	VSAT	1Hz	11/11/1999
10	MONB	37.49892	-121.87131	A-Z12	CR	FR	1Hz	7/31/1998
11	OHLN	38.00742	-122.27371	A-UZ12	CR	FR	1Hz	11/21/2001
12	ORVB	39.55463	-121.50029	NETRS	CR	FR	1Hz	11/21/1996
13	OXMT	37.49936	-122.42432	A-Z12	CR	FR	1Hz	2/12/2004
14	PKDB	35.94524	-120.54155	NETRS	CR	FR	1Hz	9/20/1996
15	PTRB	37.99640	-123.01490	A-Z12	CR	R-FR	1Hz	8/14/1998
16	SAOB	36.76530	-121.44718	NETRS	CR	FR	1Hz	8/21/1997
17	SBRN	37.68622	-122.41044	A-Z12	CR	FR	1Hz	3/5/2003
18	SODB	37.16640	-121.92552	A-Z12	CR	R-FR	15s	5/18/1996
19	SRB1	37.87436	-122.26696	T-SSE	ZG	Fiber	1Hz	11/14/2006
20	SUTB	39.20584	-121.82060	NETRS	CR	R-FR	1Hz	3/27/1997
21	SVIN	38.03318	-122.52632	A-UZ12	CR	FR	1Hz	11/20/2003
22	TIBB	37.89087	-122.44760	A-UZ12	CR	R	1Hz	6/16/1994
23	UCSF	37.76297	-122.45815	NETRS	ZG	FR	1Hz	12/22/2007
24	YBHB	41.73166	-122.71073	NETRS	CR	FR	1Hz	10/24/1996
25	EBMD	37.81500	-122.28379	T-5700	CR	R	1Hz	2/8/1999
26	UCD1	38.53621	-121.75107	NETRS	CR	WEB	1Hz	5/19/1996
27	SBRB	37.68645	-122.41090	0	ZG	FR	1Hz	8/25/2008
28	(BDM1)	37.95000	-121.87000	NETRS	CR		1Hz	
29	(PTP1)	38.00000	-122.36000	NETRS	CR		1Hz	

Table 1: List of the BARD maintained by the BSL. Four models of receiver are operating now: Trimble 4000 SSE (T-SSE), Trimble NETRS, (NETRS), Ashtech Z12 (A-Z12) and Ashtech Micro Z (A-UZ12). Most stations have Ashtech Choke-ring antennas (CR), 4 sites have Trimble Zephyr Geodetic antennas (ZG). The telemetry types are listed in column 6. FR = Frame Relay, R = Radio, VSAT= Microwave. Some sites are transmitting data over several legs with different telemetry. Station names in parenthesis indicate that permitting is complete, but installation has yet to take place.

2.3 Data Management Practices

All data collected from BARD/BSL stations are publicly available at the NCEDC (http://www.ncedc.org/bard/), both as raw data and converted into the RINEX format. High-rate (1 Hz) raw data are additionally downsampled to 15-sec sampling and archived in RINEX format to facilitate low-rate processing. With the completion of major construction for PBO, over 250 CGPS stations are now present in northern California. Where previously the NCEDC archived all northern California CGPS data, continuing to do so would now require considerably more space and be redundant with PBO's own archiving through UNAVCO. We have therefore modified our data archiving policy to include only those Northern California stations that are not otherwise archived as part of an established geodetic network and those that are telemetered directly to the BSL. No past data will be removed from the archive and stations from PBO and other networks are still included in routine processing and velocity fields.

As part of the activities funded by the USGS through the BARD network, the NCEDC is the principal archive of the 10,000+ survey-mode occupations collected by the USGS since 1992. The initial dataset archived was the survey-mode GPS data collected by the USGS Menlo Park for northern California and other locations. Quality control efforts were implemented by the NCEDC to ensure that the raw data, scanned site log sheets, and RINEX data are archived for each survey. All of the USGS-Menlo Park GPS data have been transferred to the NCEDC and data since 1992 have been archived and are available for distribution.

The NCEDC also participates in the UNAVCO-sponsored GPS Seamless Archive Center (GSAC) project, which provides access to survey-mode and continuous GPS data distributed over many archives. The NCEDC helped to define database schema and file formats for the GSAC project, and produce monumentation and data holdings records for the data archived at the NCEDC to provide GSAC with up-to-date information about our holdings.

Data from five of our sites (HOPB, MHCB, CMBB, OHLN, YBHB) are sent to the National Geodetic Survey (NGS) in the framework of the CORS (Continuously Operating Reference Stations) project (http://www.ngs.noaa.gov/CORS/). The data from these five sites are also distributed to the public through the CORS ftp site.

3. 2007-2010 MAIN ACCOMPLISHMENTS

3.1 Station Upgrades

A major accomplishment during this funding period has been the conversion of nearly all BARD stations to 1 Hz data sampling frequency. 24 of the 26 BARD CGPS stations now collect high-rate data. The data are collected continuously, as opposed to on a triggered basis, and transmitted to the BSL. This is important for inclusion of these data in real time earthquake notification and eventually early warning. It is also particularly important for observing phenomena not associated with seismic events, but that nonetheless have important information at the 1 Hz level, such as slow earthquakes. The effort to expand the high-rate data collection was helped by upgrades at 11 stations to Trimble NetRS receivers, for a total of 12 with this hardware. The NetRS receivers are remotely configurable through a web interface, making them convenient to administer. They also feature a compact data stream, which has allowed us to collect high-rate data from locations with limited bandwidth telemetry. High-rate raw data are available through the NCEDC, as are decimated 15s RINEX data files. 1 Hz RINEX files are available for all sites after May, 2010; high-rate RINEX files for earlier dates will be backfilled in the coming months.

In September 2009, the BSL established the telemetry of high-rate data from 13 PBO stations in the Parkfield region. These stations were installed as part of the collaborative

NSF/MRI program between the BSL, UC San Diego and Carnegie Institution of Washington nicknamed “mini-PBO”. 1Hz GPS data from these 13 stations flow through the T1 line from Parkfield to Menlo Park and then on to Berkeley, from here it is sent back to UCSD via a NTRIP server. We plan to participate in a regional and eventually statewide real time geodetic network that will eventually be integrated with the CISN for earthquake notification purposes. The acquisition of real time data from the Parkfield sub-network is the first step towards linking southern and northern California real time GPS networks.

3.2 Site Installations

We have grown our network by installing two stations (SRB1 and UCSF) during the funding period and have completed permitting on two more (BDM1, PTP1). Furthermore, vandalism at station SBRN precipitated the installation of a secondary station, SBRB, nearby.

SRB1 and UCSF are both roof-mounted antennas in urban areas of the SF Bay Area; locations where finding open space for GPS stations can be difficult. These specific locations were chosen because the BSL already had radio antennas for telemetry relay installed at these sites, providing ease of access, both physical and to telemetry and power. Station SRB1 is located on the Seismic Replacement Building on the UC Berkeley campus. The monument is attached to a three-legged antenna tower, attached to the building’s utility penthouse. Station UCSF is bracketed directly to the reinforced concrete shear wall at the roof-line of the 15-story Medical Science Building on the UC San Francisco campus. SRB1 was installed with a spare Trimble SSE receiver, while UCSF has a Trimble NetRS; both include a Trimble Zephyr Geodetic antenna.

Intermittent vandalism at station SBRN culminated in a 6-month data outage from March to August of 2008. To prevent a reoccurrence, a second station (SBRB) was installed in August of 2008 in a more secure location. The replacement monument is drilled and pinned into the roof of a single story concrete structure that houses both the GPS and seismic instruments. Both stations are currently running until the stability of site SBRB can be verified, at which point SBRN will be removed and SBRB will become the primary station at this location.

The two permitted sites: BDM1 will be co-located with BDSN station BDM, and PTP1 with an NHFN borehole seismic station at no additional telemetry cost. Both stations will be located in the east Bay Area, and will densify our network in an area where there are outstanding questions on the long-term slip rate of local faults.

3.3 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 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 for BARD stations and other nearby continuous GPS sites using the GAMIT/GLOBK software developed at MIT and SIO (*King and Bock*, 1999, *Herring*, 2005). GAMIT uses double-difference phase observations to determine baseline distances and orientations between ground-based GPS receivers. Cycle slips are automatically identified and fixed using the AUTCLN routine within GAMIT. Ambiguities are fixed using the widelane combination followed by the narrowlane, with the final position based on the ionospheric free linear combination (LC or L3). Baseline solutions are loosely constrained until they are combined together. GAMIT produces solutions as “H-files”, which include the covariance parameters describing the

geometry of the network for a given day and summarize information about the sites.
We combine daily, ambiguity-fixed, loosely constrained H-files using the Kalman filter approach implemented by GLOBK (*Herring*, 2005). The estimated relative baseline determinations typically have 2-4 mm long-term scatter in the horizontal components and 10-20 mm scatter in the vertical. The BARD dataset has been processed in the ITRF2000 reference frame (*Altamimi et al.*, 2002). No *a priori* constraints have been assumed. The current solutions (*Houlié and Romanowicz*, 2009) are in good agreement with previous work (e.g. *d'Alessio et al.*, 2005).

Site	Lon.	Lat.	V_E (mm/yr)	V_N (mm/yr)	σ (mm/yr)	σ (mm/yr)	Start Date
BAY1	197.29	55.19	-6.3	-25.5	0.00	0.00	1996.08
BAY2	197.29	55.19	-5.6	-25.2	0.04	0.03	1996.08
BRIB	237.85	37.92	-24.8	5.6	0.01	0.01	1993.58
CMBB	239.61	38.03	-22.9	-2.8	0.01	0.01	1993.92
CNDR	238.72	37.90	-24.4	-5.5	0.02	0.02	1999.27
DIAB	238.08	37.88	-23.7	-2.2	0.01	0.01	1998.33
FARB	237.00	37.70	-39.8	23.3	0.01	0.01	1994.00
GOLD	243.11	35.43	-18.2	-5.4	0.00	0.00	1989.95
HCRO	238.53	40.82	-18.0	-8.7	0.14	0.15	2003.50
HOPB	236.93	39.00	-31.1	6.8	0.01	0.01	1995.58
JPLM	241.83	34.21	-36.6	11.8	0.00	0.00	1989.44
LUTZ	238.14	37.29	-31.7	9.5	0.01	0.01	1996.33
MHCB	238.36	37.34	-24.2	-2.4	0.01	0.01	1996.33
MODB	239.70	41.90	-16.9	-9.1	0.02	0.02	1999.83
MOLA	237.58	37.95	-30.5	9.7	0.01	0.01	1993.75-2002.22
MONB	238.13	37.49	-27.5	2.7	0.01	0.01	1998.50
MUSB	240.69	37.17	-22.3	-4.0	0.01	0.01	1997.83
OHLN	237.73	38.01	-26.4	4.4	0.02	0.02	2001.83
ORVB	238.50	39.56	-22.7	-6.6	0.01	0.01	1996.83
OXMT	237.58	37.50	-36.9	18.0	0.06	0.06	2004.12
P181	237.62	37.92	-29.0	9.6	0.38	0.40	2005.09
P198	237.39	38.26	-29.2	7.9	0.09	0.10	2004.77
P200	237.55	38.24	-24.3	4.7	0.20	0.22	2005.73
P222	237.92	37.54	-31.5	10.0	0.11	0.12	2005.26
P224	237.78	37.86	-26.9	5.5	0.10	0.11	2005.25
P225	237.94	37.71	-25.2	2.7	0.09	0.10	2005.14
P227	238.21	37.53	-28.6	-0.4	0.58	0.63	2006.20
P228	238.31	37.60	-23.5	1.0	0.43	0.47	2005.93
P229	238.02	37.75	-26.8	1.6	0.11	0.12	2005.29
P230	238.21	37.82	-22.5	-3.1	0.11	0.12	2005.15
P261	237.78	38.15	-21.0	-0.5	0.09	0.10	2004.50
P262	237.90	38.03	-24.2	1.2	0.11	0.12	2005.32
PKDB	239.46	35.95	-43.0	18.7	0.01	0.01	1996.67
PPT1	237.61	37.19	-40.7	22.1	0.00	0.00	1996.14
PTRB	236.98	38.00	-37.7	22.2	0.01	0.01	1998.58
S300	238.44	37.67	-22.9	-4.4	0.02	0.02	1998.48
SAOB	238.55	36.77	-41.4	22.0	0.01	0.01	1997.58
SBRN	237.59	37.69	-32.0	14.2	0.03	0.03	2003.18
SODA	26.39	67.42	18.7	34.1	0.14	0.16	1994.70
SODB	238.07	37.17	-33.1	11.7	0.01	0.01	1996.33
SUAA	237.83	37.43	-33.7	12.4	0.01	0.01	1994.30

SUTB	238.18	39.21	-23.1	-6.7	0.01	0.01	1997.33
SVIN	237.47	38.03	-30.5	10.3	0.04	0.04	2003.89
THAL	238.07	37.35	-32.0	9.5	0.20	0.22	2003.00
TIBB	237.55	37.89	-30.8	11.2	0.01	0.01	1994.42
UCD1	238.25	38.54	-23.1	-6.0	0.01	0.01	1996.38
VNDP	239.38	34.56	-42.2	20.9	0.00	0.00	1992.48
YBHB	237.29	41.73	-15.8	-6.7	0.01	0.01	1996.75

Table 2: Long-term velocities for BARD stations and other regional continuous GPS stations, including PBO stations and several global IGS sites. All velocities and estimated errors (σ) are indicated in mm per year.

3.4 Rigidity Contrast Across the San Andreas Fault

BARD stations are also an integral component of the Bay Area Velocity Unification (BAVU). BAVU is the primary source of central-California data used in ongoing compilations of California-wide velocity fields. The sparsely distributed, but continuously operating CGPS BARD and PBO networks provide a precise geodetic backbone with high temporal resolution into which we integrate campaign-mode measurements collected by our and other groups. Repeated campaign GPS measurements by our group and the USGS provide appropriate densification (Figure 2).

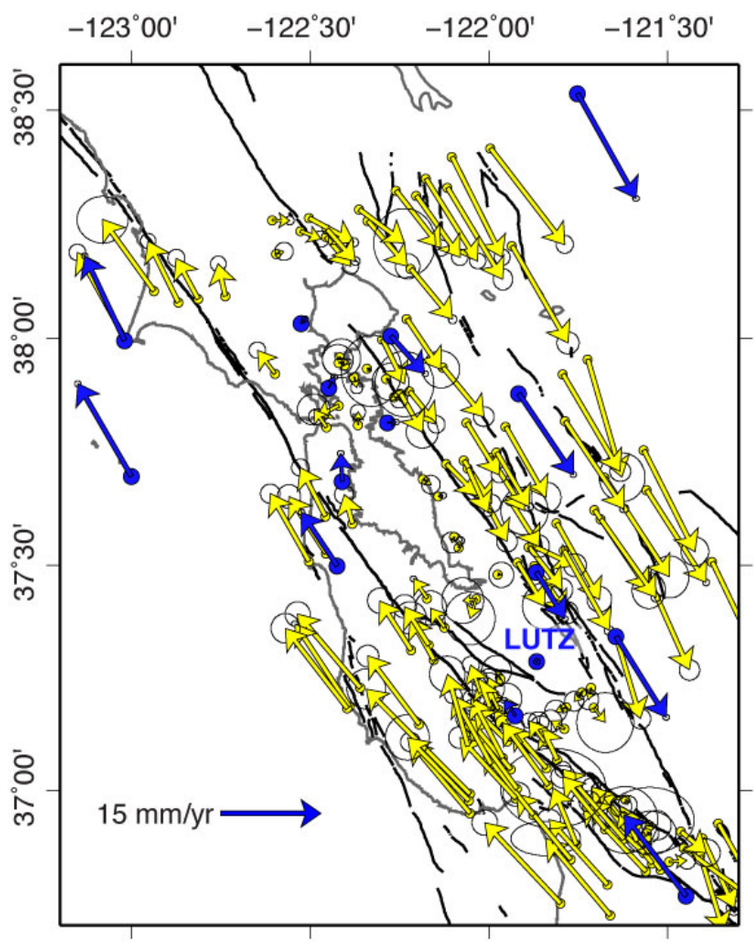

Figure 2: Site velocities from BAVU2 within the SFBA, including BARD (in blue), PBO and campaign stations. Shown relative to station LUTZ.

The BAVU2 velocity solution was used by *Jolivet et al*. (2009) to constrain the rigidity contrast across the San Andreas fault near Point Reyes. *Jolivet et al*. describe how analyses of trilateration data by *Prescott and Yu* (1986) and *Lisowski et al*. (1991) found asymmetric patterns of strain accumulation on either side of the fault, which *Le Pichon et al.* (2005) explain with higher rigidity material on the southwest side of the fault. BARD site velocities together with campaign and PBO velocities (BAVU2) and also nine years of InSAR data were used to constrain a 2D elastic model of strain accumulation with contrasting material properties and also a finite-element model including a compliant zone around the fault (Figure 3). The compliant zone properties trade-off strongly with fault locking depth and as a consequence the existence of a compliant zone cannot be constrained by the geodetic data alone. Nonetheless, *Jolivet et al*. (2009) show that the data are best fit with materials on the west side of the fault 1.4 times more rigid than the eastern side. Including the rigidity constrast changes the inferred slip rate on the San Andreas and Roger's Creek faults from 23 ± 1 mm/yr to 18 ± 1 mm/yr and 8 ± 1 mm/yr to 11 ± 1 mm/yr, respectively. The adjustments to the slip rates well outside the formal uncertainties of the model results and could produce important adjustments to seismic hazard estimates on these faults.

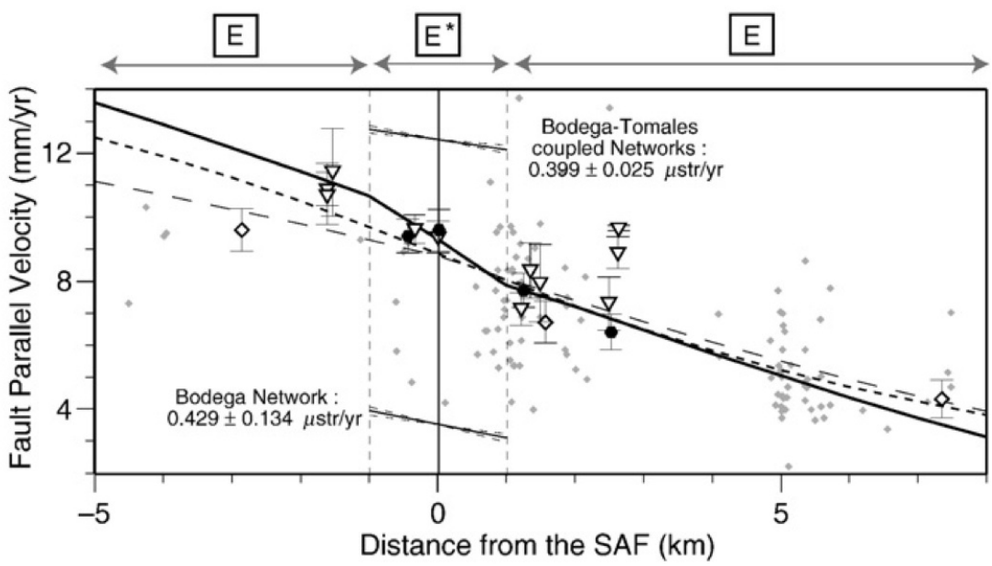

Figure 3: From *Jolivet et al.* (2009): Best dislocation model for the Bodega Bay deformation pattern. The black circles are the fault-parallel GPS velocities in Bodega Bay with their associated error bars with respect to the station LUTZ (121.865° W, 37.287° N), the white diamonds correspond to the Point Reyes profile velocities. The white inverted triangles are fault-parallel EDM-derived velocities from the Bodega Bay network. The grey dots are the PS-SAR data from *Funning et al.* (2007) projected onto the profile assuming that the range change is due to fault-parallel motion only. The continuous black line is our preferred Compliant Fault Zone Model, with a ratio E*/E = 0.4. The short-dashed line is the best homogeneous model, with a 7 km locking depth and a 18 mm/yr slip rate. The long-dashed line is the asymmetric model of the Point Reyes profile. The short black lines represent the velocity gradient through the fault zone in Bodega Bay with the associated errors from *Chen and Freymueller* (2002). The grey arrows show the extent of the compliant fault zone.

3.5 Analysis of High-rate GPS data from the Parkfield Earthquake

A long-term goal of the BARD network is to integrate real-time, high-rate data with the Northern California Seismic System (NCSS). The NCSS is a co-operative effort between the BSL and the USGS to develop a robust system to automatically detect earthquakes and rapidly provide information to first-responders and the public. In particular, the products include moment tensor calculations and ShakeMap. The 2004 Parkfield earthquake provided

an opportunity to test analysis and modeling methods for 1 Hz GPS data for a well-studied and well-characterized event.

High-rate (1 Hz) data is available from 13 sites in the Parkfield region: 12 PBO stations and BARD's station PKDB. *Houlié et al.* (2007) processed data from these sites for the 2004 Parkfield earthquake to obtain "displacement waveforms" (Figure 4). The GPS data match data from co-located broadband seismometers well, but slight variations suggest we may need to account for the differences between surface and sub-surface instrument, or take into account the response of the GPS monument to shaking before inferring ground motion.

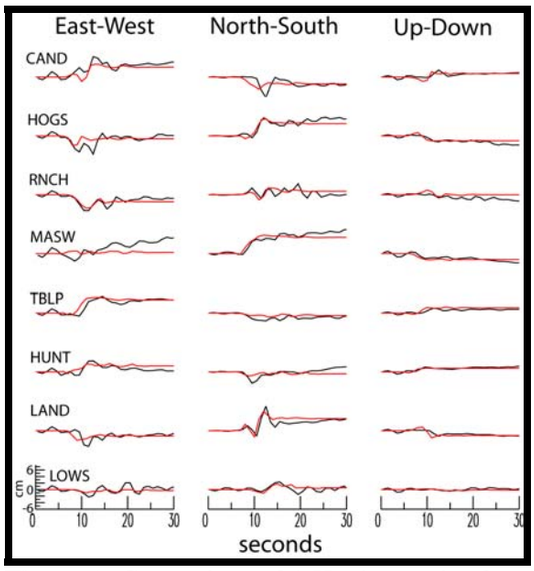

Figure 4: Comparison of 1 Hz time series from GPS stations in the Parkfield area (red lines) to waveforms from co-located broadband seismometers (black lines).

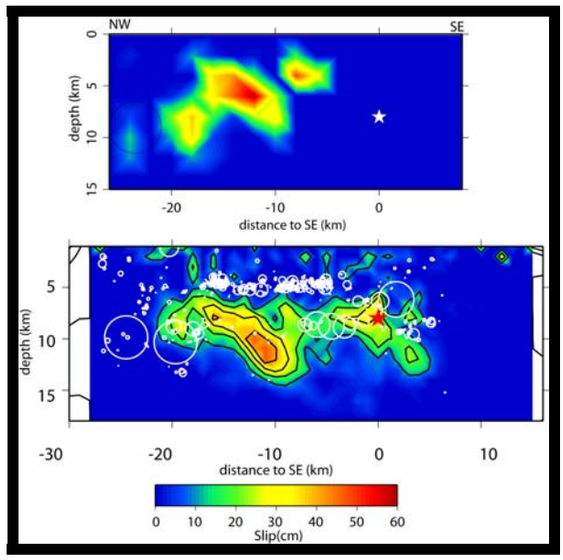

Figure 5: Upper plot, results of inverting coseimic offsets derived from high-rate GPS data for slip in the 2004 Parkfield earthquake. Lower plot, inversion result of *Kim and Dreger* (2007) for slip using strong motion, GPS and InSAR data.

The slip distribution inferred by *Houlié et al.* (2007) for the Parkfield earthquake from coseismic offsets derived from the high-rate time series, is similar to the distribution obtained by *Kim and Dreger* (2007) using strong-motion and geodetic data. The largest mis-match occurs near the Parkfield hypocenter, where a lack of GPS stations directly above this fault section likely leads to poor model resolution, even with the best data. The overall agreement implies that the GPS data are capable of separating coseismic and postseismic displacements at least as well as seismic data.

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FINAL TECHNICAL REPORT

AWARD NUMBER: 07HQAG0031

THE BARD CONTINUOUS GPS NETWORK: MONITORING EARTHQUAKE HAZARDS IN NORTHERN CALIFORNIA AND THE SAN FRANCISCO BAY AREA: A collaboration between UC Berkeley and the USGS 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 this 3-year project period, we performed enhancements to the existing network and operation procedures, installed new stations and upgraded the majority of our network to high-rate data sampling. The data were used in several studies of crustal deformation in the San Francisco Bay Area, including *Jolivet et al.* (2009), who looked into how the earth's properties vary across the San Andreas fault and an investigation by *Houlié et al.* (2007) into applying high-rate GPS data to studying the 2004 Parkfield earthquake.