FINAL TECHNICAL REPORT

SPACE GEODETIC MEASUREMENTS AND MODELS OF CRUSTAL DEFORMATION IN THE SAN FRANCISCO BAY AREA

National Earthquake Hazard Reduction Program

U.S. Geological Survey

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Award Number: **G09AP00134**

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Technical Abstract:

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. This project incorporates acquisition, processing, analysis and integration of a comprehensive GPS data set for central California, the BAVU time series and velocity field. 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 of precise regional surface deformation to determine long-term strain accumulation rates.

The observational program for this year entailed GPS measurements of a select subset of stations in our GPS campaign network: near the rupture area of the 1989 Loma Prieta earthquake and on the San Francisco Peninsula segment of the San Andreas fault. The former has been observed regularly with campaign GPS, which show anomalous motion perhaps due to continued postseismic deformation from the Loma Prieta earthquake. The latter has not been observed since 1996-97 and could provide important information on the mechanics of the San Andreas fault in this segment. The GPS results together with an increasingly comprehensive and precise InSAR range-change-rate field form the data constraints for models of the deformation and loading of the Bay Area fault system. All data and processed data products are freely available to other researchers.

Non-technical Abstract:

This project addresses the seismic potential and natural hazard presented by major faults in the San Francisco Bay Area through the use of space geodesy, focusing on improved constraints from both campaign style and continuous GPS measurements. We also obtained new campaign observations on two important areas of interest. 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 due to time-dependent deformation processes.

Introduction

GPS Monitoring of Active Bay Area Deformation

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. 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. The proposed observational program entails GPS measurements of a select group of ~30 stations in our GPS campaign network and processing, archiving and full integration of the campaign data with the complete USGS campaign data sets and a full set of CGPS solutions to produce repeatedly updated BAVU time series and velocity field products. Given the density of CGPS measurements and size of the SGPS network, we now try to remeasure sites only every two or three years, as opposed to the yearly intervals we previously sought.

The BAVU velocity field (Figure 1a shows most recent update) forms a core component of the recently developed California-wide velocity map (CMM 4, Figure 2), 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 1 (1993-2003, published by *d'Alessio et al*. 2005), and northern California and Pacific Northwest SGPS networks (1993-2004). We believe it is important to 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 allows us to reduce and focus the number of SGPS surveys we propose, but do not make them expendable.

Data collected by InSAR satellites since 1992 form a valuable complement to the GPS measurements. Interferograms provide denser coverage than would be possible with GPS and the data are often acquired routinely at monthly intervals. However, InSAR measurements are strongly impacted by atmospheric and other error sources, and coherence and thus determination of a deformation signal is problematic over vegetated and rough topography, which still dominate over wide portions of the region. Work done using InSAR strongly complements this project, both benefiting from and benefiting the GPS analysis.

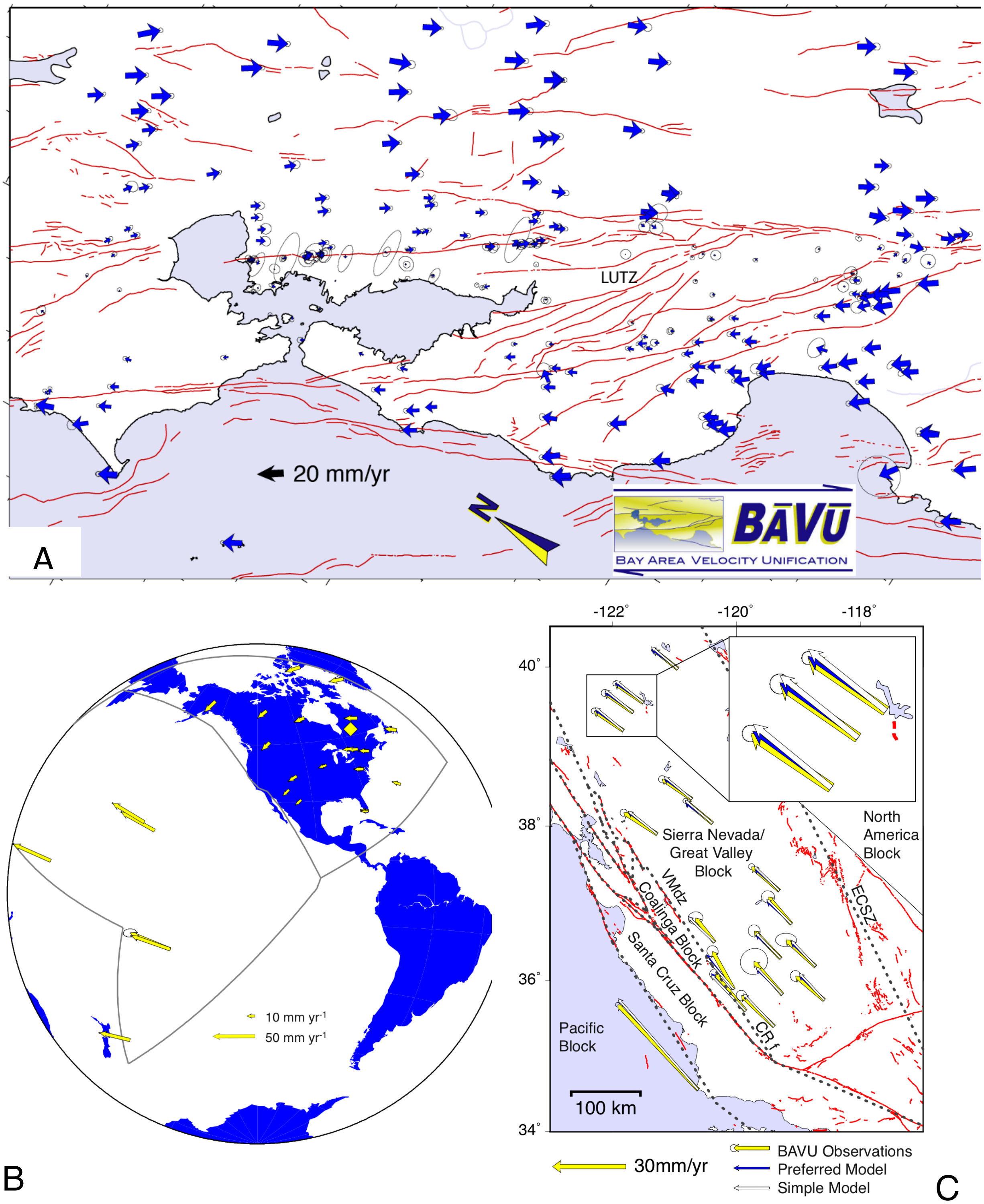

Figure 1. (A) Updated BAVU velocity field referenced to a local site (LUTZ) on the central Bay Block spanning 1994-2006. The map is in an oblique Mercator projection about the pole of Pacific-plate-to-SNGV block rotation. (B) Global and (C) central California scale BAVU velocity field also showing fit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

Understanding Active Bay Area Deformation

The GPS results form the data constraints for increasingly physical models of the deformation and loading of the Bay Area fault system. We propose an integrated effort in which the observational component of this project provides data for kinematic and dynamic models of regional earthquake-cycle deformation in the Bay Area. Crustal deformation models allow us to translate surface deformation data into information relevant for earthquake hazard. Rigorous kinematic inversions for fault slip rates in the context of a regional rigid block model is a powerful approach to interpret the regional deformation pattern and provides well-constrained geodetic estimates of slip rates on major faults (*d'Alessio et al*., 2005). However, this approach does not take into consideration important time dependent effects due to the largest earthquakes in recent history. To properly address time dependent deformation and loading, we will build on models that incorporate vertical stratification of both elastic and viscous rheology of the lithosphere (e.g., *Pollitz et al*., 2004; *Freed et al*., 2007). Careful and rigorous consideration of such end-member representations of crustal deformation (rigid elastic blocks vs. deformation dominated by viscous processes at depth) which will be refined based on continually improving constraints on Bay Area deformation and deep structure, will provide new insights into the deep workings of the Bay Area fault system.

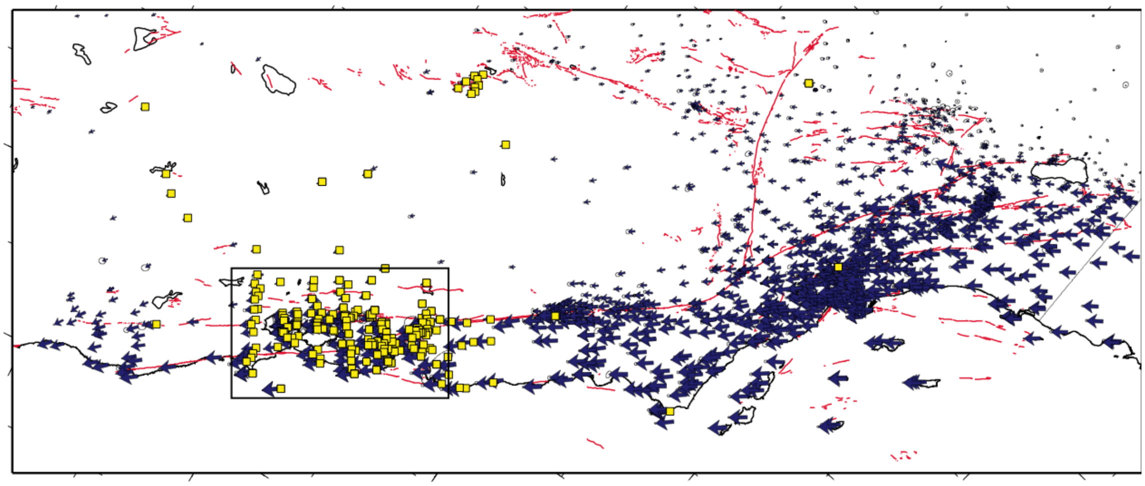

Figure 2. BAVU sites shown together with California-wide velocities of the Crustal Motion Map (CMM 4.0) compiled by King, Agnew, Shen and Murray.

Results

This project involved surveys of a portion of the campaign GPS network we have established over the years. Additional GPS data incorporated in our processing and analysis come from the continuous BARD and PBO networks and USGS campaign measurements observed along several profiles across the Bay Area (Figure 2). Figure 1 shows the latest available horizontal site velocities in the Bay Area integrated in our recently completed BAVU 2.0 velocity model, which is based on a fully reprocessed analysis, using the GAMIT/GLOBK processing software (*d'Alessio et al*., 2005). Since the first version of BAVU, we have added the data summarized in Table 1 to the analysis. The spacing of the sites is well suited for the precise determination of strain accumulation and thus estimation of long-term fault slip rates in the region.

Campaign GPS Observations.

Data collection for this project was conducted using Trimble 5700 GPS receivers with Trimble Zephyr Geodetic antennas. This campaign consisted solely of sites that could be left unattended; we were therefore able to occupy each for a minimum of 72 continuous hours.

A

B

Figure 3: A) Photo of BMT8, showing a typical campaign setup including a tripod-mounted Zephyr Geodetic antenna, connected to a Trimble 5700 receiver and powered by dual 18-AmpHr batteries. B) Only one sites was suitable for a spike mount (RF1_). We used a 0.5 m fixed height mount on loan from UC Riverside.

The first focus of our field measurement efforts continues to be the structurally complex region in the southern Bay Area that experienced numerous historic earthquakes, including the 1989 Loma Prieta earthquake. Geologic and seismologic evidence suggests dominant strike-slip deformation along northwest trending faults and subsidiary thrust faulting and left-lateral strike slip on conjugate faults. The area also includes the transition region between the locked and creeping portions of the San Andreas fault near San Juan Bautista is one of the most complexly deforming regions along the San Andreas fault system with several historic M 5-6 earthquakes, slow earthquakes, and secular creep. The pattern of deformation observed immediately following the Loma Prieta earthquake suggests significant postseismic contraction across the youthful southern Santa Cruz Mountains northeast of the San Andreas fault. Since about 1994, relatively shallow afterslip appears to have subsided (*Segall et al.,* 2000), however, lower-crustal relaxation processes appear to persist (*Pollitz et al*., 1998; *Bürgmann, et al*., 2006).

We re-occupied a set of benchmarks in the southern Bay Area, near the Loma Prieta rupture area (Figure 4). All were recovered in good condition. Site TRAL was not recovered due to the property being for sale and without an occupant, but may be recoverable in the future. All the benchmarks re-surveyed in the Loma Prieta area have measurements spanning back to 1994 and earlier, creating a time history including Loma

Prieta postseismic deformation that can't be replicated with contemporary continuous data.

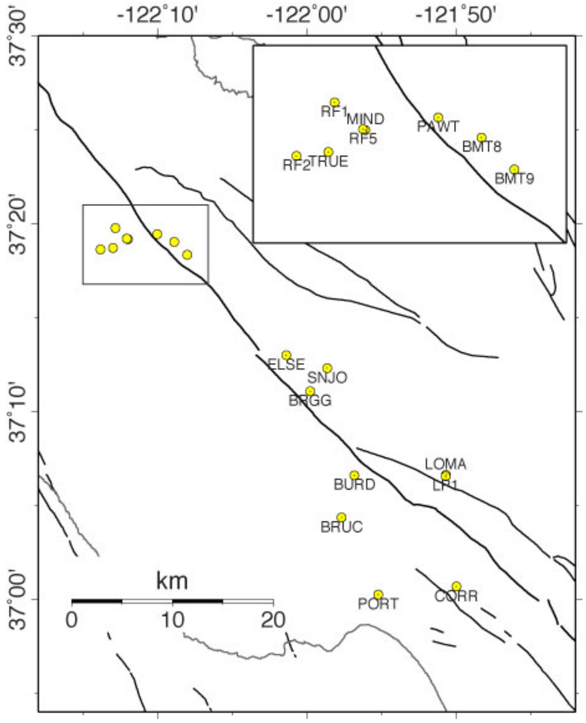

Figure 4: Locations of campaign sites observed as part of this project, plotted with major faults. Inset map is a close up of the Black Mountain network (black rectangle in upper left corner).

We also attempted to recover 11 sites in the Black Mountain area of the San Francisco Peninsula (Figure 4); all (except one) are now within the Midpeninsula Regional Open Space Preserve. A couple sites (BM1R, TRUE, PAWT) had data from as recently as 2005, but the majority had not been surveyed since the University of Alaska did so in 1996 and 1997 (*Chen and Freymueller*, 2002).

We were unsuccessful in recovering 3 of the Black Mountain sites. The likely location of site BM07 was found, but not the monument. There was evidence nearby that the monument has been destroyed (Figure 5A). BM11 was also not recovered; remnants of the tripod footholds were found dislodged and laying on the hillside, but there was no evidence of the monument. The soil appeared to be quite thick in this location and it's very possible the monument is intact, but buried. Site BM1R has been recovered by the USGS as recently as 2005, but we were unable to find it (Figure 5B). We found one destroyed marker, but were unable to determine if it was the reset mark that we were looking for, or the original, which was known to be destroyed.


Figure 5: A) Apparent imprint of removed benchmark on nearby rock, indicating that site BM07 is likely destroyed. B) Rod missing its marker near the location of BM1R. It was not clear if this is the original BM10, known already to be destroyed.

The eight remaining marks (Figure 4) were all recovered in good condition. We were able to survey three sites on the eastern side of the San Andreas fault and five on the western side, such that the quality of the network was not much diminished by the loss of the three stations.

Processing and Analysis.

Our GPS analysis relies on the GAMIT/GLOBK processing and analysis system developed at the Massachusetts Institute of Technology (*Herring et al.,* 2010a&b). We include five global stations from the International GPS Service (IGS) network (ALGO, KOKB, GOL2. DRAO, FAIR) and a dozen nearby continuous stations from the BARD and PBO networks in each of our local processing runs. We combine daily ambiguity-fixed, loosely constrained solutions using the Kalman filter approach implemented by GLOBK (*Herring et al*., 2010b). 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. A global set of stations is used for stabilization into an ITRF2005 reference frame (*Altamimi et al*., 2007).

Loma Prieta Area

A very preliminary velocity solution for Loma Prieta area sites was obtained and the results are shown in Figure 6. The results compare favorably to those from BAVU (blue arrows in Figure 6), but with a slight difference in rotation visible at PORT, but also BRUC. The rotation is in a direction that would reduce the fault perpendicular component of motion in model results (e.g. *Johanson and Bürgmann*, 2005) that appears to indicate continued post-Loma Prieta relaxation.

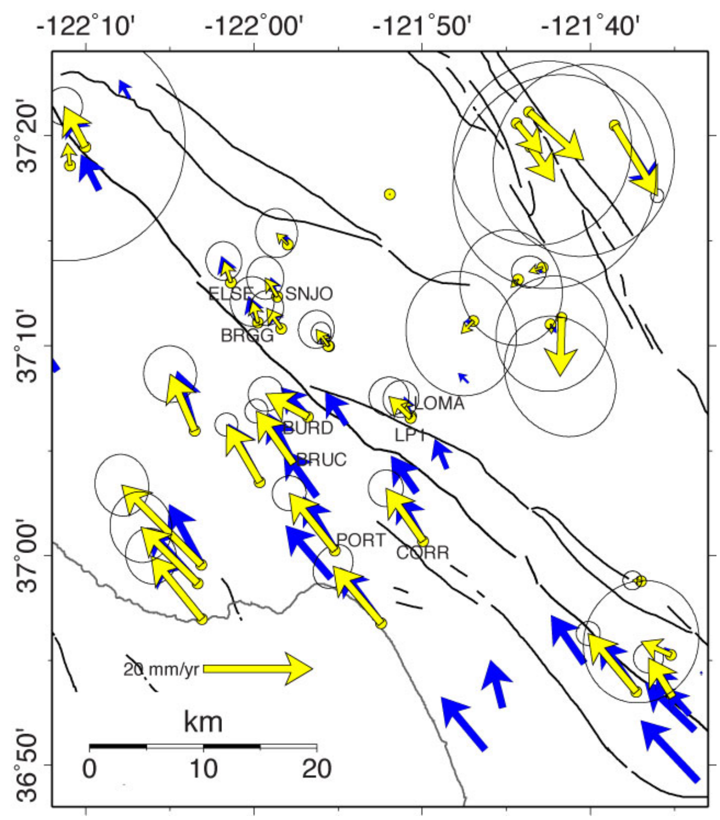

Figure 6: Comparison of preliminary results from this study (yellow vectors with 95% confidence ellipses) with BAVU 1.0 (blue vectors). Small changes in rotation southwest of LOMA are just barely detectable.

Preliminary time series also seem to indicate that site motions have some nonlinearity in the time span 1994-2010 (Figure 7), with a change in rate occurring in 1997-98. This is particularly visible in the North component. However these are still within the scatter of the campaign measurements. A statistical analysis of the entire network will be needed to determine if these excursions from linear motion are significant. Continued measurements of crustal deformation can help us resolve further details in the strain accumulation patterns in the region and better constrain contributions of enduring postseismic relaxation.

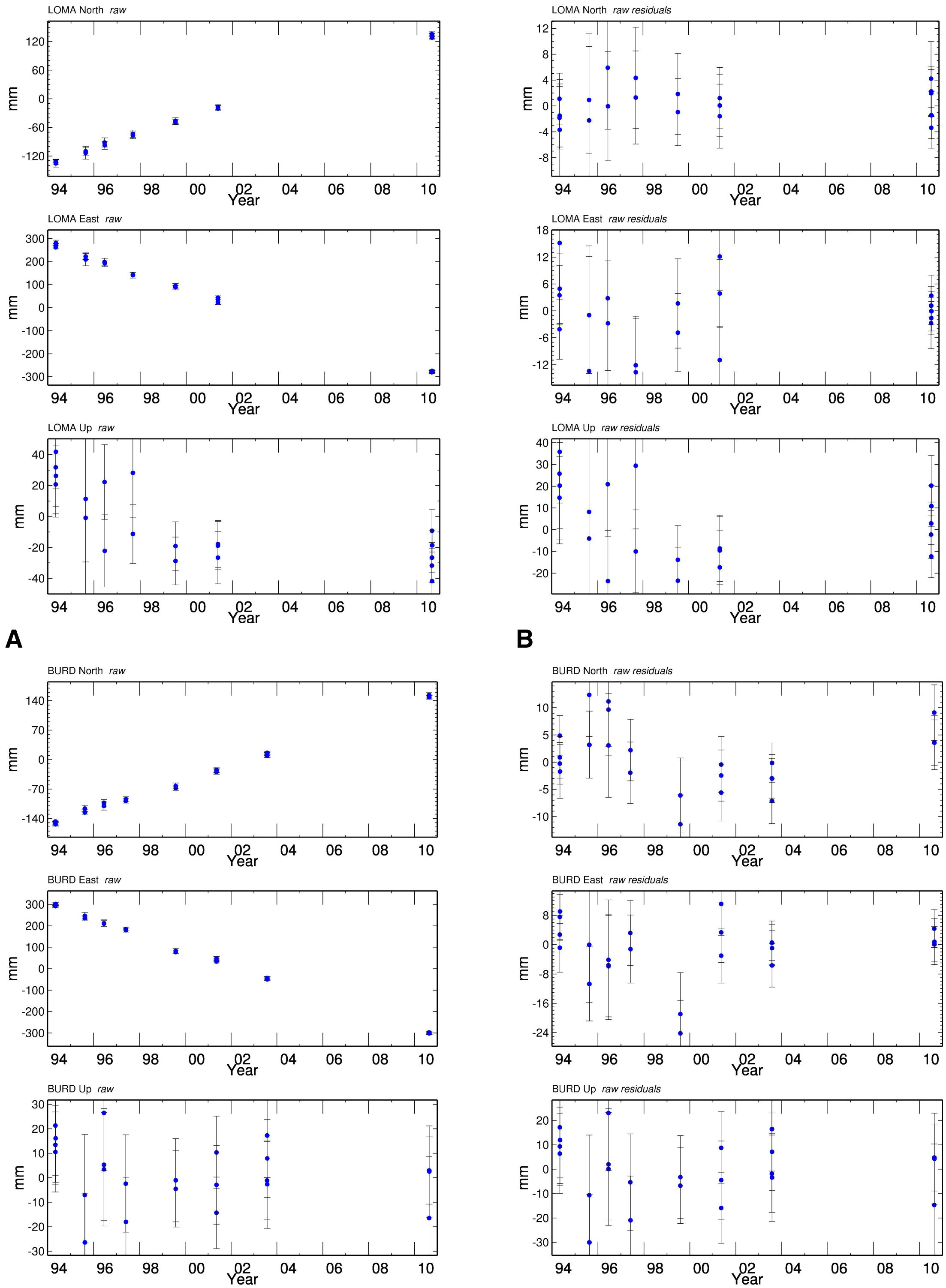

Figure 7: Time series of site displacements from multiple campaigns, for sites LOMA (A&B) and BURD (C&D). A and C show site displacements in the ITRF2005 reference frame, B and D have a linear trend removed.

San Andreas Fault – Black Mountain network

Although some of the sites in the Black Mountain network had only one prior occupation with GPS, the nearly 15 year gap means that obtaining a well-constrained average velocity is still possible. We obtained data for UAF's 1996 and 1997 (*Chen and Freymueller*, 2002) surveys via the UNAVCO archive and processed the data using GAMIT/GLOBK as described above. In out preliminary velocity solution, sites that are aligned parallel to the fault have similar station velocities (e.g. PAWT-BMT8-BMT9 and RF5_-MIND-RF1_), which is a nice check on the solution's consistency.

The velocity solution shows about 2 mm/yr of relative motion within ~4 km of the San Andreas fault and ~1.5 mm/yr of relative motion with ~2 km. These appear to indicate localized deformation, either as a result of fault creep or a near-fault compliant zone. It is worth noting that there have been no indications of creep on this section of the San Andreas from other sources. On the other hand, previous studies have found that strain rates and velocity profiles are well described by models including a compliant zone with a rigidity value about half that of the far-fault region for both this network (*Chen and Freymueller*, 2002) and on the San Andreas fault near Bodega Bay, north of this location (*Jolivet et al.,* 2009). This additional data seems to support those earlier conclusions.

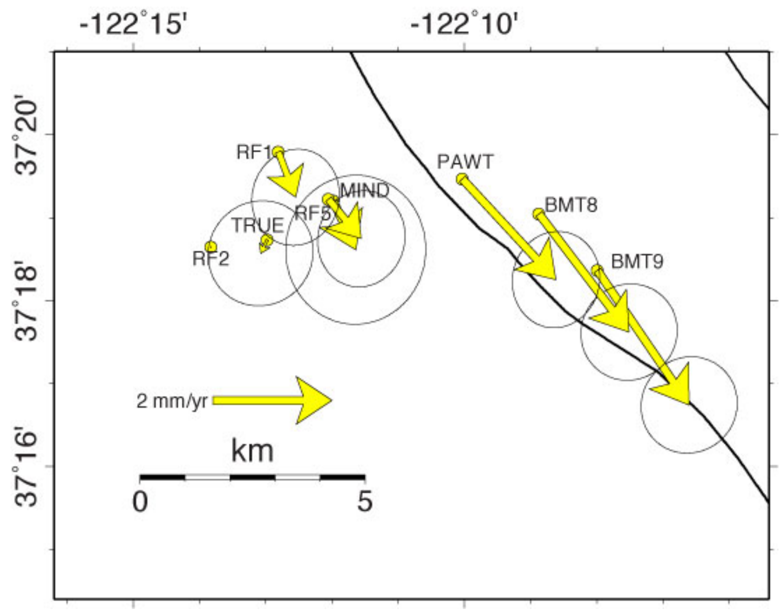

Figure 8: Preliminary velocity solution for the Black Mountain network with 95% confidence ellipses. The San Andreas fault runs through the network from northwest to southeast.

There is also a slight rotation apparent in PAWT- BMT8- BMT9. With BMT9 having a more southerly head than PAWT. This is likely due to a local bend in the San Andreas fault at this location. The difference in motion between PAWT and BMT9 is small (~0.25 mm/yr). This translates to 3.5 mm over 14 years, which is detectable, but could also represent benchmark instability. BMT9 is on the side of a ridge, with a slope dipping to the southeast. This is the same direction as its differential motion with PAWT, which therefore could be due to down slope motion. However BMT9 and BMT8 are both installed on rock, though PAWT is not as clearly on stable substrate.

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