FINAL TECHNICAL REPORT

SPACE GEODETIC CONSTRAINTS ON FAULT SLIP RATES AND THE DISTRIBUTION OF ASEISMIC SLIP ON BAY AREA FAULTS

National Earthquake Hazard Reduction Program

U.S. Geological Survey

NEHRP Program Element: I, Products for Earthquake Loss Reduction

Award Number: 05-HQGR-0102

Principal investigator:

Roland Bürgmann

University of California, Berkeley
Department of Earth and Planetary Science
307 McCone Hall
Berkeley, CA 94720-4767
Telephone: (510) 643-9545;
Fax:(510) 643-9980;
e-mail: burgmann@seismo.berkeley.edu

SPACE GEODETIC CONSTRAINTS ON FAULT SLIP RATES AND THE DISTRIBUTION OF ASEISMIC SLIP ON BAY AREA FAULTS

Award Number: 05-HQGR-0102

Roland Bürgmann

University of California, Berkeley
Department of Earth and Planetary Science
307 McCone Hall
Berkeley, CA 94720-4767
Telephone: (510) 643-9545;
Fax:(510) 643-9980;
E-mail: burgmann@seismo.berkeley.edu

Technical abstract:

Our investigations aim to constrain secular fault slip rates and the distribution of aseismic slip. Measurements of horizontal site velocities using the Global Positioning System (GPS) and range change rates determined with satellite radar interferometry (InSAR) allow us to resolve tectonic surface motions in the San Francisco Bay Area at great precision. The space geodetic measurements provide information on the nature of elastic strain accumulation about seismogenic faults, their locking depth and slip rates, and any variations of those parameters in space and time. We utilize the surface deformation measurements and elastic dislocation mdeols to determine the distribution of locked and creeping sections along the Calaveras-Hayward-Rodgers Creek fault zone. Our inversions and the distribution of repeating microearthquakes show that a shallow aseismically creeping fault surface directly connects the central Calaveras and southern Hayward fault at depth. The Rodgers Creek fault is also recognized to creep at 4-6 mm/yr in the upper ~5km of the crust near Santa Rosa. Increasingly detailed models of the fault slip process illuminate the locked source areas of past and future large earthquakes along these faults.

Non-technical abstract:

Measurements of horizontal site velocities using the Global Positioning System (GPS) and range change rates determined with satellite radar interferometry (InSAR) allow us to resolve tectonic surface motions in the San Francisco Bay Area at great precision. We utilize these measurements to determine the distribution of locked and creeping sections along the Calaveras-Hayward-Rodgers Creek fault zone. We find that a shallow aseismically creeping fault surface connects the central Calaveras and southern Hayward fault at depth. Near Santa Rosa, the Rodgers Creek fault is also recognized to creep at 4-6 mm/yr in the upper ~5km of the crust. Increasingly detailed models of the fault slip process illuminate the locked source areas of past and future large earthquakes along these faults.

SPACE GEODETIC CONSTRAINTS ON FAULT SLIP RATES AND THE DISTRIBUTION OF ASEISMIC SLIP ON BAY AREA FAULTS

1. INTRODUCTION

1.1 Project components

Our investigations aim to constrain secular fault slip rates and the distribution of aseismic slip. Geodetic measurements provide information on the nature of elastic strain accumulation about seismogenic faults, their locking depth and slip rates, and any variations of those parameters in space and time. This research relies on the analysis and modeling of space geodetic data and interpretation of those results in the context of their mechanical behavior and earthquake potential. GPS and InSAR are complementary techniques for making precise measurements of displacements of the Earth's surface. These can be related to sources of deformation at depth (e.g. faults) by mechanical models. We formally invert the geodetic data for model fault parameters such as depth of locking and slip rate.

2. OBSERVATIONS

2.1 GPS data

Imaging strain accumulation about faults with sufficient precision and spatio-temporal resolution is a difficult task, plagued especially by limits in the accuracy and spatial density of the surface measurements. A mix of campaign mode (SGPS) yearly GPS measurements and data from a core network of continuously operating GPS stations (CGPS) of the BARD and PBO networks contribute to a precise (at mm/yr level) representation of the surface velocity field.Over 10 years of GPS data have now been collected in the San Francisco Bay Area, providing high precision measurements of horizontal surface velocities across the whole plate boundary zone. In this project, we develop and use velocities from the BAVU (Bay Area Velocity Unification) compilation of continuous GPS data from the BARD network and campaign data collected by UC Berkeley and the US Geological Survey since 1994. This project incorporates acquisition, processing, analysis and integration of a comprehensive GPS data set for central California, building on the BAVU velocity field (Figure 1). The sparsely distributed, but continuously operating CGPS BARD and PBO networks provide a precise 3D geodetic framework with high temporal resolution. Repeated campaign GPS measurements in the Bay Area by our group and data obtained by the USGS provide appropriate densification of precise regional surface velocities to determine long-term strain accumulation rates.

Our GPS analysis relies on the GAMIT/GLOBK processing and analysis system developed at the Massachusetts Institute of Technology (Herring, 2005; King and Bock, 2005). We include five global stations from the International GPS Service (IGS) network and four to six nearby continuous stations (PPT1, BAY1, JPLM, HARV, GOLD, VNDP) in each of our local processing runs. We combine daily ambiguity-fixed, loosely constrained solutions using the Kalman filter approach implemented by GLOBK. We include data processed locally as well as solutions for the full IGS, PBO and BARD networks processed by SOPAC at the Scripps Institution of Oceanography (http://sopac.ucsd.edu/) and the PBO analysis centers. To reduce errors from strong tropospheric gradients in the SGPS data, we will benefit from troposphere delay maps produced at the BSL every 4 hours, based on analysis of the real-time BARD network. Using the Kalman filter, we combine all daily solutions to generate an average solution for each month, giving each observation equal weight. We then estimate the average linear velocity of each station in the network from these monthly files. We fix the final positions and velocities of the IGS stations into the ITRF2000 global reference frame (Altamimi et al., 2002). We then rotate the solution into a stable North America reference frame by solving for the best fitting relative pole of rotation. One benefit of this data analysis approach lies in the increased ease in which the processing can be integrated with data products from the regional BARD and PBO GPS sites and the global IGS network, which significantly improves the reference stability and also the precision of our velocities. We continue to streamline and automate the BAVU processing scripts which cover all the steps from data downloading to production and posting of time series and velocity tables and maps on the BAVU web page http://seismo.berkeley.edu/~burgmann/RESEARCH/BAVU/index.html.

We scale the measurement errors following the method used by the Southern California Earthquake Center's Crustal Motion Map team (SCEC CMM 3.0; Robert W. King, pers. comm., 2003). We add white noise to the formal uncertainties of all stations with a magnitude of 2 mm/yr for the horizontal components and 5 mm/yr for the vertical component. To account for “benchmark wobble" we add Markov process noise to the solutions with a magnitude of 1 mm $yr^{-1/2}$. For the velocity field shown in Figure 1A we establish a local reference frame centered around station LUTZ (a BARD continuous site on the Bay Block, roughly near the network centroid). We subtract LUTZ's velocity from all stations and propagate the correlations in uncertainty to calculate the error ellipses (95 % confidence intervals) shown in Figure 1.

The BAVU compilation includes survey-mode GPS data from over 200 GPS stations throughout the greater San Francisco Bay Area from Sacramento to San Luis Obispo collected from 1991 to 2007 by U. C. Berkeley, the U.S. Geological Survey, the California Department of Transportation, Stanford University, U. C. Davis and the Geophysical Institute in Fairbanks, AK. These are combined with continuous GPS data from the BARD and PBO networks. BAVU provides a consistent velocity field for monitoring fault slip and strain accumulation throughout the greater San Francisco Bay region. Up-to-date data products are available at http://seismo.berkeley.edu/~burgmann/RESEARCH/BAVU/index.html .

The BAVU velocity field (Figure 1a shows most recent update) forms a core component of the recently developed California-wide velocity map, developed by D. Agnew, R. King, Z-K Shen, and M. Murray. This velocity model, recently provided to the California Earthquake Authority (CEA) includes data from the SCEC Crustal Motion Map (CMM 3) (1986-2001), the SCIGN CGPS network (1996-2003), BAVU (1993-2003), and northern California and Pacific Northwest SGPS networks (1993-2004).

We continually update and improve the BAVU time series and velocity solutions for use by the research community, including future version of the crustal motion map. In addition to the role of GPS measurements in allowing for the precise determination of interseismic deformation rates, the existence of a solid geodetic network will also be important as part of the scientific response to the next large earthquake in the Bay Area. Studies of coseismic and postseismic deformation will greatly benefit from a well-developed network of continuously operating CGPS and survey-mode SGPS sites. Such data will be used to develop kinematic models of earthquake ruptures to aid in better understanding of source characteristics. The slowly increasing number of CGPS sites in the region (especially thanks to PBO) and availability of InSAR have allowed us to reduce and focus the SGPS surveys, but do not make them expendable.

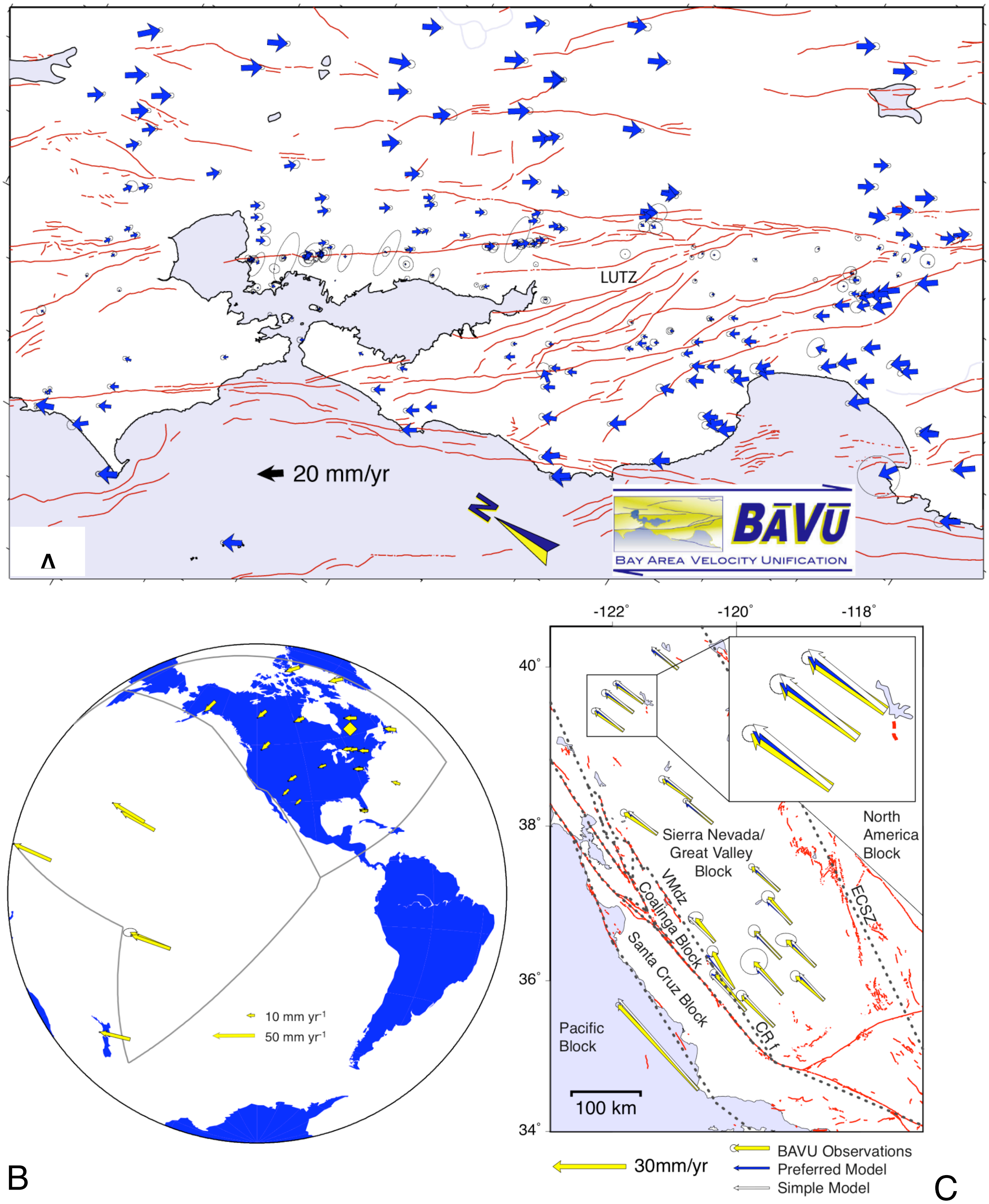

Figure 1. (A) Updated BAVU velocity field referenced to a local site (LUTZ) on the central Bay Block spanning 1994-2006. The map is in an oblique Mercator projection about the pole of Pacific-plate-to-SNGV block rotation. (B) Global and (C) central California scale BAVU velocity field also showing fit of a block model developed by *d'Alessio et al.* (2005).

2.2 PS-InSAR data

InSAR provides a one-dimensional measurement of change in distance along the look direction of the radar spacecraft. Given the orientation of the track direction of polar, sun-synchronous satellites, this measurement is affected by deformation in both horizontal components and, particularly, in the vertical. We have had significant success in the recent past in applying conventional InSAR to both the horizontal and the vertical surface deformation in the San Francisco Bay Area, revealing cm-level uplift and subsidence patterns related to the seasonal drawdown and recharge of the Santa Clara valley aquifer (Schmidt and Bürgmann, 2003); rapid motions of deep-seated landslides (Hilley et al., 2004); a possible sub-mm/yr contribution of an east-side-up, dip-slip component to the range change offset across the creeping northern Hayward fault (Hilley et al., 2004; Schmidt et al., 2005); and allowing the estimation of the distribution of fault creep on the Hayward fault, and therefore the extent of the part of that fault that remains locked (Schmidt et al., 2005). Recent work during the project period using the PS-InSAR data in conjunction with our GPS measurements has focused on resolving vertical motion in the Bay region (Bürgmann et al., 2006) and on resolving aseismic slip on the Hayward-Rodgers Creek faults (Funning et al., 2007).

We incorporate 49 European Remote Sensing satellite (ERS-1 and 2) acquisitions collected from 1992 to 2000 of our Bay Area target scene (track 70, frame 2853) (Figure 2). Points whose displacements vary in a highly non-linear fashion, such as a large area of rapid seasonal uplift and subsidence in the Santa Clara Valley (Schmidt and Bürgmann, 2003) are excluded from the final data set. The PS-InSAR data provide range-change rates at 115,487 points including targets in vegetated or mountainous areas that are unsuitable for standard InSAR. In addition, this dataset contains a time-series of displacement, which allows us to identify regions in which there is a significant time-varying, often seasonal component to the deformation field.

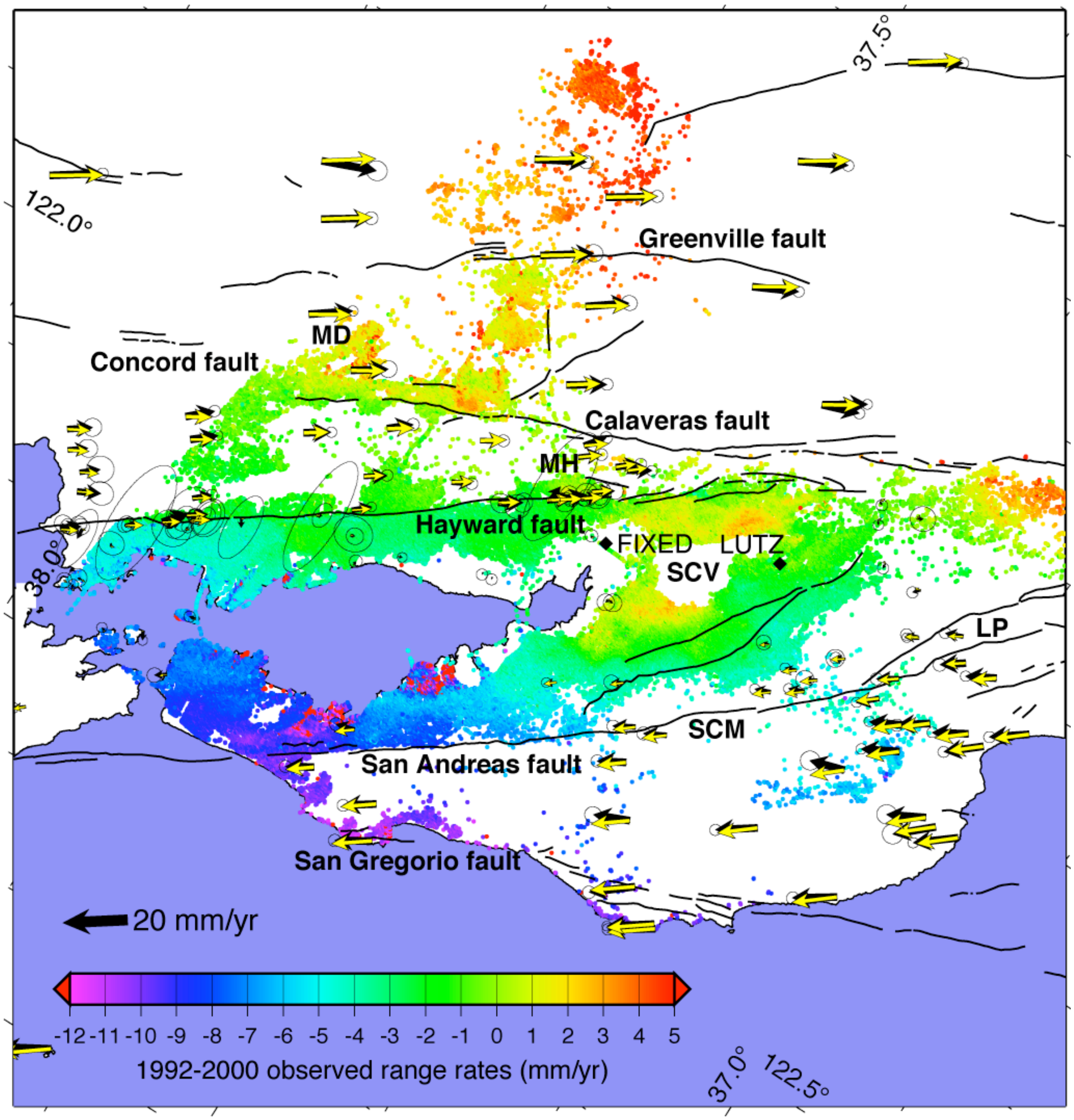

Figure 2: Surface deformation rate data used in this study. Each colored dot on land indicates the location of a permanent scatterer on the ground; red colors indicate points where the distance, or range, between the satellite and the ground increases with successive satellite passes (i.e. movement away from the satellite), blue colors indicate movement towards the satellite. Black arrows are horizontal velocities from the BAVU compilation of GPS data (d'Alessio et al., 2005) with 2σ error ellipses, relative to the fixed station LUTZ; yellow arrows are modeled horizontal velocities assuming that the deformation in the region can be described as the motions of a series of subparallel rigid blocks. (SCM – Santa Cruz Mountains, LP – Loma Prieta, MD – Mount Diablo, MH – Mission Hills). From Bürgmann et al., 2006.

When interpreted in terms of vertical motions, the residual range-change rate field of bedrock target points includes three larger areas of subsidence and three regions of uplift at 0.5-1.5 mm/yr rate (Figure 3). One area of apparent subsidence is located east of the Greenville fault and we have no obvious explanation for this feature. The second area of subsidence at rates of up to ~2 mm/yr appears localized about the epicentral region of the 1989, M_w = 6.9 Loma Prieta earthquake and coincides with the region of horizontal contraction evident in the residual GPS velocities. A third zone of slow (~0.5 mm/yr) subsidence along the northern San Francisco peninsula may be related to an extensional bend in the SAF and/or interaction with the offshore San Gregorio fault zone. Uplifted regions along the East Bay Hills, the Santa Cruz Mountains to the northeast of the SAF near Black Mountain and in the southern foothills of Mt. Diablo appear to reflect tectonic uplift along restraining discontinuities of Bay Area strike-slip faults (Bürgmann et al., 2006).

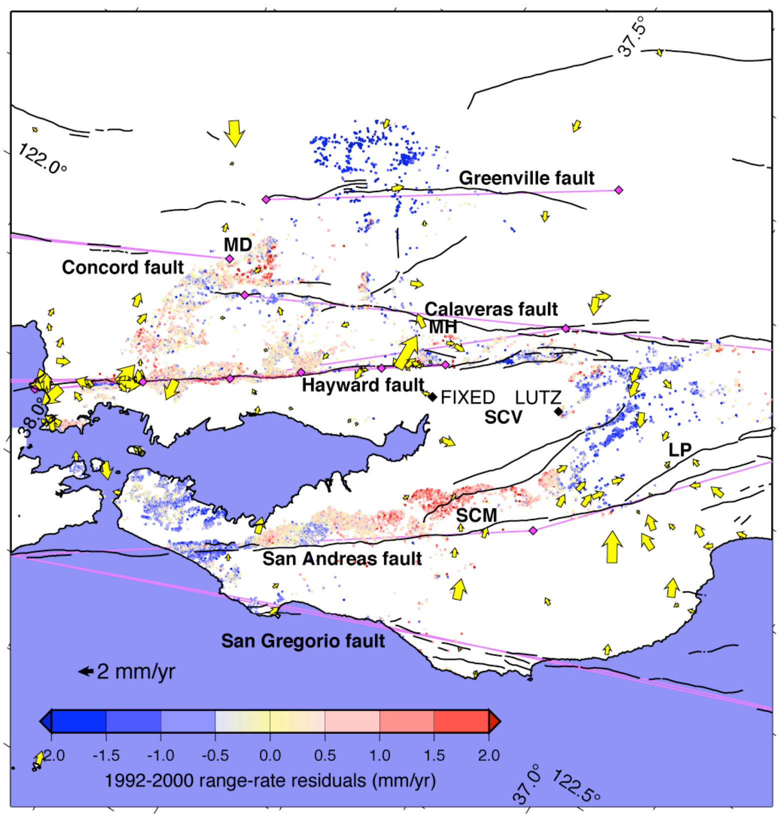

Figure 3: Residual surface velocities after correction for the horizontal strain field due to strike-slip faulting. Only PS points located on bedrock are shown, to ensure that non-tectonic signals related to the behavior of Quaternary substrate are removed. Areas of red here indicate uplifiting zones conversely, blue areas indicate subsidence. Yellow arrows are the residuals of the fit of the dislocation model to the GPS data. Note the uplift signals associated with Mount Diablo (MD), the Santa Cruz Mountains (SCM) and the Mission Hills (MH), and the subsidence seen at Loma Prieta (LP). Purple lines are the surface projections of the shallow and/or deep dislocations used to model the horizontal strain field.

3. RESULTS

3.1 Hayward-Calaveras Connection

Seismic studies of the Hayward-Calaveras step-over have suggested that the southern Hayward fault may dip into and merge with the central Calaveras Fault south of Fremont. This suggests that the Calaveras fault directly transfers slip to the Hayward Fault via a continuous structure. We find characteristic repeating earthquakes between 4 and 7 km depth in this region that indicate that active creep indeed occurs between the two faults.

Improved GPS-derived surface velocities and consideration of new PS-InSAR range-change rates in the Hayward-Calaveras stepover area help verify and constrain this proposed geometry, and allows a reevaluation of slip on these faults. A dislocation model combining seismically derived geometry and GPS velocities confirms that active fault creep occurs on the continuation of the dipping surface of the Hayward Fault effectively linking the Hayward and Calaveras Faults along a contiguous structure (Figures 4 and 5). The revised model provides an estimate of the distribution of creep on the three-dimensional fault surface through the stepover region, thus aiding in evaluating the seismic potential and rupture scenarios in the area.

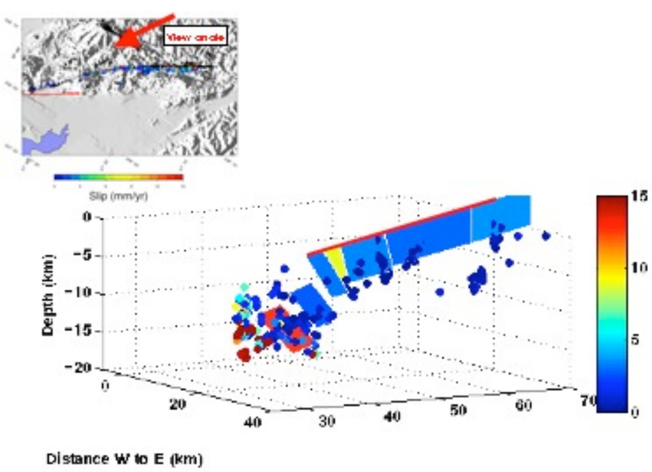

Figure 4: View from southeast looking at Hayward fault segments as used in the dislocation model. Hayward surface trace shown in red. The northernmost segments in the figure are vertical; progressing to the south, the patches dip as shallowly as 45°. Dots indicate location and slip rates of repeating microearthquakes, scaled with the same color scale (mm/yr). We find creep rates of 4mm/yr in the vertical segments (near Berkeley) with rates generally increasing towards the Calaveras. From Evans et al. (2007).

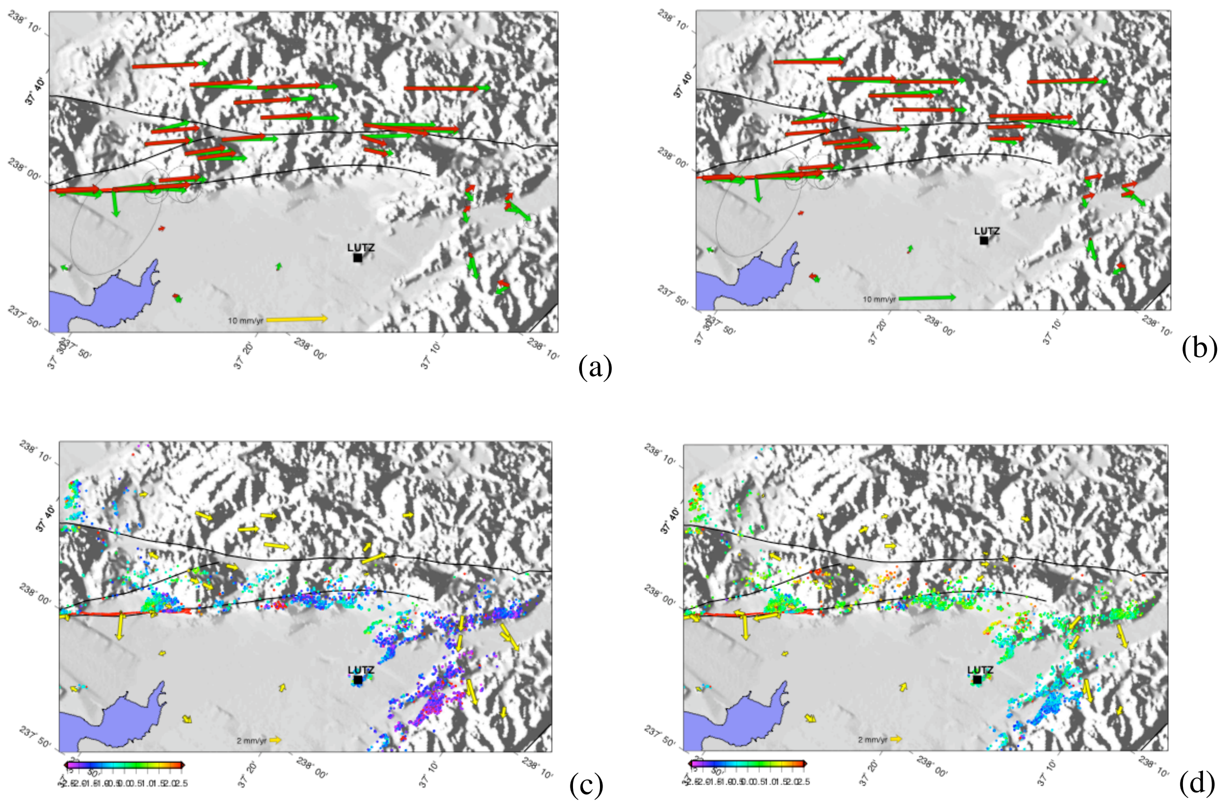

Figure 5: Comparison of modeled velocities and PS range change from (a), (c) a vertical Hayward fault model (from *Bürgmann et al.*, 2006) and (b), (d) our dipping contiguous Hayward model (Figure 1). In general, the dipping Hayward causes residuals to greatly improve in the stepover region. From Evans et al. (2007).

3.2 Rodgers Creek Fault Creep

The GPS and PS-InSAR dataset covering the North Bay Area allows us to extend our analysis to the faults in that area. Deformation in the northern San Francisco Bay Area is dominated by a series of sub-parallel strike-slip faults. Existing GPS observations provide some constraint on the slip rates of these faults, however these have only limited resolution for resolving shallow fault behavior, such as brittle creep. The Rodgers Creek fault zone is seismically active and considered to pose a risk to nearby cities – in particular Santa Rosa, the largest city in the North Bay, which straddles the mapped fault trace (Figure 6). Two damaging (ML 5.6 and 5.7) earthquakes occurred on the fault just north of Santa Rosa in 1969, and paleoseismic investigations on its southern portion imply that the fault slipped 2 m in the last major (M ≈ 7) event on that segment, probably in the 18th Century. Both the Hayward and Maacama faults, which link to the Rodgers Creek fault at its northwestern and southeastern extents, respectively, are known to undergo brittle creep in their upper portions, and it has been an open question whether the Rodgers Creek fault is behaving similarly.

Together with BAVU GPS data, we use a 30-image Permanent Scatterer InSAR dataset spanning the time interval 1992–2001 to dramatically increase the density of surface deformation observations. We find a discontinuity in observed surface velocities across the northernmost portion of the Rodgers Creek fault, around Santa Rosa and further north, which is consistent with shallow creep at rates of up to 6 mm/yr (Figure 6, Funning et al., 2007). We find that the Rodgers Creek fault is creeping at the surface with a rate of 4 ± 1 mm/yr at Santa Rosa. Creep may extend further to the NW, however there are insufficient points to make a determination of the rate. The creeping segments are located in areas of local transtension, suggesting that lowered normal stresses may play a role in the distribution of creep.The creeping segments are located in areas of local transtension, suggesting that lowered normal stresses may play a role.

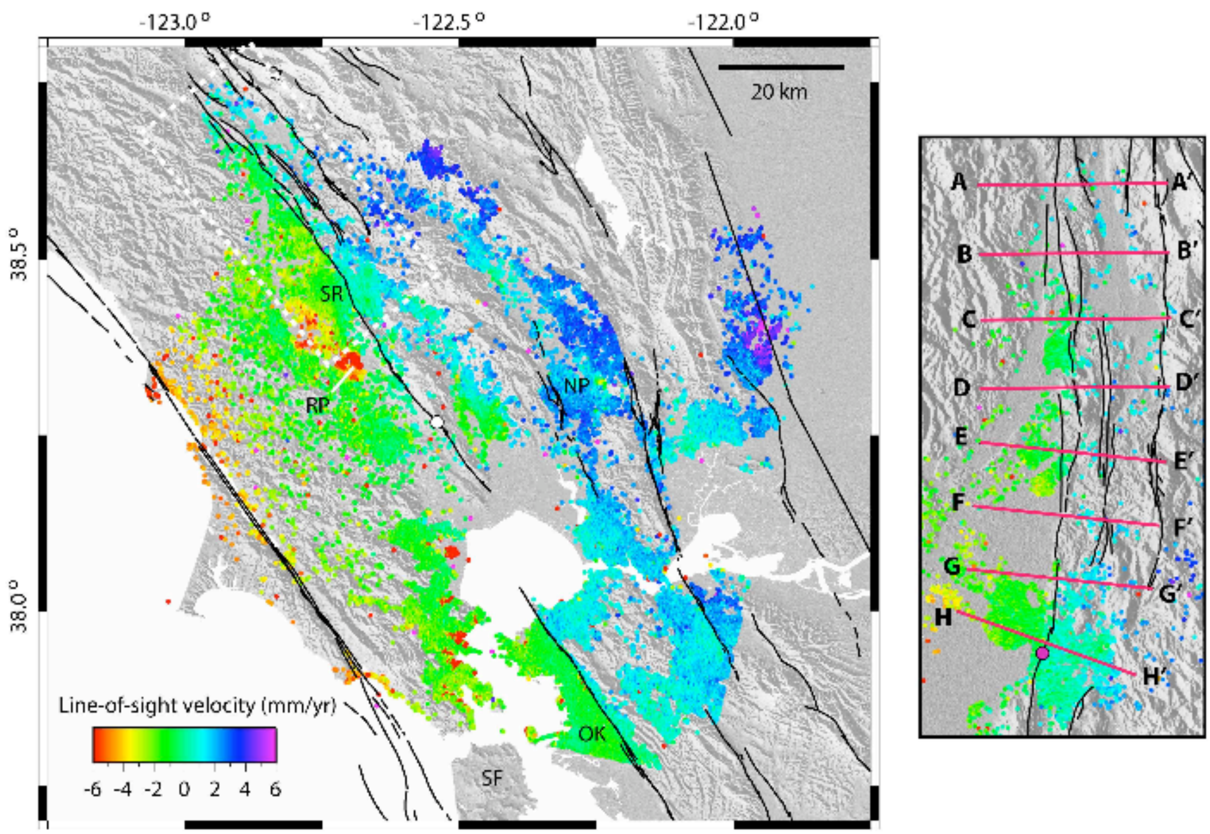

Figure 6: PS-InSAR data for the northern San Francisco Bay Area (track 342, frame 2835). Red colors indicate motion away from the satellite (range increase); blue, motion towards. SR: Santa Rosa, RP: Rohnert Park, NP: Napa, SF: San Francisco, OK: Oakland. Inset: Detail of velocities in the Santa Rosa area, after removal of points on weak substrate and thick sediment. From Funning et al. (2007).

Shallow brittle creep on other faults, in the San Francisco Bay Area and further south, is often accompanied by sequences of characteristic repeating earthquakes. The magnitudes and repeat intervals of these events can be related to the creep rate (e.g., Schmidt et al., 2005). Although, to our knowledge, no such earthquake sequences have been identified along the Rodgers Creek fault, the area has not hitherto been a target for such studies. Certainly, the distribution of earthquakes along the fault suggests some link between creep and microseismicity – cataloged seismicity shows that events are concentrated on the portion of the Rodgers Creek fault that we believe to be creeping, whereas the southern, locked, portion is largely aseismic.

4. SIGNIFICANCE OF FINDINGS

The geodetic measurements help constrain the seismic potential of Bay Area faults, which can be used to further refine earthquake forecast probabilities. The contiguity of faulting and aseismic creep across the stepover region between the Hayward and Calaveras fault has important implications for rupture scenarios and mechanics of interaction between the two fault zones. We are currently exploring the implications of this finding, also in the context of the recent Alum Rock earthquake and its afterslip, which occurred at the southern end of the transfer structure. The existence of creep on the Rodgers Creek fault could reduce expected moment release in future earthquakes and will allow us to more precisely determine the rupture area of past and future large earthquakes on the fault, which thus has implications for seismic hazard assessment.

4. DATA AVAILABILITY

Data from GPS campaigns are publicly available from the UNAVCO Campaign Data Holdings Archive. Both raw GPS data and accompanying metadata are included and freely accessible at http://facility.unavco.org/data/gnss/campaign.php

Data collected by our group for this project are archived under the PI Name (Burgmann) for campaigns named "Calaveras Fault", "Hayward Fault", "Central San Andreas" and "Loma Prieta."

Please see http://www.unavco.ucar.edu/data_support/data/general.html for policies regarding the use of these freely available data. Additional data used in this study included RINEX format files obtained from the U.S. Geological Survey and the Bay Area Regional Deformation Network (BARD). These files include campaign-style surveying (USGS) and continuous GPS stations (BARD) and are available at the NCEDC at UC Berkeley.

Processed GPS solutions, including the BAVU velocity field, time series and GAMIT-format solution files (h-files) are available via the BAVU web pages at:

http://seismo.berkeley.edu/~burgmann/RESEARCH/BAVU/

http://seismo.berkeley.edu/~dalessio/BAVU/FILES/gamit.html

For more information regarding data availability, contact:

Dr. Roland Bürgmann
Department of Earth and Planetary Science, University of California, Berkeley
307 McCone Hall, Berkeley, CA 994720-4767
e-mail:burgmann@seismo.berkeley.edu

URL:http://www.seismo.berkeley.edu/~burgmann

5. REFERENCES

Altamimi, Z., Sillard, P., and Boucher, C., 2002, ITRF2000: A new release of the International Terrestrial Reference Frame for earth science applications: J. Geophys. Res., v. 107, p. doi:10.1029/2001JB000561.

Bürgmann, R., Hilley, G., Ferretti, A., and Novali, F., 2006, Resolving vertical tectonics in the San Francisco Bay area from GPS and Permanent Scatterer InSAR analysis: Geology, v. 34, p. 221-224.

Evans, E., Bürgmann, R., and Nadeau, R.M., 2007, Linking Faults: Subsurface Creep on a Contiguous Fault Structure Connecting the Hayward and Calaveras Faults: Eos Trans. AGU, v. 88, p. Fall Meet. Suppl. Abstract S21A-0240.

Funning, G., Bürgmann, R., Ferretti, A., Novali, F., and Fumagalli, A., 2007, Creep on the Rodgers Creek fault from PS-InSAR measurements: Geophys. Res. Lett., v. 34, p. doi:10.1029/2007GL030836.

Herring, T.A., 2005, GLOBK, Global Kalman filter VLBI and GPS analysis program, Version 10.2: Mass. Instit. of Tech., Release 10.2.

Hilley, G.E., Bürgmann, R., Ferretti, A., Novali, F., and Rocca, F., 2004, Dynamics of slow-moving landslides from permanent scatterer analysis: Science, v. 304, p. 1952-1955.

King, R.W., and Bock, Y., 2005, Documentation for the GAMIT GPS Analysis software: Mass. Instit. of Tech., Scripps Inst. Oceanogr., Release 10.2.

Schmidt, D.A., and Bürgmann, R., 2003, Time dependent land uplift and subsidence in the Santa Clara valley, California, from a large InSAR data set: J. Geophys. Res., v. 108, p. doi:10.1029/2002JB002267.

Schmidt, D.A., Bürgmann, R., Nadeau, R.M., and d'Alessio, M.A., 2005, Distribution of aseismic slip-rate on the Hayward fault inferred from seismic and geodetic data: J. Geophys. Res., v. 110, p. doi:10.1029/2004JB003397.