Multidisciplinary exploration for slow aseismic slip and low-frequency earthquakes in the Anza Gap (San Jacinto fault zone)

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Investigators: Roland Bürgmann (UCB), William Frank (USC), Baptiste Rousset (UCB)

I. Project Overview

A. Abstract

In the box below, describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the abstract. (Maximum 250 words.)

We used a multidisciplinary approach to systematically search for slow aseismic transient slip in the Anza Gap of the San Jacinto fault zone using continuous geodetic and seismic datasets. The spatial and temporal distribution and evolution of aseismic transients is essential information to understand whether long-term tectonic strain in the Anza Gap is building up to a future large (M > 7) earthquake, or if a significant amount of strain is released aseismically. Recent work has identified both aseismic transients and triggered tectonic tremor in the Anza Gap following significant regional and local earthquakes [Chao et al., 2012; Wang et al., 2013; Inbal et al., 2017]. We build on these studies by independently searching in the continuous geodetic data for slow slip and in the continuous seismic data for low-frequency earthquakes, the principal constituent of tectonic tremor.

B. SCEC Annual Science Highlights

Each year, the Science Planning Committee reviews and summarizes SCEC research accomplishments, and presents the results to the SCEC community and funding agencies. Rank (in order of preference) the sections in which you would like your project results to appear. Choose up to 3 working groups from below and re-order them according to your preference ranking.

Fault and Rupture Mechanics (FARM)

Tectonic Geodesy

Stress and Deformation Through Time (SDOT)

C. Exemplary Figure

Select one figure from your project report that best exemplifies the significance of the results. The figure may be used in the SCEC Annual Science Highlights and chosen for the cover of the Annual Meeting Proceedings Volume. In the box below, enter the figure number from the project report, figure caption and figure credits.

Figure 3: Repeats of the low-frequency earthquake (LFE) triggered by the 2002 Denali Earthquake, identified by Wang et al. [2013], and its time-reversed copy. The recurrence intervals are measured as the time between sequential repeats. The time-reversed waveforms were used to establish what threshold should be used to minimize the number of false detections (false positives). The dashed line indicates the timing of the 2002 Denali Earthquake. Clustered activity (short recurrence intervals) is a characteristic feature of LFEs [Frank et al., 2016], but is not observed here.

D. SCEC Science Priorities

In the box below, please list (in rank order) the SCEC priorities this project has achieved. See *https://www.scec.org/research/priorities* for list of SCEC research priorities. *For example: 6a, 6b, 6c*

This work address science objectives (P1.a) geodetic measurements to constrain fault-based deformation models, (P2.a) what fraction of seismic moment accumulation is relaxed by aseismic processes and (P1.e) how the stress transfer among fault segments depends on time and to what degree inelastic processes contribute to stress evolution.

E. Intellectual Merit

How does the project contribute to the overall intellectual merit of SCEC? *For example: How does the research contribute to advancing knowledge and understanding in the field and, more specifically, SCEC research objectives? To what extent has the activity developed creative and original concepts?*

By searching for transient deformation signals both on seismic and geodetic continuous records, this study aims at better characterizing the spatio-temporal variations of slip and stress on faults, and particularly on the Anza segment of the San Jacinto fault. The spatial and temporal distribution and evolution of aseismic transients is essential information to understand whether long-term tectonic strain in the Anza Gap is building up to a future large (M > 7) earthquake, or if a significant amount of strain is released aseismically.

F. Broader Impacts

How does the project contribute to the broader impacts of SCEC as a whole? *For example: How well has the activity promoted or supported teaching, training, and learning at your institution or across SCEC? If your project included a SCEC intern, what was his/her contribution? How has your project broadened the participation of underrepresented groups? To what extent has the project enhanced the infrastructure for research and education (e.g., facilities, instrumentation, networks, and partnerships)? What are some possible benefits of the activity to society?*

The project provided support for a master student at USC. She is now a PhD student at Universität Bern (although no longer in seismology…).

G. Project Publications

None yet related to that particular project.

II. Technical Report

A. Context and Objectives

Despite being in the middle of the most seismically active region of the San Andreas plate boundary, the Anza Gap of the San Jacinto fault zone has not ruptured during a large (M > 7) earthquake for more than 200 years [Sanders and Kanamori, 1984]. Long-term geological and geodetic observations estimate 19 mm/yr of tectonic motion over the system of faults within the Anza Gap [Lindsey and Fialko, 2013], strongly suggesting low seismic coupling and that aseismic slip plays a role in accommodating the tectonic strain. Because estimates of locking depth from interseismic InSAR and GPS velocity fields are dependent on the poorly constrained fault zone shear modulus [Lindsey et al., 2014], the depth of aseismic slip is highly uncertain. These long-term estimates are also unable to constrain whether aseismic creep occurs in a continuous or episodic fashion [e.g. Avouac, 2015]. The recent discovery of transient slow slip events along the San Andreas fault [e.g. Linde et al., 1996], the North Anatolian Fault [Rousset et al., 2016] and in subduction zones around the world [e.g. Dragert et al., 2001] would argue for episodic, and not continuous, slow slip as an important driver behind long-term estimates of aseismic deformation. With the Anza Gap playing a key role with regards to a potential M > 7 rupture extending through the entire San Jacinto fault zone [Salisbury et al., 2012], there is an important need for high temporal resolution observations of slow transients to understand the rheology and the mode of fault slip within the Anza Gap. In this study, we continuously searched for low frequency earthquakes in the seismological records and transient signals associated with slow fault slip in geodetic time series (Figure 1).

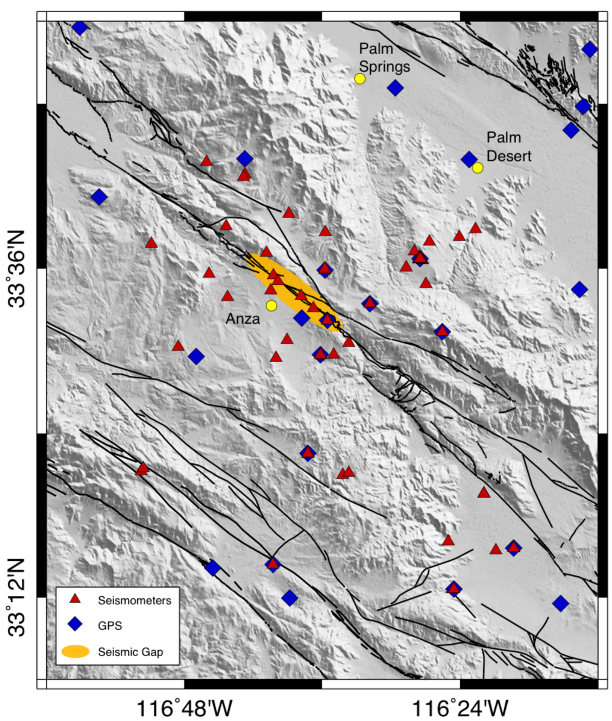

Figure 1: *Map of the seismometers (red triangles) and continuous GPS (blue diamonds) networks around the Anza Gap in the San Jacinto fault zone. The Anza Gap along the Clark fault in the San Jacinto fault zone, indicated by the yellow ellipse, exhibits long-term slip rates of ~ 19 mm/yr and could potentially be a bridge to link the San Jacinto fault zone together in a future M > 7 earthquake.*

B. Seismic analysis of past tremor "sightings" (Frank and Cesar)

A master's student from Grenoble (France), Camila Cesar, spent 4 months at USC for her Master's research project to analyze the tectonic tremor reported by Hutchison and Ghosh [2017] (HG2017 from here on). The objective was to determine whether there were repetitive low-frequency earthquakes (LFEs) within the tremors. If this were the case, we would then be able to use these LFEs as templates to scan the continuous seismic data for repeats of the same LFE sources.

We started the study by reproducing the figures of the seismic waveforms presented in HG2017 to attempt to visually identify impulsive LFEs within the tremor; this approach has been successful in detecting LFEs in both Parkfield, California [e.g. Shelly, 2017] and Guerrero, Mexico [Frank et al., 2013]. Despite discovering one of the figures in HG2017 was mislabeled, we were unable to identify any obvious impulsive arrivals within the tremor waveforms.

Given that LFEs are repetitive, even within the same tremor burst [Frank et al., 2014], we then pursued a brute force approach to detect any repetitive signal within all the reported tectonic tremors. We divied up the waveforms of each reported tectonic tremor (of which there are five) into 5 second windows. Using a matched-filter search [Gibbons and Ringdal, 2006], we then used each of these windows as a template to scan all of the tectonic tremor waveforms. The template waveforms are correlated with the continuous seismic data at all time steps; the correlation coefficients at each time step are then summed across the network. Figure 2 shows an example of two different potential templates where there are no detections beyond the templates themselves.

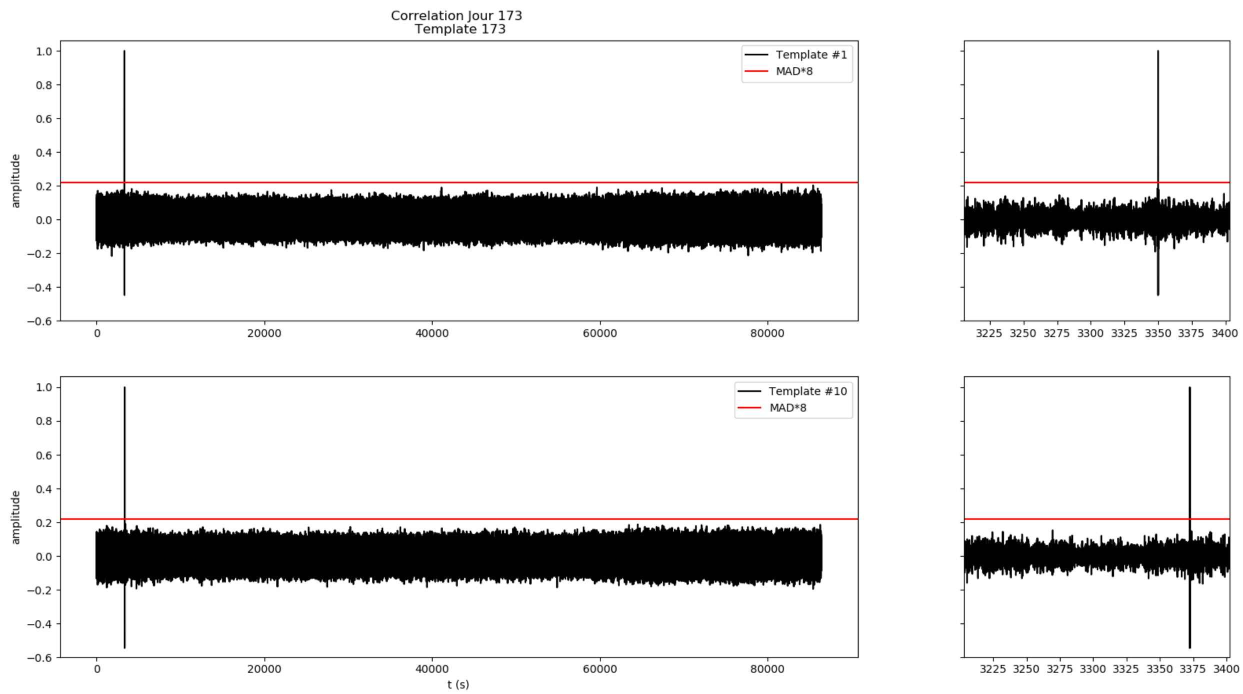

Figure 2: *Correlation coefficient sums (normalized to 1) for June 22, 2011; HG2017 identified a tremor between 3225 and 3375 seconds (right panels). The top panels represent the template derived from the first 5 second window of the reported tremor; the bottom panels represent the template derived from the last 5 second window. We use a typical correlation threshold (red line) of eight times the median absolute deviation (MAD). We have found no repetitive waveforms within the reported tremors; this is unexpected for tremor as their constituent LFEs consistently repeat during tremor. Modified after Cesar [2018].*

In the interest of producing “positive” results for Camila’s Master’s project, we changed tack to investigate the tectonic tremor triggered by the 2002 Denali earthquake in Anza reported by Wang et al. [2013] (W2013). The waveforms of Figure 5 from W2013 show a likely LFE, and we used these waveforms as a template to scan the HG2017 tremors; we limited the analyzed stations to those that were active both in 2002 and 2011 and did not undergo any significant instrument changes. This approach would only work if the potential tremor source in 2011 is located close to the LFE source triggered by the 2002 Denali earthquake; the seismic network must also remain relatively stable. Unfortunately, the Denali-triggered LFE was not significantly well correlated with any of the waveforms within the tremors reported by HG2017.

Camila then wrote up her Master's thesis, and successfully defended her Master's project in June in Grenoble. She started as a PhD student at Universität Bern in planetary geophysics in September 2018.

As a last step after Camila left, we extended the matched-filter search with the Denali triggered LFE template to 15 years of continuous data, from 2002 to the end of 2016. To establish a reasonable correlation threshold for identifying repeats, we followed the approach of Slinkard et al. [2014]: a time-reversed copy of the template waveforms is used to determine how often false detections occur for a given threshold. Figure 3 shows the catalog of detections for two different thresholds. Given the number of detections by the time-reversed template, which are considered to be false positives, a more reasonable threshold of 10 times was chosen. With this stricter threshold, however, the pattern of "robust" detections is not suggestive of LFE activity, which is tightly clustered in time [Frank et al., 2016].

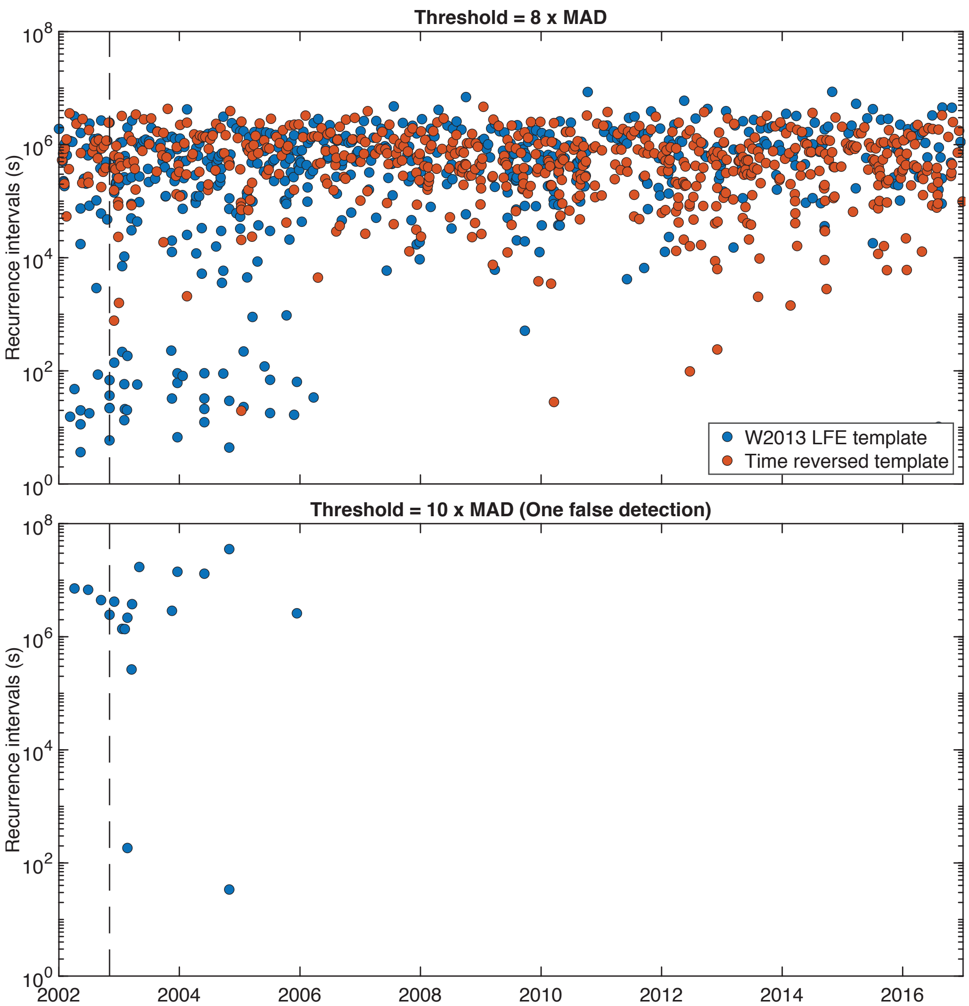

Figure 3: *Repeats of the low-frequency earthquake (LFE) triggered by the 2002 Denali Earthquake, identified by Wang et al. [2013], and its time-reversed copy. The recurrence intervals are measured as the time between sequential repeats. The time-reversed waveforms were used to establish what threshold should be used to minimize the number of false detections (false positives). The dashed line indicates the timing of the 2002 Denali Earthquake. Clustered activity (short recurrence intervals) is a characteristic feature of LFEs [Frank et al., 2016], but is not observed here.*

From this initial seismic analysis, we conclude: (i) there is little evidence to support that the HG2017 tremors resemble "typical" tectonic tremors (this corroborates the results of Inbal et al. [2017]); and (ii) the tremor and LFE source triggered by the Denali earthquake did not generate repetitive seismicity since 2002. We maintain that this is an initial analysis, and while not as promising as we would hope, a more systematic analysis might be more successful in detecting tremor and LFEs and could be the subject of a follow-up project.

C. Analysis of transient events in the GPS time series

We post-processed the GPS PBO level 2b combined solutions recorded at 30 stations around the Anza gap. We corrected for the co- and post-seismic signals associated to the 1999 Hector Mine and the 2010 El mayor Cucapah earthquakes. Two month-long transient signals with amplitudes of about 1 cm are clearly emerging in 2014 and 2015 (Figure 4). These transient signals are not associated with slip on the San Jacinto fault because the displacement is homogeneous at the scale of the network we analyzed. It also doesn't seem to coincide with a seasonal hydrological loading. The origin of these transients remains unclear.

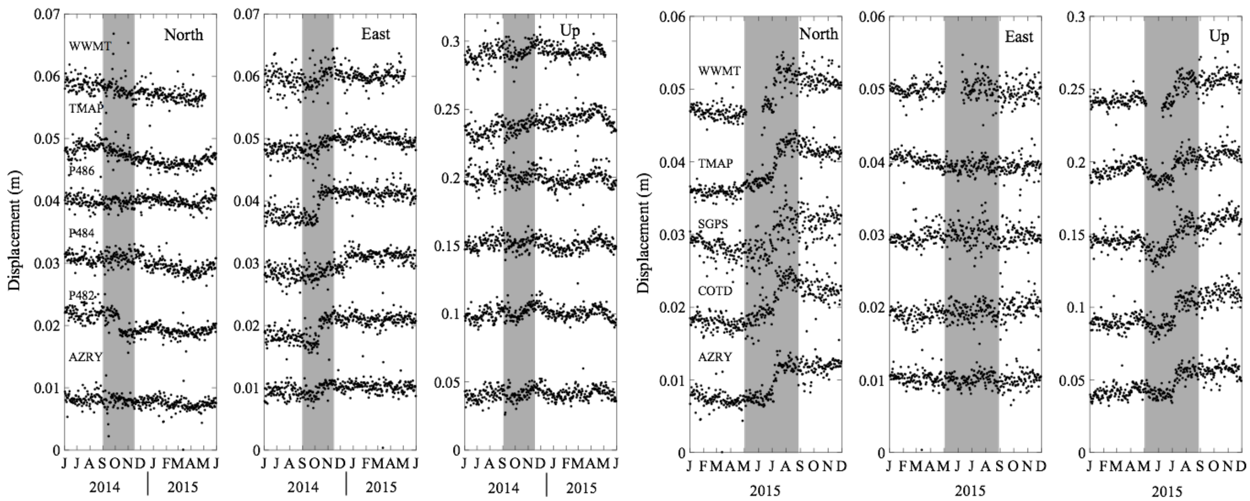

Figure 4: *Non-tectonic transient events observed in GPS time series. In October 2014 (left) and May to July 2015 (right), transient signals with amplitudes of about 1 cm are observed all other the GPS network.*

We then computed the synthetic templates for 600 4 km^2 patches located from 0 to 30 km depth. We performed the normalized and weighted correlation analysis between the synthetic templates and the post-processed GPS time series [rousset et al., 2017]. The output correlations don't present clearly emerging amplitudes from the noise level (Figure 5a). One of the highest amplitude (June 2010) coincides with timing of the nearby Mw 5.4 Collins Valley earthquake that is already known to have triggered a transient slow slip event at 15 km depth on the southern edge of the Anza gap [Inbal et al., 2017]. The location of the highest correlation amplitudes is consistent with the slip inverted by Inbal et al., [2017] (Figure 5b).

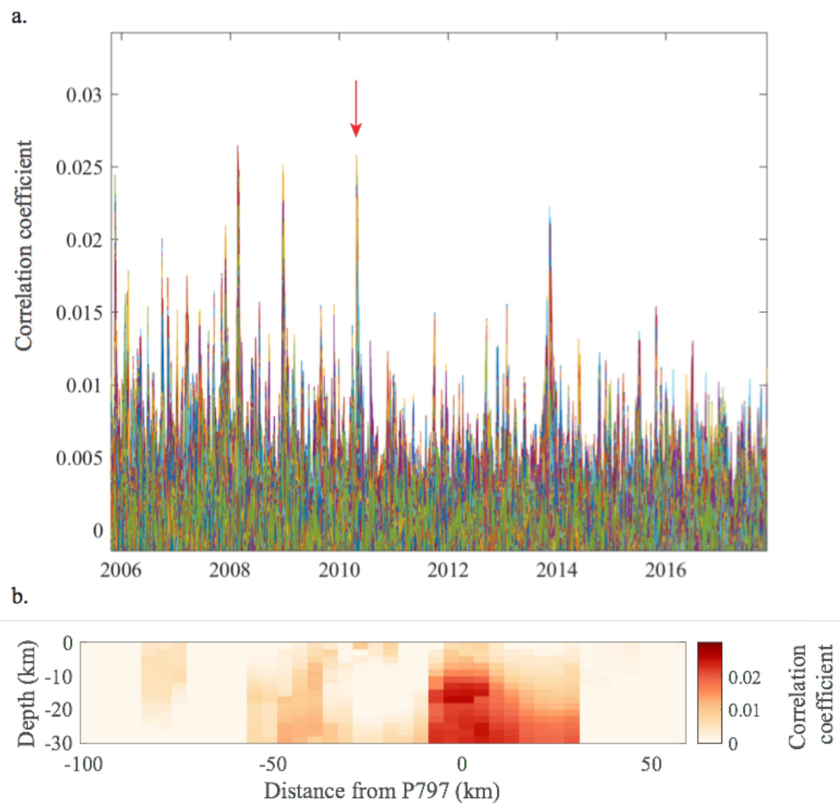

Figure 5*: Geodetic matched filter analysis. (a) output from the correlation between post-processed GPS time series and synthetic dislocation slip models. The different colors indicate different patches. (b) Amplitude of the correlations on the fault plane June 12th 2010, as indicated by the red arrows in a.*

D. References

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