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Final Technical Report

Kinematics of Faulting in the Northern San Francisco Bay Region from GPS measurements: Collaborative Research with the Massachusetts Institute of Technology and University of California, Riverside

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Abstract

We re-observed 107 survey GPS sites in the North San Francisco Bay Area, from San Pablo Bay in the south to Clear Lake in the north and the Pacific coast in the west to Lake Berryessa in the east. This area contains the coastal San Andreas, Rodgers Creek, southern Maacama and Green Valley Faults comprising the Pacific-North America plate boundary in the region. These new data build upon previous measurements at the sites and augment continuous GPS sites in the region to improve the density and precision of current GPS velocity solution in the area. This updated GPS velocity solution is now mature enough to enable viable and detailed studies of the kinematics of faults in the North San Francisco Bay Area.

Our network, along with a network of survey GPS sites observed by the USGS, also straddles the West Napa Fault, which ruptured in the August 24, 2014, M_w6.0 South Napa earthquake. We were active in the field at the time of the earthquake and we orchestrated a GPS rapid response alongside colleagues from the USGS and UC Berkeley.

Here, we report the distribution and quality of the survey GPS data acquired during the two regular surveys that we conducted in July and August 2014, as well as the rapid response that was undertaken in the immediate aftermath of the South Napa earthquake. The primary goal and achievement of this project was GPS data acquisition but we also show preliminary results of kinematic modeling and evidence for rapid afterslip following the South Napa earthquake.

1. Introduction

The primary goal of this project is to extend the GPS time series of a network of survey marks throughout the North San Francisco Bay Area in California (hereafter referred to as the "North Bay" or "field area") in order to improve the coverage, accuracy and precision of geodetic measurements of crustal motion and fault slip rates. For the purpose of our study, the field area is loosely defined as extending from the Golden Gate and San Pablo Bay in the south to a line between Point Arena and Clear Lake in the north, and from the Pacific coast in the west to a line between Lake Berryessa and Clear Lake in the east (see Figure 1). As such, we work within all of Marin, Sonoma and Napa Counties, and southernmost Lake and Mendocino Counties. This area contains a section of the Pacific-North America plate boundary system, including the coastal San Andreas Fault, Rodgers Creek and southern Maacama Faults, and Green Valley Fault. Minor faults include the West Napa Fault. (This area also includes The Geysers geothermal power production field at the boundary of Sonoma, Lake and Mendocino Counties, although no additional GPS survey work was undertaken there as part of this current project and The Geysers will not be discussed further here.)

Our motivation for enhancing the GPS coverage in this region is that the Rodgers Creek Fault, along with the Hayward Fault further south, presents a relatively high seismic hazard (e.g. Field et al., 2013). However, unlike the Hayward Fault and other faults in the Greater San Francisco Bay Area, the North Bay is relatively sparsely instrumented. The Plate Boundary Observatory (PBO) network of continuous GPS (cGPS) sites exists throughout the field area but the Bay Area Regional Deformation (BARD) cGPS network and cGPS sites operated by the USGS are concentrated in the Greater Bay Area. Consequently, our knowledge of the relative slip rates of the suite of parallel strike-slip faults in the Pacific-North American plate boundary in the North Bay region is poorly constrained. We delimit our study region as described above to avoid overlap with and complement survey networks operated by the US Geological Survey (USGS) to the north and south-east (green symbols in Figure 1), and the denser GPS coverage within the Greater Bay Area generally to the south. Some areas of our field area remain challenging to establish GPS studies due to relatively extensive forest canopies, such as across the Gualala River watershed in coastal Sonoma and Mendocino Counties, or land ownership. Performing reconnaissance and measurements in such areas requires more targeted field work and support with a lower expected data yield due to their relative isolation and sparser road network.

2. Survey GPS field work

2.1. Acquisition of field permits

In preparation for our field work, we sought a permit to conduct field work within the boundary of Point Reyes National Seashore from the National Parks Service, as required. We submitted our application for a scientific research permit on June 2, 2014, which was approved on June 25, 2014 and finalized on June 30, 2014. We proceeded to conduct observation at nine survey sites within Point Reyes National Seashore from July 8 to July 11, 2014.

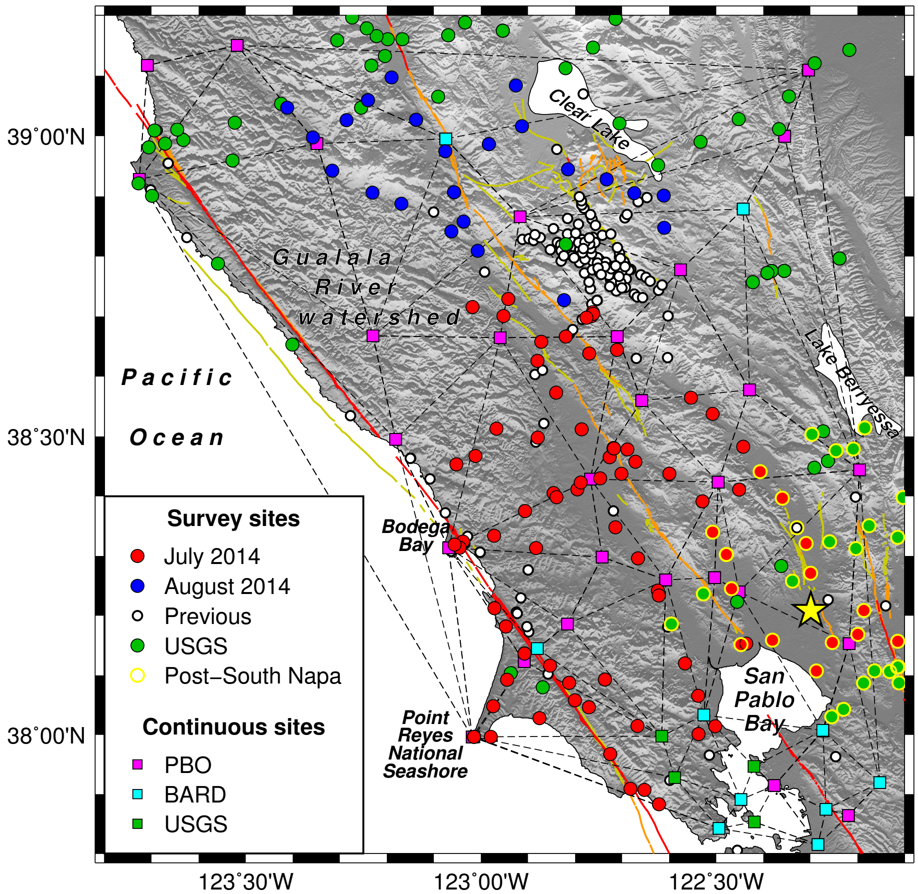

Figure 1: Summary of survey GPS observation activities undertaken for this project. Dots are survey sites observed during the July 2014 field work (red; see Section 2.2), August 2014 field work (blue; see Section 2.3), and post-South Napa earthquake (yellow circles; see Section 2.4). Survey sites within USGS networks are represented by green dots and others previously observed by the authors or included in the GPS solution (see Figure 5) from publicly available data but not re-observed during this current project are white (see Section 2.5). The Geysers are clearly seen by the cluster of white dots just south of Clear Lake. Squares represent continuous GPS sites operated by PBO (magenta), BARD network (cyan) and the USGS (green). Dotted lines represent Delaunay triangles between continuous GPS sites (see Section 3 for discussion). Faults marked are those with historic (red), Holocene (orange) and Late Quaternary (yellow) ruptures (USGS & CGS, 2006).

2.2. July 2014 survey

Our first round of field work occurred over 14 days from July 2 to July 15, 2014. This survey focused measurement efforts on the southern half of the North Bay field area (red dots in Figure 1). Two field groups operated simultaneously, one led by M. Floyd with one of G. Funning's graduate students and one led by G. Funning with a local contact. M.

Floyd's group made measurements along the coast in Marin and Sonoma Counties, from the Golden Gate to Jenner and the Russian River Valley, including Point Reyes National Seashore and Bodega Bay. G. Funning's group made measurements inland throughout Sonoma and Napa Counties.

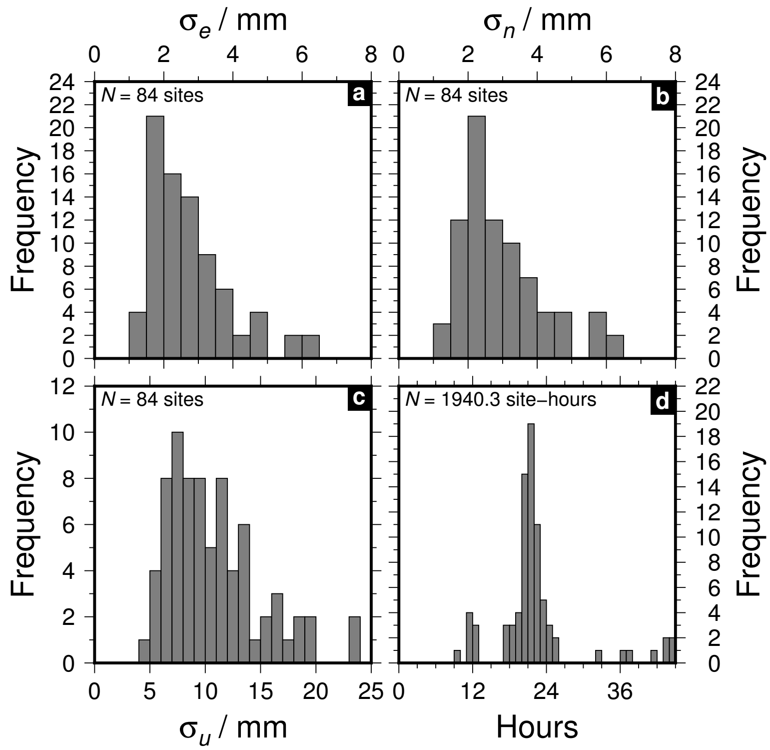

Figure 2: Summary of GPS data acquisition statistics for July 2014 survey: Position uncertainty distribution for (a) east, (b) north and (c) up components of processed results; (d) Distribution of observation periods at sites measured. The majority of sites were observed for nearly 24 hours.

In total, 84 survey sites were measured, all but four of which had at least one previous measurement taken by the authors or by others whose data are publicly available. Of the four that did not, two were new sites in locations that we considered strategic to our goals and future work, and two were "reset" sites that were new by virtue of the fact that the original marker was destroyed or displaced.

During this survey, three sites were disturbed by unknown causes during observation. Kinematic (epoch-by-epoch) processing was carried out to determine the exact epoch of disturbance and the resulting RINEX files truncated at that epoch. The results are summarized in Table 1.

Site	First epoch	Last good epoch	Useful data-hours
04NF	2014-07-05T20:59:30	2014-07-06T09:03:30	12.1
6908	2014-07-02T21:32:30	2014-07-03T06:20:00	8.8
E480	2014-07-08T19:39:30	2014-07-08T20:54:00	1.2

Table 1: Summary of disturbed GPS setups during the July 2014 survey. All times are GPS time.

2.3. August 2014 survey

Our second round of field work occurred over 4 days from August 21 to August 24, 2014. This survey focused measurement efforts on the northern half of the North Bay field area (blue dots in Figure 1). Again, two field groups operated simultaneously, one consisting of M. Floyd alone and one led by G. Funning with his graduate student. M. Floyd made measurements along Anderson Valley and Route 101. G. Funning's group made measurements between The Geysers and Clear Lake. In total, 23 survey sites were measured, all of which had at least one previous measurement taken by the authors or by others whose data are publicly available.

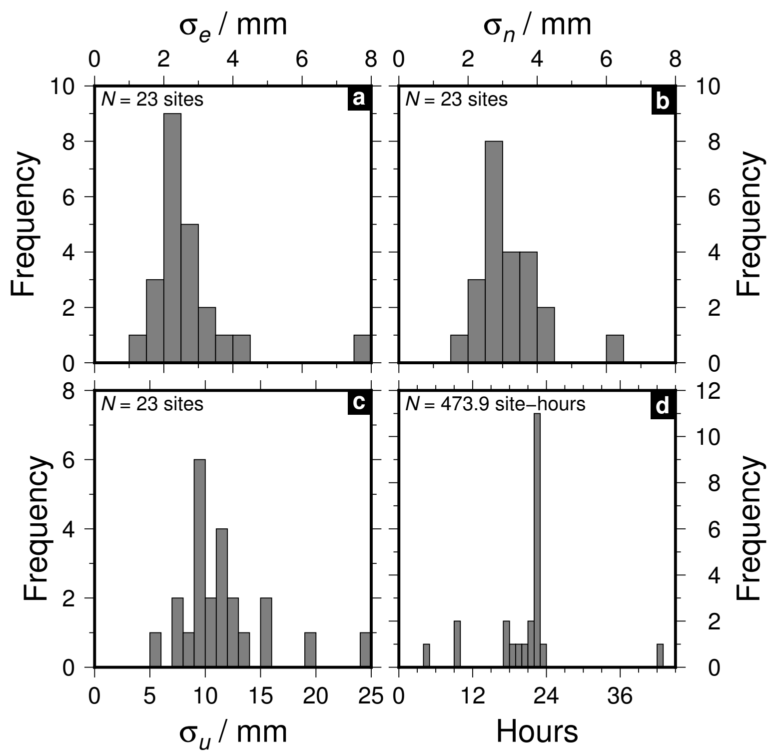

Figure 3: Summary of GPS data acquisition statistics for August 2014 survey: Position uncertainty distribution for (a) east, (b) north and (c) up components of processed results; (d) Distribution of observation periods at sites measured. The majority of sites were observed for nearly 24 hours.

This survey was planned to be longer (7 days) but was interrupted on August 24, 2014, by the M_w6.0 South Napa earthquake, which is discussed separately in Section 2.4, below.

2.4. The 2014-08-24 South Napa earthquake

At 3:21am local time (Pacific Daylight Time; 10:21 UTC) on August 24, 2014, a strong (M_w6.0) earthquake occurred along a segment of the West Napa Fault between American Canyon and Napa, California (yellow star in Figures 1 and 5; bright yellow line in Figure 7). Both field groups were observing GPS sites to the south and west of Clear Lake at the northern end of our field area on the day before the South Napa earthquake, and were based in Upper Lake, just north-west of Clear Lake and about 130 km (80 miles) NNW of the earthquake itself, over the night of August 23–24, 2014. As soon as we became aware of the earthquake's occurrence, about 3 hours afterwards at 7am local time (14:00 UTC), we established where the earthquake had occurred, which survey (and continuous) sites were nearby, and planned to retrieve our instruments from sites being observed overnight to install them at sites around the epicenter. We utilized the Southern California Earthquake Center Response Forum (http://response.scec.org/) to gather helpful reports and guidance from other researchers, where we also uploaded and shared information of our own regarding our presence in the field and our intentions to re-observe survey sites in the epicentral region.

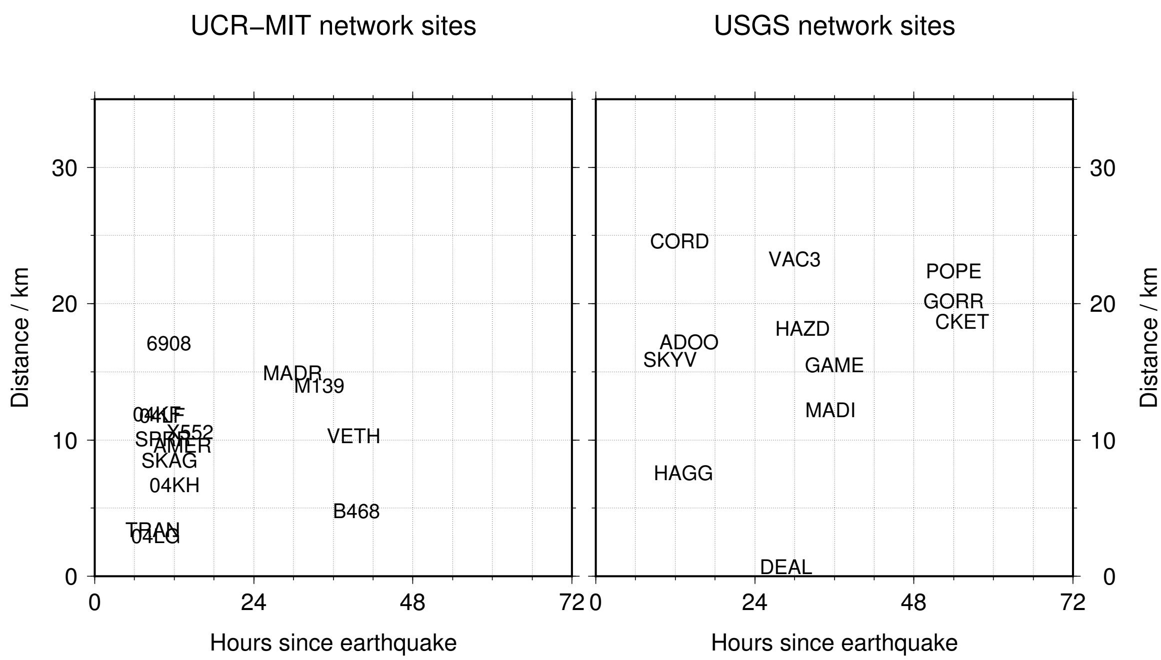

Figure 4: Survey GPS response to the South Napa earthquake by teams from UCR-MIT (current project workers) and the USGS. Site IDs are plotted at the time of first observation after the earthquake and distance is from the site to the observed surface rupture. The authors and the USGS re-observed their own networks for the most part, except for the measurement of HAGG by the UCR-MIT team.

The two teams arrived in the epicentral region at about 11:00am local time (18:00 UTC) and the first sites were installed at that time, about 8 hours after the earthquake. In total, 23 survey sites within 25 km of the surface rupture were re-observed within 48 hours of the earthquake (yellow circles in Figure 1). Of these, 10 sites within 13 km of the rupture were re-observed within 15 hours. The rapid response re-observation effort is summarized in Figure 4, above.

M. Floyd concentrated re-observation efforts on the west side of the surface rupture and G. Funning on the east side of the rupture to avoid travel through congestion due to road work which was in full effect on California Highway 12 and other routes that passed over the ruptured fault. M. Floyd was joined by field assistants from UC Berkeley on the afternoon of August 24 to provide help re-observing as many sites as possible as quickly as possible. M. Floyd also returned to UC Berkeley to collect one more GPS instrument that was made available.

We made direct contact with a USGS scientist (Jerry Svarc) during the evening of August 24, 2014, to discuss which sites were already being re-observed and further logistics regarding critical targets for the next morning. In general, survey sites within the USGS network were re-observed by the USGS and those within the UCR-MIT network (i.e. those measured during the July 2014 survey described in Section 2.2) were re-observed by our field teams.

This rapid response was vital to the observation of post-seismic processes because it quickly became obvious that significant afterslip had occurred within the first few hours and days. Each of the sites observed at this time were maintained over the next three weeks to ensure short-term continuous measurements of post-earthquake processes were gathered (see Figure 8). All data was immediately shared with the USGS and vice versa.

2.5. Sites not reobserved

Due to the rapid response to the South Napa earthquake undertaken by the authors during this project, several sites unfortunately were not observed again. These are marked as white dots in Figure 1. These sites will act as primary targets during future work in the area.

3. Improvement to GPS velocity solution in the North San Francisco Bay Area

3.1 Contribution of survey GPS

The continuous GPS network in the North Bay area, consisting of the combination of PBO, BARD and USGS networks, provides a median inter-site distance of 16.1 km (assessed by means of Delaunay triangulation as shown in Figure 1). With the addition of the complete survey GPS network in the North Bay Area, not just the 107 sites re-observed during the current project, this inter-site distance is reduced to about 7 km. This is important in consideration of the geophysical signal sought here. Given that the locking depth associated with strike-slip faults in northern California is 10–15 km and the separation of parallel faults is 20–30 km, a distribution of geodetic measurements that is of the same order cannot adequately constrain geophysical parameters of interest, such as fault slip rate and locking depth, nor correlations between those estimates on parallel faults.

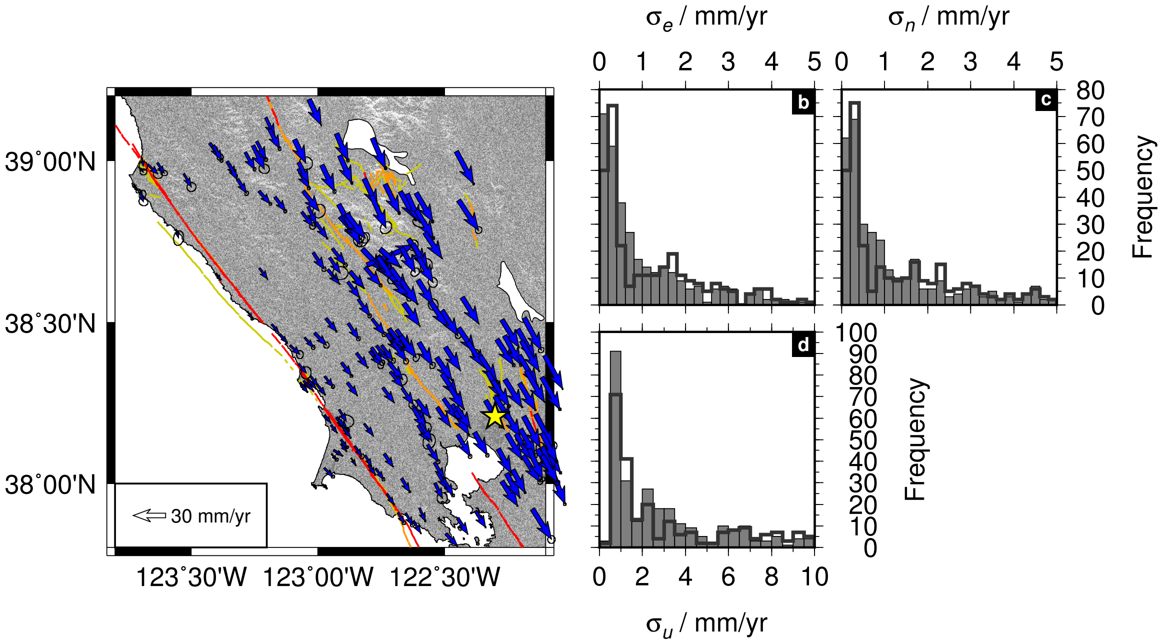

Figure 5: (a) GPS velocity solution for the North San Francisco Bay after the current project work, relative to the Pacific plate as defined by Altamimi et al. (2012). Histograms summarize the statistical differences of the velocity uncertainties in east (b), north (c) and up (d) components between the solution before (thick dark gray stair-step lines) and after (gray bars) the current project work.

3.2 GPS velocity solution

With the addition of the (pre-South Napa earthquake) 2014 survey measurements, precision of the velocity solution has improved significantly both in terms of data coverage and precision of velocity. The most important difference is that a significant number of sites that previously had horizontal velocity uncertainties of > 1.5 mm/yr are now below the 1.5 mm/yr velocity uncertainty level due to these latest observations (see dark gray stair-step lines compared to gray bars in Figure 5). This provides a viable geodetic solution with which to perform modeling of the kinematics of the region.

We present here preliminary estimates of fault slip rates based on the UCERF2 (WGCEP, 2008) fault geometry with all faults fully locked (i.e. creep rate or “aseismic factor” is not taken into account). However, considering the occurrence of the South Napa earthquake, we also present a modified form of the UCERF2 fault geometry, which includes a model West Napa Fault. This work will be updated in the future to follow the UCERF3 (Field et al., 2013) fault geometries as well as exploring our own fault geometries, especially locking depths and creep rates.

The form of the kinematic modeling approach undertaken here, using TDEFNODE (e.g. McCaffrey, 2002), requires closed polygons. Therefore, the discontinuous nature of the West Napa Fault system is accounted for by adding a “pseudo-fault” segment following Napa Valley from west of Napa to the southern end of the Maacama Fault east of Healdsburg. We test two end-member scenarios where this connector is allowed to slip freely or is locked to an effectively infinite depth. The former produces a discontinuity in velocity between blocks on either side of the connector, which is philosophically unrealistic if one has no evidence for a true fault cutting through the area. We suggest that the latter approach may be employed to simulate a broad shear zone between blocks, over which deformation is diffuse and not confined to any given pseudo-fault trace.

Regardless of the approach, all variations of the models, of which the free-slip version is shown in Figure 6, estimate right-lateral strike-slip rate on the West Napa Fault of < 1 mm/yr, with little effect on the other faults in the area. Likewise, the inclusion of the West Napa Fault itself in the models has very little effect on the estimated slip rates of other faults in the area. The coastal San Andreas Fault is estimated to slip at 15.7–17.2 mm/yr, the Rodgers Creek and southern Maacama Faults at 12.0–13.6 mm/yr and the Green Valley Fault at 4.5–9.5 mm/yr, although this is poorly constrained by our network.

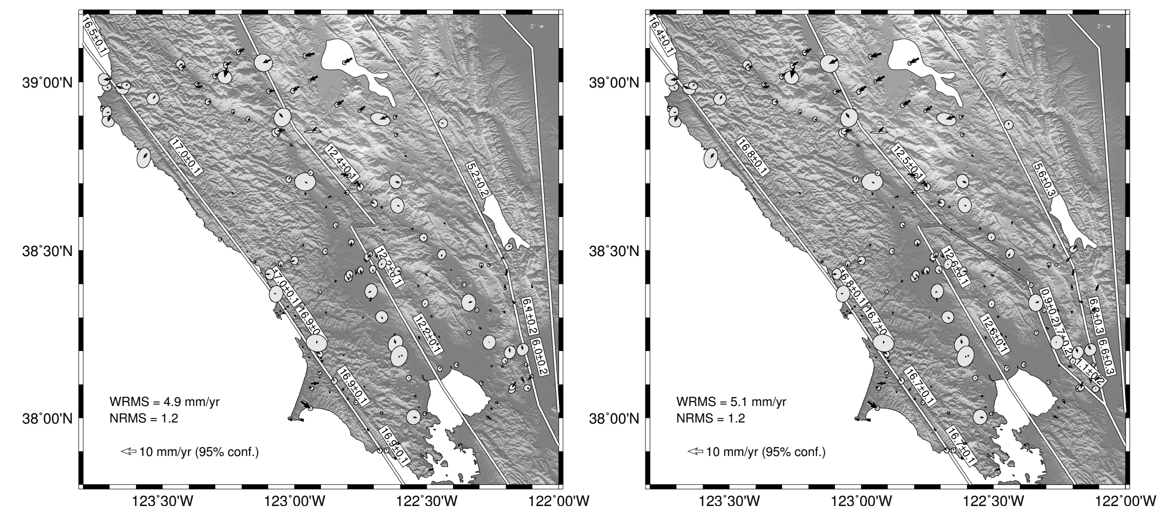

Figure 6: Preliminary kinematic model of fault slip rates based on the UCERF2 fault geometries (left), and including a West Napa Fault (right). White lines represent faults following the UCERF2 fault geometry (location and locking depth) and gray lines represent freely slipping “pseudo-faults” to close polygons in the case of discontinuous mapped faulting. Annotations are estimated right-lateral strike-slip rates (mm/yr). Large residual velocities are confined to the north of our field area.

4. The 2014-08-24 M_w6.0 South Napa earthquake

The current project had observed several sites in the vicinity of the South Napa earthquake during the July 2014 survey just seven weeks prior. This therefore provided an accurate pre-earthquake position from which to estimate displacement due to the earthquake. The earthquake occurred in an area covered by two survey networks, one observed by the UCR-MIT team and the other by the USGS, as well as several continuous GPS sites from the PBO, BARD and USGS networks.

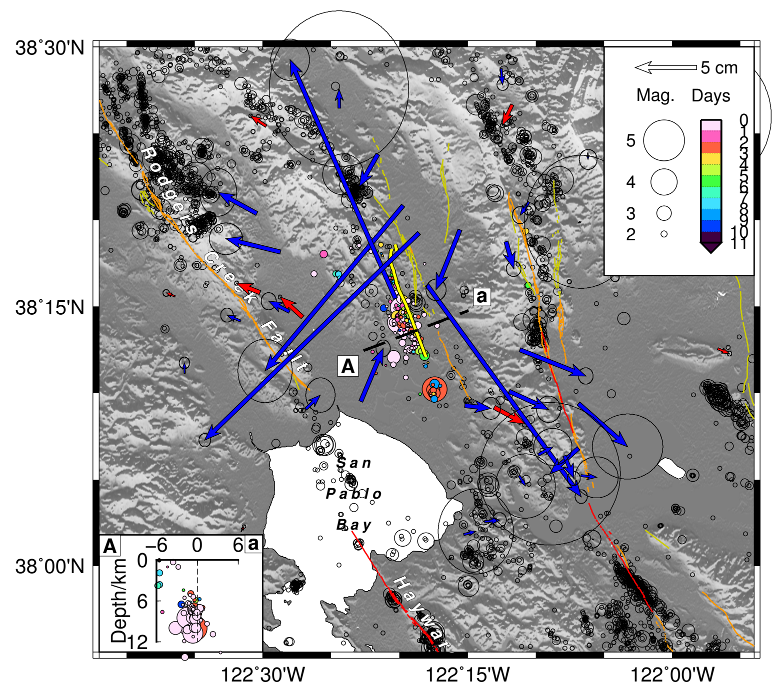

Figure 7: GPS displacements for the 2014-08-24 M_w6.0 South Napa earthquake at continuous (red) and survey (blue) sites. The surface rupture of the South Napa earthquake is shown in bright yellow. Black circles are pre-earthquake seismicity from Felix Waldhauser's double-difference relocated Northern California catalog (Waldhauser and Schaff, 2008; http://www.ldeo.columbia.edu/~felixw/NCAeqDD/). Colored dots and the inset box show aftershocks by day after the mainshock.

Maximum coseismic displacements of > 20 cm were observed at sites DEAL and 04LG, on the west and east side of the rupture, respectively. Both sites are within 3 km of the surface rupture, whereas the nearest cGPS sites are P200 and P261, approximately 10 km to the west and south-east of the rupture, respectively. In total, 8 survey sites were re-observed and provided coseismic displacements within the distance from the rupture of the nearest cGPS sites.

With assistance from scientists from the USGS and UC Berkeley, survey sites were maintained to record continuously for three weeks or more after the earthquake to capture any post-earthquake motions. These motions accounted for an additional displacement of about 20% of the coseismic displacement at nearby sites. Surveys have continued episodically since, in October 2014 (USGS), December 2014 (USGS and UCR), and January 2015 (USGS and UCR).

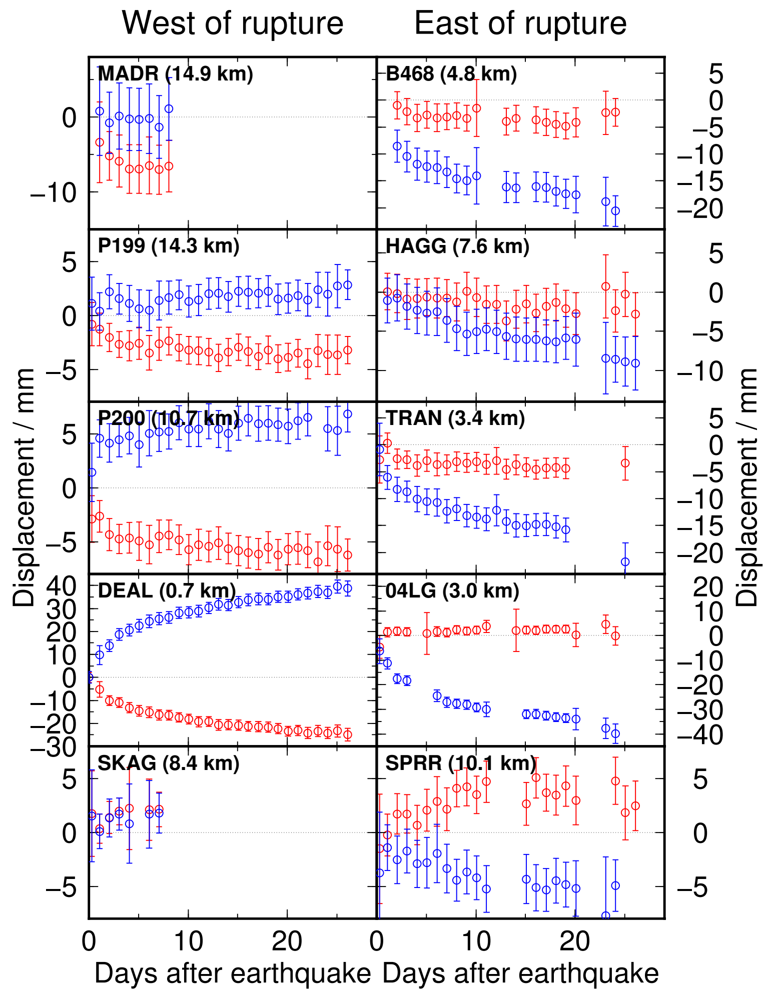

Figure 8: Time series in the immediate aftermath of the South Napa earthquake, plotted relative to each site's pre-earthquake velocity (see Figure 5), showing significant continuing post-earthquake motion at several sites. All are examples of survey sites run continuously for a few weeks after the earthquake except P199 and P200 (PBO).

5. Summary

A total of 2414 site-hours of new GPS data were acquired over 18 days of field work at 107 survey sites in the North San Francisco Bay Area of California. Additional GPS data were acquired continuously in the three weeks following the 2014-08-24 M_w6.0 South Napa earthquake, at which time the authors were serendipitously conducting a second round of field work in the North Bay region. Many of the sites re-observed had been measured during our first round of field work only seven weeks prior. The former set of data were processed along with data from 43 continuous GPS sites to refine a GPS velocity solution in the study region. The latter set of data were processed similarly, and with survey GPS data acquired in the vicinity of the earthquake between 1992 and 2009 by the USGS, to provide a means by which to constrain the coseismic displacement and immediate post-earthquake afterslip associated with the earthquake.

We demonstrate here the value of continued survey GPS measurements for fault kinematics, tectonic geophysics and earthquake hazard and response. We therefore encourage the continuation of survey GPS observations where continuous GPS networks are non-existent or sparse relative to the geophysical signal of interest (here, the slip rates of parallel strike-slip faults separated by a few locking depths).

References

Altamimi, Z., L. Métivier and X. Collilieux (2012), ITRF2008 plate motion model, *J. Geophys. Res.*, *117*, B07402, doi:10.1029/2011JB008930.

Field, E.H., Biasi, G.P., Bird, P., Dawson, T.E., Felzer, K.R., Jackson, D.D., Johnson, K.M., Jordan, T.H., Madden, C., Michael, A.J., Milner, K.R., Page, M.T., Parsons, T., Powers, P.M., Shaw, B.E., Thatcher, W.R., Weldon, R.J., II, and Zeng, Y., 2013, Uniform California earthquake rupture forecast, version 3 (UCERF3)—The time-independent model: U.S. Geological Survey Open-File Report 2013–1165, 97 p., California Geological Survey Special Report 228, and Southern California Earthquake Center Publication 1792, http://pubs.usgs.gov/of/2013/1165/.

McCaffrey, R. (2002), Crustal block rotations and plate coupling, in *Plate Boundary Zones*, *Geodyn. Ser.*, vol. 30, edited by S. Stein and J. Freymueller, pp. 101–122, AGU, Washington, D. C.

U.S. Geological Survey and California Geological Survey, 2006, Quaternary fault and fold database for the United States, accessed Apr 29, 2015, from USGS web site: http//earthquake.usgs.gov/hazards/qfaults/.

Waldhauser, F., and D. P. Schaff (2008), Large-scale relocation of two decades of Northern California seismicity using cross-correlation and double-difference methods, *J. Geophys. Res.*, *113*, B08311, doi:10.1029/2007JB005479.

2007 Working Group on California Earthquake Probabilities (2008), The Uniform California Earthquake Rupture Forecast, Version 2 (UCERF 2): U.S. Geological Survey Open-File Report 2007-1437 and California Geological Survey Special Report 203, http://pubs.usgs.gov/of/2007/1091/.

Bibliography

Elliott, J., M. Floyd, G. Funning, A. Hooper, Y. Larsen, P. Marinkovic, M. Plain, S. Samsonov, R. Walters and T. Wright (2015), Probing the 2014 Mw 6.0 South Napa (California) earthquake and postseismic deformation with Sentinel-1 InSAR and GPS, Paper 307 presented at 2015 Fringe Meeting, Frascati, Italy, 23–27 Mar.

Floyd, M., G. Funning, J. Murray, J. Svarc, T. Herring, I. Johanson, J. Swiatlowski, K. Materna, C. Johnson, O. S. Boyd, J. Sutton and E. Phillips (2014), Surface deformation before, during and after the 2014 South Napa, California, earthquake from a spatially dense network of survey and continuous GPS sites, Abstract S33F-4904 presented at 2014 Fall Meeting, AGU, San Francisco, Calif., 15–19 Dec.

Funning, G. J., M. A. Floyd, R. J. Walters, J. R. Elloitt, T. J. Wright, P. Marinkovic and Y. Larsen (2015), Complexity in the Coseismic Fault Geometry and in the Postseismic

Slip Distribution of the South Napa Earthquake, from Sentinel-1A InSAR and Near-Field GPS Data, presented at SSA Annual Meeting, Pasadena, Calif., 21–23 Apr.

Murray, J., J. Svarc, F. Pollitz, M. Floyd, G. Funning and I. Johanson (2014), Coseismic and postseismic deformation due to the South Napa earthquake inferred from modeling of Global Positioning System data, Abstract S31G-03 presented at 2014 Fall Meeting, AGU, San Francisco, Calif., 15–19 Dec.

Murray, J. R., J. Svarc, F. Pollitz, M. Floyd, G. Funning, I. Johanson and B. Brooks (2015), Coseismic and Postseismic Deformation Due to the South Napa Earthquake Inferred from Geodetic Data, Poster #113 presented at SSA Annual Meeting, Pasadena, Calif., 21–23 Apr.

Wright, T. J., J. R. Elliott, R. J. Walters, A. J. Elliott, M. Floyd, G. Funning, P. J. Gonzalez, A. J. Hooper, Y. Larsen, P. Marinkovic and M. Plain (2014), Co- and Post-Seismic Deformation for the 2014 South Napa Valley Earthquake from Sentinel-1A Interferometry, Abstract S33F-4902 presented at 2014 Fall Meeting, AGU, San Francisco, Calif., 15–19 Dec.

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