2013 SCEC Project Report

Project #13071
Transient Detection using PBO data with contributions to the CGM

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Abstract

We are undertaking two main tasks in this SCEC grant: (1) Development of transient signal detection methods and (2) analyses for the Community Geodetic Model (CGM). For the transient detection development we have submitted our algorithms to the Colaboratory for the Study of Earthquake Predictability (CSEP) and they are now running operationally. For the CGM contribution we are continuing analyses of functional or physical parameters associated with time-dependent motions in southern California and to begin action towards data collation for the CGM.

We contributed to a first geodetic publication on the El Mayor-Cucapah earthquake using survey data from within Mexico (Gonzalez-Ortega et al., 2014). The data used for this have also been collected, verified and processed here for further analysis through physical modeling. This allows long-term background motions to be better known, from which superimposed transient events may be detected even in the presence of post-seismic motion. Furthermore, the handling of these survey data demonstrates the necessary action required moving forward with the CGM.

In anticipation of the CGM reaching beyond the simple presentation of geodetic velocities to some form of kinematic model, and following the work of Smith-Konter et al. (2011), we have approached the problem of relatively shallow geodetically-derived fault locking depths and their appropriate interpretation within the framework of the earthquake cycle and recurrence times. This work explores conditions under which that velocity profiles across faults invert to give shallow locking depths using the common Savage and Burford (1973) formulation, despite synthetic input having slip deficit accumulate that estimated depth. We suggest that direct interpretation may lead to moment accumulation rate being underestimated and recurrence times being overestimated (by up to a factor of two) in cases where the fault does not behave in the simple, homogeneous, fully-locked manner described by this model.

Technical Report

Data processing and modeling of post-seismic motions following the 2010-04-04 M_w7.2 El Mayor-Cucapah earthquake

One aspect of the ability to detect transient motions is knowledge of the background rates of motion. Since the M_w7.2 El Mayor-Cucapah earthquake in April 2010, a major change in geodetic velocities has occurred in the presence of post-seismic deformation that has perturbed previously known motions. An accurate model of these changes in velocity is therefore required.

Survey GPS measurements in the aftermath of this earthquake have continued through other SCEC-funded projects (e.g. #11075, #12204). These measurements to date have now been processed and preliminary analysis on the time series has contributed to the publication of Gonzalez-Ortega et al. (2014).

M Floyd has continued efforts to collate all GPS data, and has verified the associated metadata that have been acquired since the El Mayor-Cucapah earthquake with collaborators at UC Riverside (G Funning), UC San Diego (Y Fialko, D Sandwell and E Lindsey), and CICESE (A Gonzalez-Ortega and J Gonzalez-Garcia) for inclusion in either the SCEC or, more likely, publicly available UNAVCO archive.

We have also completed data processing and time series generation using these data. This activity, within the scope of this SCEC project, has ensured that the most accurate set of time series is available. More advanced physical modeling accounting for the spatial correlation of the observations and putting them in the context of physical driving mechanisms may now be undertaken. Ultimately, such physical models, including secular fault motions, may provide a basis for the Community Geodetic Model (CGM) and facilitate the identification of deviations that would be attributed to transient events. We anticipate such physical modeling to proceed within this goal in mind.

The Community Geodetic Model

T Herring and M Floyd attended and both gave presentations at the CGM Workshop in Menlo Park in May 2013. M Floyd also attended the Community Stress Model (CSM) Workshop immediately preceding it. Both participated in the CGM break-out session at the 2013 SCEC Annual Meeting in Palm Springs.

A collation and verification exercise similar to that described above for the El Mayor-Cucapah post-seismic data must be undertaken for all survey GPS data that has been acquired in southern California (and beyond) before rigorous reprocessing or combination of all available results is possible. We have liaised with other groups in the CGM (GPS) community to agree that this target be reached in the upcoming year.

This systematic collation of survey GPS measurements for the CGM will provide a number of benefits to SCEC researchers and the community at large. The SCEC GPS database has not been completely updated for over five years when the Crustal Motion Model (CMM) was last revised (Shen et al., 2011). Many surveys have been undertaken since, including such measurements as those taken in Baja

California as part of the El Mayor-Cucapah post-seismic observations. We identified sites within southern California that, to the best of our knowledge, have only been occupied once (see Figure 1). This information was presented to and shared with SCEC collaborators to form the basis of proposed target areas for immediate further data acquisition.

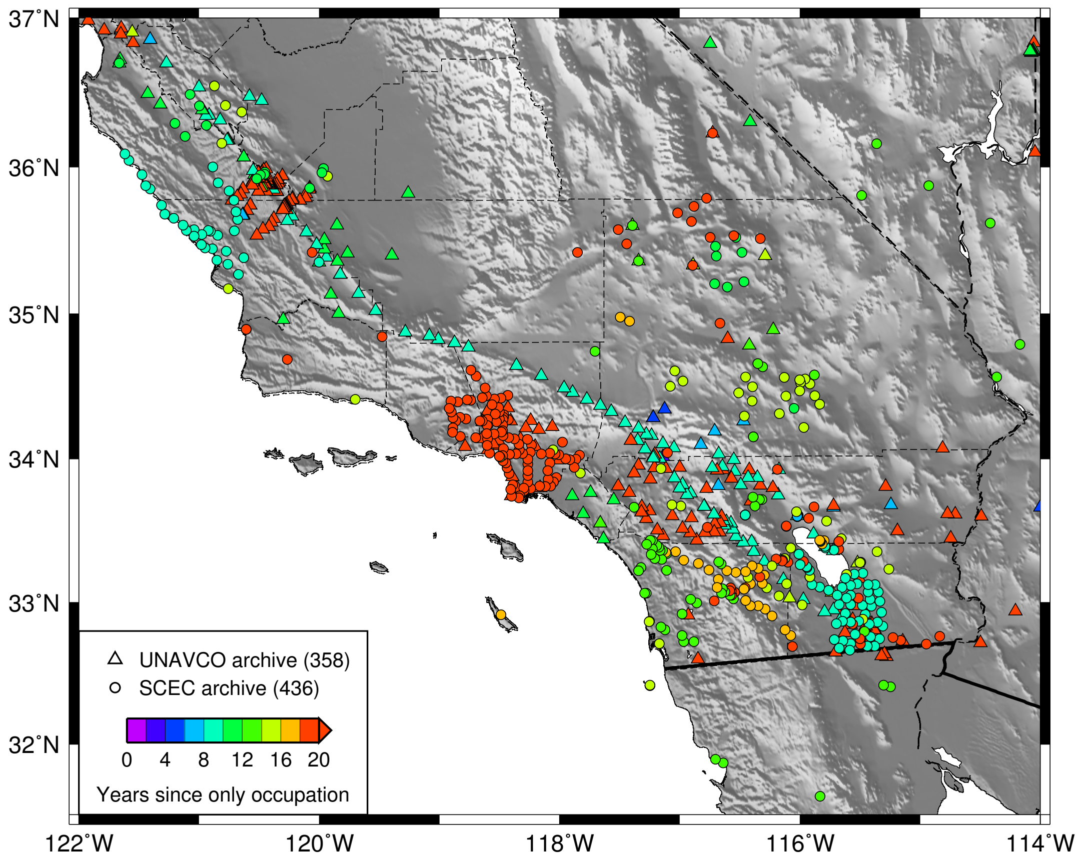

Figure 1: Survey GPS marks that have only been measured once, according to the SCEC GPS database and other, publicly accessible archives. Many of these sites have in fact been occupied multiple times and may therefore provide geodetic velocities. A primary goal of future CGM work is to identify such sites and archive or process the available data. The other, truly single-occupation sites constitute viable and immediate targets for further geodetic measurement.

We have also undertaken some simple analyses that we anticipate will ultimately be useful when analysing the data of the CGM by inversion to estimate parameters pertinent to the earthquake cycle. Such parameters that the UCERF version 2 and recent version 3 models ultimately provide as a framework for research and seismic hazard assessment models are fault slip rates, locking depths and "aseismic factors", which must be estimated and correctly interpreted when constructing such analyses. There is a recognized discrepancy between locking depth that is determined seismologically versus that determined geodetically (e.g. Smith-Konter et al., 2011).

We have performed a set of synthetic experiments that use Savage and Burford's (1973) arctangent function to estimate fault slip rate and locking depth by inverting synthetic profiles of GPS velocities perpendicular to a vertical strike-slip fault with a given (uniform or variable) slip deficit profile with depth. This model implicitly assumes that a fault is completely locked and accumulates slip deficit uniformly at the far-field fault slip rate down to the locking depth. For our input slip deficit rates, the depth below which a fault does not accumulate slip (and therefore moment) deficit may be considered the locking depth.

The inversions show that fault slip rate is generally well recovered with an adequate coverage of geodetic velocity measurements. However, any violation of the classic model tends to manifest itself in a shallower locking depth than the depth to which some slip deficit accumulates in the input. If creep very near the surface dominates the slip deficit accumulation profile with depth, this result is exacerbated. Such an effect is also seen as a consequence of strain localization near faults due to, for example, compliant zones. Nevertheless, locking depth estimated by inversion of the GPS data has a positive correlation with effective coupling coefficient (here defined as the ratio of depth-averaged slip deficit rate and far-field fault slip rate): if the effective coupling coefficient reduces, the estimated locking depth is shallower. Comparison of the input moment deficit rate (per unit along strike) versus that expected from the estimates of fault slip rate and locking depth as in the model definition (slip rate x locking depth x elastic modulus) shows that the moment deficit rate is still generally estimated between a factor of 0.5 and 1 of the input. The consequence of this underestimation is that the expected recurrence interval of an earthquake of a given magnitude may be overestimated by up to a factor of 2. This is in agreement with the conclusions of Smith-Konter et al. (2011).

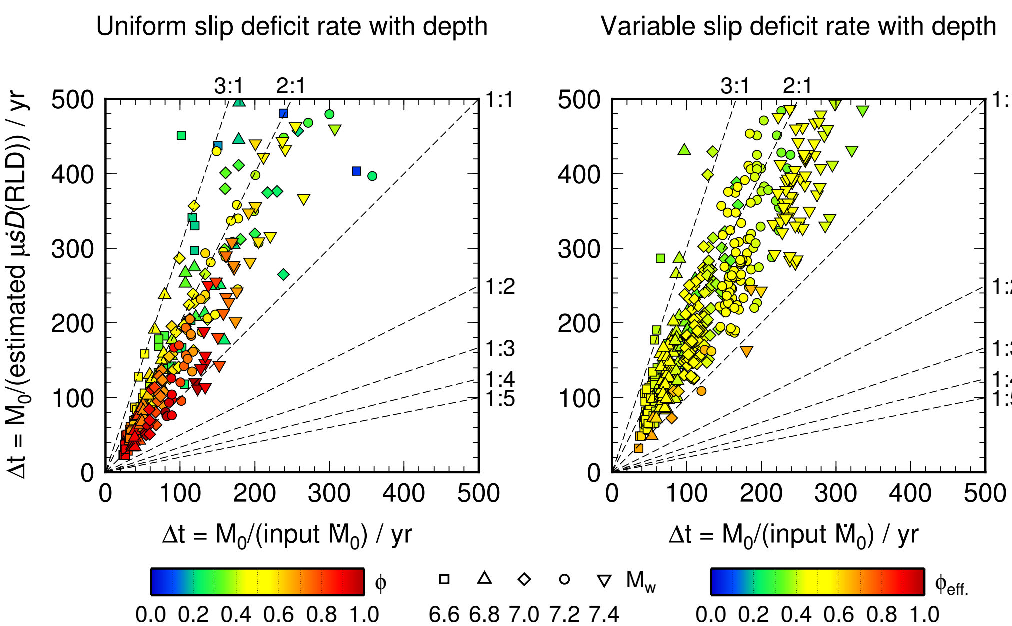

Figure 2: Estimated versus input recurrence times for various magnitudes of earthquake (symbol shape) and effective coupling coefficients (symbol color). The

input recurrence time is the seismic moment of a given magnitude earthquake divided by the input moment deficit rate. The estimated recurrence time is the seismic moment divided by the moment deficit rate using the estimated fault slip rate and estimated locking depth. Both quantities use the same rupture length quantity ("RLD") determined from the Wells and Coppersmith (1994, Table 2A) relationship to moment magnitude in the calculation of moment deficit rate. The same relationships would hold, per unit along strike, without using this factor.

This result has two key implications: First, the way in which we interpret and discuss locking depth estimated from geodetic data using a simple elastic dislocation model must be more carefully considered; Second, regardless of a debate over appropriate physical interpretation, a straightforward inversion and direct interpretation may introduce an error of up to about a factor of 2 on the estimate of recurrence interval. A corollary of this is that it may be possible, given the relationship between effective coupling coefficient and locking depth, that an additional constraint on locking depth from, for example, seismology may be employed to estimate the slip/moment deficit accumulation rate relative to the far-field rate. All of these quantities are important in various ways for constraining models of fault system kinematics and the conversion of geodetic observations, such as those coming from the Community Geodetic Model, to seismic hazard assessment models, including UCERF.

Transient detection

Our transient detection algorithms are running operationally within the CSEP framework. They are currently detecting the end of an Episodic Tremor and Slip (ETS) event in Northern California here the repeat period is 230-240 days, uplift in Long Valley and a small signal in the Parkfield region that may be due to creep on the San Andreas fault. The Northern California ETS are interesting in that the near periodic behavior provides a method for monitoring the automatic detection scripts. In Figure 3 we show the CSEP detection output figure for region. However, there is another transient signal in this region that the current algorithms, which are targeted at shorter period phenomena, are not detecting. The long period transient (and the shorter ETS one) can be seen in Figure 4. In both the north and height coordinates we see an approximately 7-year period oscillation with amplitude of 2 and 6 mm in each component. This long period signal is not apparent on the east coordinate. Other sites in the region with long spans of data also show long period variations but with different amplitudes. These longer variations area possibly artifacts of long term stability of the reference frame we are using to define motions in California or they could be representative of a long term variations which changes in ground water use being one possible explanation. We will be exploring these variations more thoroughly as we combine data from different regions.
The Parkfield transient that we are now just starting detect is difficult to see in the time series and we will be monitoring it to see how it develops. The current detection is shown in Figure 5.

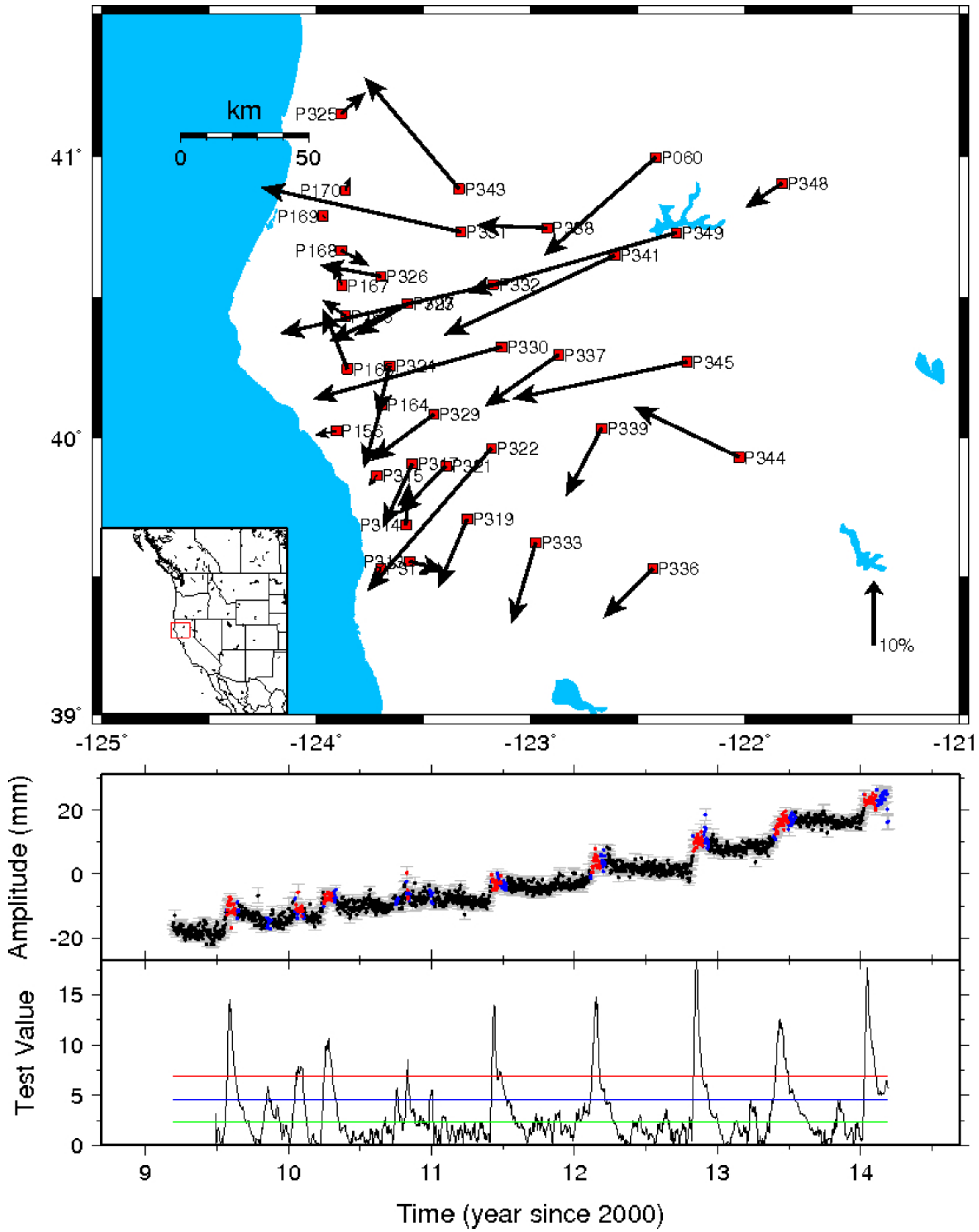

Figure 3: Example of the near real-time transient detection algorithm called the Targeted Projection Operator (TPO) applied to episodic tremor and slip (ETS) events in northern California. The top frame shows the spatial pattern being detected and the bottom frames show the time evolution and statistical chi-square test on the existence of the pattern. This case is useful for evaluating the algorithms since the ETS events repeat in a periodic fashion.

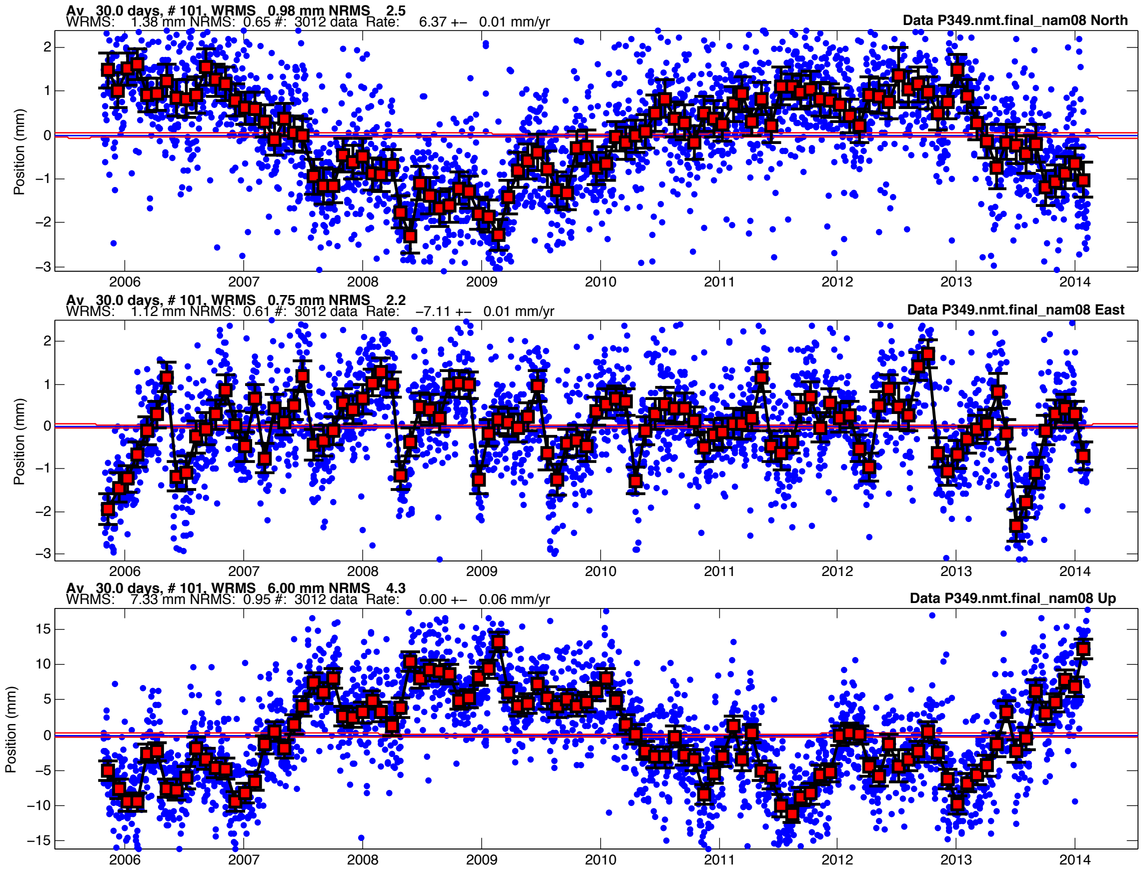

Figure 4: Residual time series for PBO site P349 in Northern California. 30-day average values are shown as red symbols to more clearly show the patterns in the residuals. The east component clearly shows the 232-day period ETS signal (see amplitude spectrum in Figure 5) with a new event starting at the beginning of 2014. There is also a very evident multiyear signal in north and east that represents a transient signal at much longer times scales (annual signals with amplitudes of 0.8, 0.3 and 8.0 mm have been removed from the residuals).

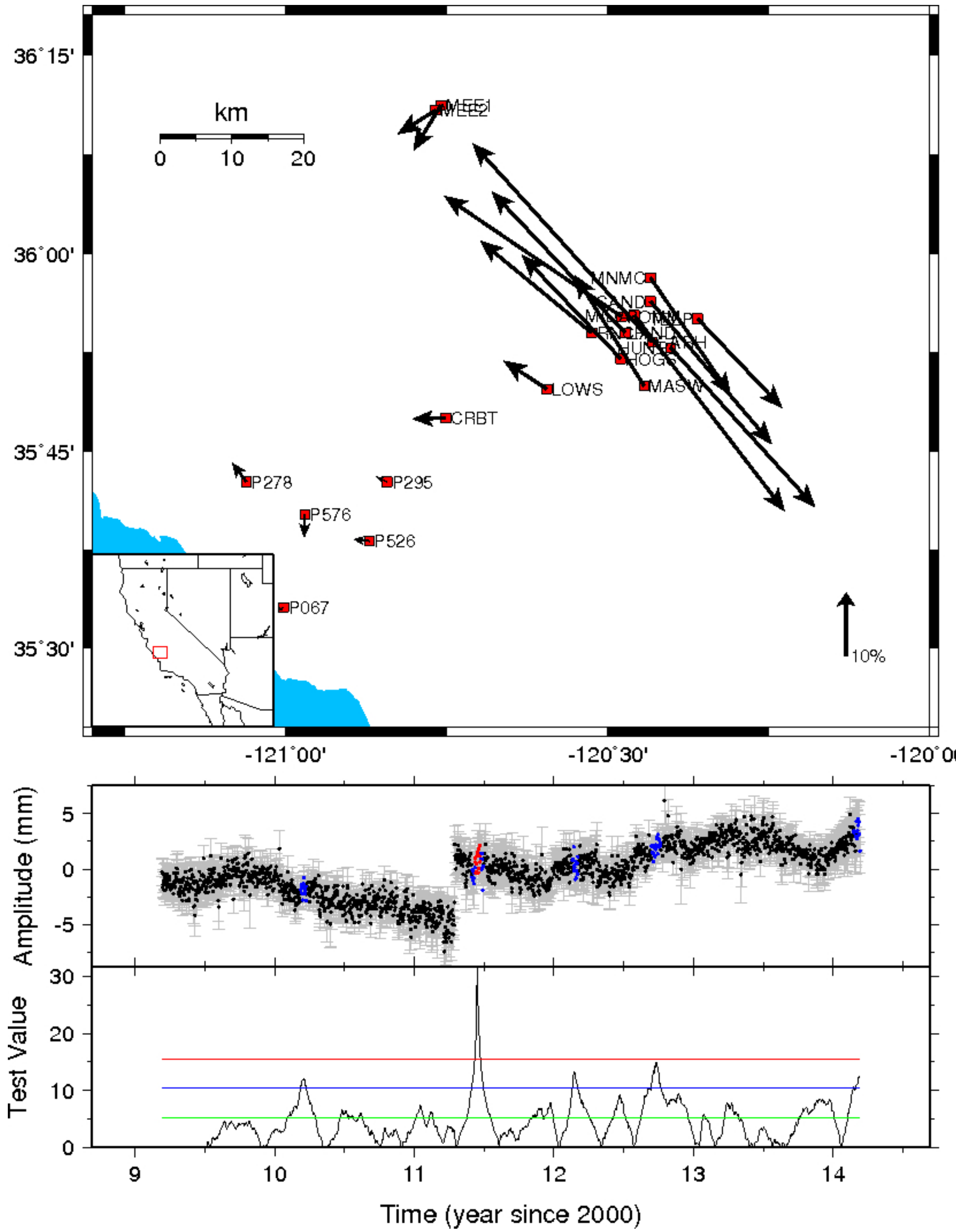

Figure 5: Parkfield transient that has just started. The projection operator matches the post-seismic deformation pattern after the Sept 28 2004 Parkfield earthquake.

Intellectual Merit & Broader Impacts

Our research is contributing to the transient signal detection and the development of the Community Geodetic Model. These activities are targeted at developing an understanding of the complex deformation modes California and the relationship of this deformation to earthquake occurrence.

The accurate modeling of post-seismic motions surrounding the 2010-04-04 El Mayor-Cucapah earthquake has profound implications in two key areas.

First, regarding this research specifically, short-period transient motions may not be confidently detected if longer term motions are not adequately known, especially in the presence of time-variable motions. The proximity of several creeping faults in the Imperial Valley and geothermal sources such as the Salton Sea north of the US-Mexico border and Cerro Prieto south of the border must be determined within the framework of the broader time-dependent motions in the aftermath of the El Mayor-Cucapah earthquake.

Second, more generally, the El Mayor-Cucapah earthquake represents a unique perspective on post-seismic motions in a region of tectonic transition, from pure strike-slip in the north to that with an increasing component of extension in the south, combined with a thinner crust and higher geothermal gradient. The relaxation and dispersion of stresses induced by the earthquake over time must continue to be measured and analysed to understand how the stresses on faults to the north of the rupture's termination are changing and whether this may promote or inhibit future rupture initiation in those areas.

Both areas of research contribute to our understanding of and eventual ability to monitor crustal motions in California in real-time or near real-time. The project continues to engage and foster close collaborations our community's neighbors in Mexico.

Publications

Gonzalez-Ortega, A., Y. Fialko, D. Sandwell, F. A. Nava-Pichardo, J. Fletcher, J. Gonzalez-Garcia, B. Lipovsky, M. Floyd, G. Funning (2014), El Mayor-Cucapah (M_w 7.2) earthquake: Early near-field postseismic deformation from InSAR and GPS observations, *J. Geophys. Res.*, doi:10.1002/2013JB010193.

Ji, K. H. and T. A. Herring, Testing Kalman Smoothing/PCA Transient Signal Detection Using Synthetic Data, *Seismol. Res. Letters*, May/June 2013, *84*, 433-443, doi:10.1785/0220120155, 2013.
http://srl.geoscienceworld.org/content/84/3/433.full.pdf+html?sid=089502f6-6d45-4004-887b-2ebef5b8cbc2

References

Savage, J. C. and R. O. Burford (1973), Geodetic Determination of Relative Plate Motion in Central California, *J. Geophys. Res.*, 78, 832-845.

Shen, Z.-K., R. W. King, D. C. Agnew, M. Wang, T. A. Herring, D. Dong and P. Fang (2011), A unified analysis of crustal motion in Southern California, 1970–2004: The SCEC crustal motion map, *J. Geophys. Res.*, 116, B11402, doi: 10.1029/2011JB008549.

Smith-Konter, B., D. T. Sandwell and P. Shearer (2011), Locking depths estimated from geodesy and seismology along the San Andreas Fault System: Implications for seismic moment release, *J. Geophys. Res.*, 116, B06401, doi:10.1029/2010JB008117.

Wells, D. L. and K. J. Coppersmith (1994), New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement, *Bull. Seismol. Soc. Amer.*, 84, 974-1002.