Triggered and spontaneous slow slip transients on the Anza segment of the San Jacinto fault zone, southern California

Heather R. Shaddox[1]; Susan Y. Schwartz[1]; Noel M. Bartlow[1,2]

[1]University of California-Santa Cruz, Santa Cruz, CA, USA; [2]University of Kansas, Lawrence, KS, USA

Contact: Heather Shaddox (hshaddox@ucsc.edu)

INTRODUCTION

Slow slip transients have been triggered on the Anza Segment of the San Jacinto fault (SJF) by local moderate-sized local earthquakes. There have been 4 Mw > 4.5 earthquake since 2010.

Question 1. Can we detect additional triggered or spontaneous slow slip transients by combining borehole strainmeter (BSM), general seismicity, and burst-type repeating earthquake data?

Question 2. How important are moderate-sized local earthquakes for triggering slow slip?

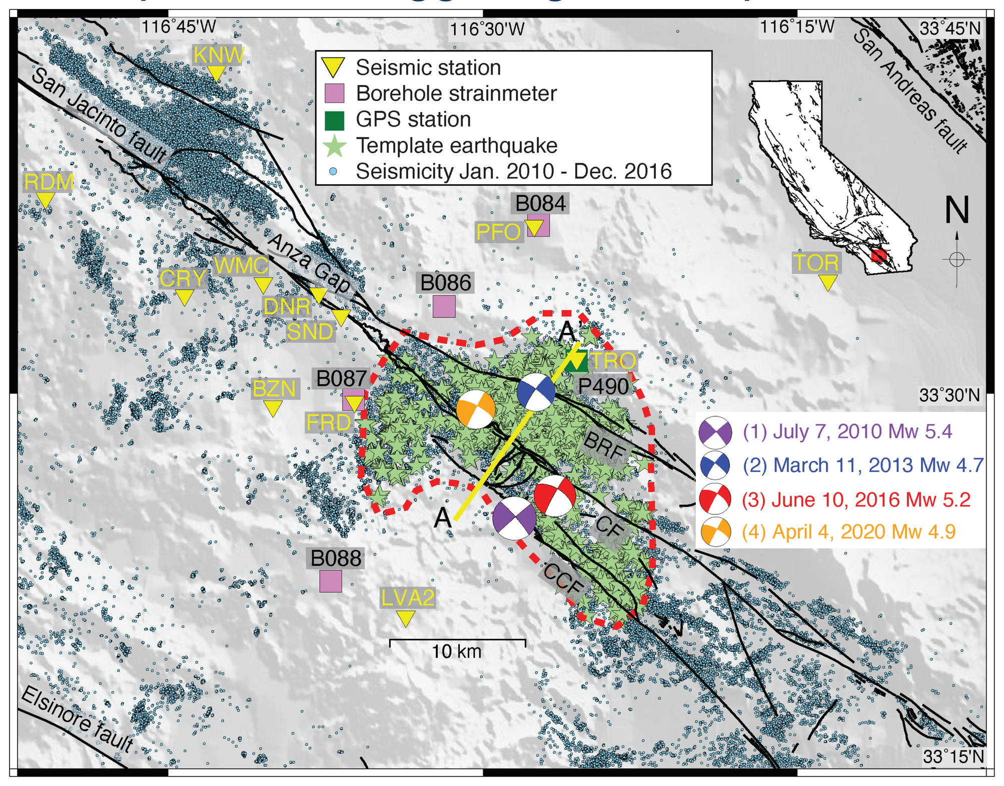


Figure 1. Seismicity map of the trifurcation area of the SJF near Anza in southern California. Focal mechanisms of the Mw 5.4 July 7, 2010 (1; purple), Mw 4.7 March 11, 2013 (2; blue), Mw 5.2 June 10, 2016 (3; red), and Mw 4.9 April 4, 2020 (4; orange) earthquakes are shown. The study region is outlined by the red dashed line. CCF – Coyote Creek fault; CF – Clark fault; BRF – Buck Ridge fault. Profile of repeating earthquakes and seismicity along cross-section A-A' during triggered slow transients is shown in Figure 4.

Background: The SJF is one of three main faults in the SAF system in southern California and is the most seismically active. The Anza seismic gap is the 20 km locked section of the SJF centered near Anza that is thought to be capable of a large (~Mw 7) earthquake. Future earthquake rupture of the Anza gap is likely to start on either end of this locked zone, thus it is important to understand fault behavior just outside of the Anza gap where there is a locking transition. Southeast of the Anza gap the SJF is referred to as the trifurcation area since it splays into three sub-parallel strands (Fig. 1). Four Mw>4.5 earthquakes occurred in the trifurcation area from 2010-2020: Mw 5.4 July 7, 2010; Mw 4.7 March 11, 2013; Mw 5.4 June 10, 2016; Mw 4.9 April 4, 2020 (Fig. 1). Seismicity in the trifurcation area of the SJF extends to 17 km depth, inconsistent with the geodetic locking depth of 10.4 +/- 1.3 km (Lindsey et al., 2014). One possible explanation for the disparity between the seismic and geodetic locking depths is a zone of deep creep driving deep microseismicity beneath the locked upper 10 km (Wdowinski, 2009). Another explanation for the shallow geodetic locking depth is the existence of a transitional region with spatially heterogeneous frictional properties, resulting in ubiquitous but intermittent slow slip transients below the locked zone (Jiang & Fialko, 2016). Inbal et al. (2017) identified deep (>10 km locking depth from Lindsey et al., 2014) aseismic slip on the SJF near Anza following the local July 7, 2010 local Mw 5.4 earthquake. Agnew et al. (2013) also identified a strain transient in this region following the March 11, 2013 local Mw 4.7 earthquake. Each of these transients were identified on borehole strainmeters (BSMs) and appear to increase with log(time). Cataloging and quantifying these deep slow slip transients is important for understanding the interplay of seismic and aseismic slip and seismic hazard.

FINDING SLOW SLIP TRANSIENTS

Method Summary:To identify slow slip transients we combine observations of general seismicity, burst-type repeating earthquakes, and strain changes across four BSM stations. We use the locations of burst-type repeating earthquake families to infer the geometery of faults hosting slow slip and model the slow slip transients as rectangular Okada dislocations where possible. Study area is selected based on seismicity patterns during the 2010 and 2013 transients.

1. Burst-type repeating earthquake detection

Template matching using EQcorrscan (Chamberlain et al., 2017):

* 1,103 template earthquakes selected from the Quake Template Matching (QTM) seismicity catalog (Ross et al., 2019) with ML >= 1.5 in the Study Area (Fig.1) from Jan. 1, 2010 - Dec. 31, 2016
* Vertical components of 10 Anza Seismic Network and 2 SCSN seismometers (Fig. 1); 5 seconds from the P-wave; 3-10 Hz bandpass filter; Jan. 1, 2010 - Dec. 31, 2016
* Repeating earthquake candidate: average correlation coefficient > 0.9 at 4-12 stations

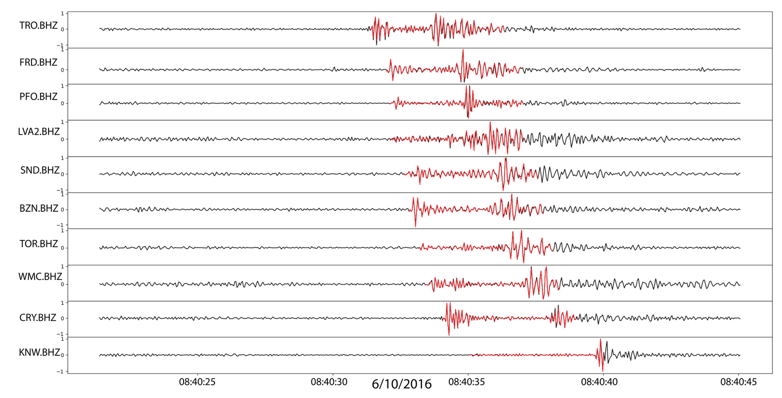


Figure 2. Example of repeating earthquake candidate with station average correlation coefficient of 0.96 using 10 stations. Template time: 6/10/2016 08:39:51. Detection time: 6/10/2016 08:40:31.

2. Borehole strainmeter data

To identify strain change signals:

* 4 BSM stations from the Plate Boundary Observatory (PBO)
* 5-minute level 2 processed strain data calibrated using earth tides (corrected for tidal effects, earthquake offsets and other large static offsets, long-term borehole trends from settling, and barometric pressure)

3. Slow slip distribution

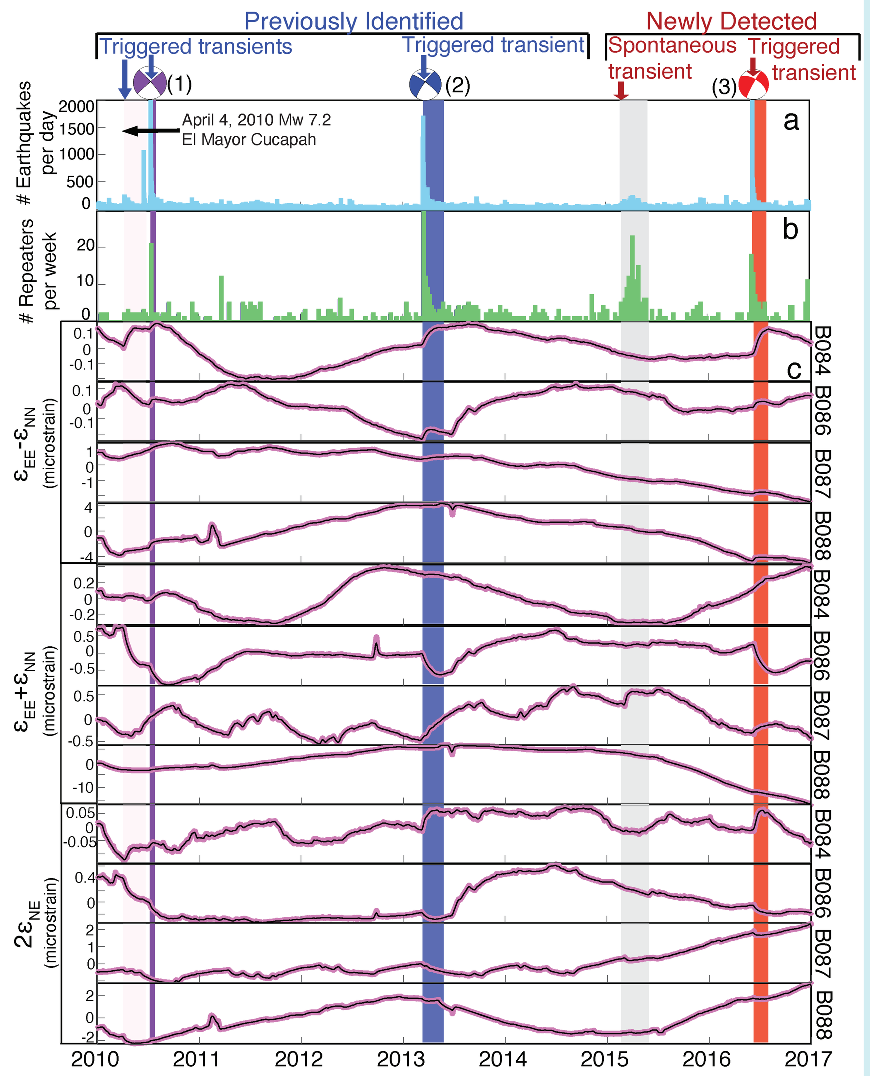
Models of slow slip transients:

* Rectangular Okada dislocations (Beauducel, 2020; Okada, 1985).
* Identified the orientation and dimension (strike, dip, center) of the slow slip fault planes using the location of the majority of burst-type repeating earthquake families
* Grid search to determine the optimal fault length, width, slip and rake.

RESULTS

Summary

Figure 3. Seismicity, burst-type repeating earthquakes, and BSM data in the study region from 2010-2016. (a) Daily seismicity rates from the QTM catalog. (b) Repeating earthquake candidates in 1-week bins. (c) Corrected level 2 5-minute microstrain data from borehole strainmeter stations B084, B086, B087, and B088 (Figure 1) shown in magenta. Two-week running average of corrected strain shown in black. Differential shear strain (εEE-εNN top), areal strain (ε EE+εNN; middle) and engineering shear strain (2εNE; bottom) components included. Extension is positive. Focal mechanisms of 3 moderate-sized earthquakes from the SCSN are indicated and color coded to match their locations on the map in Figure 1. Triggered and spontaneous slow slip transient times are highlighted.



Detected 2 new triggered (2016 & 2020) & 1 spontaneous (2015) slow slip transient

Each triggered slow slip transient is accompanied by sharp increases in seismicity, burst-type repeating earthquakes, and strain change signals across BSM stations

Based on burst-type repeating earthquakes, slow slip occurs on multiple faults, both on and off the mainshock faults

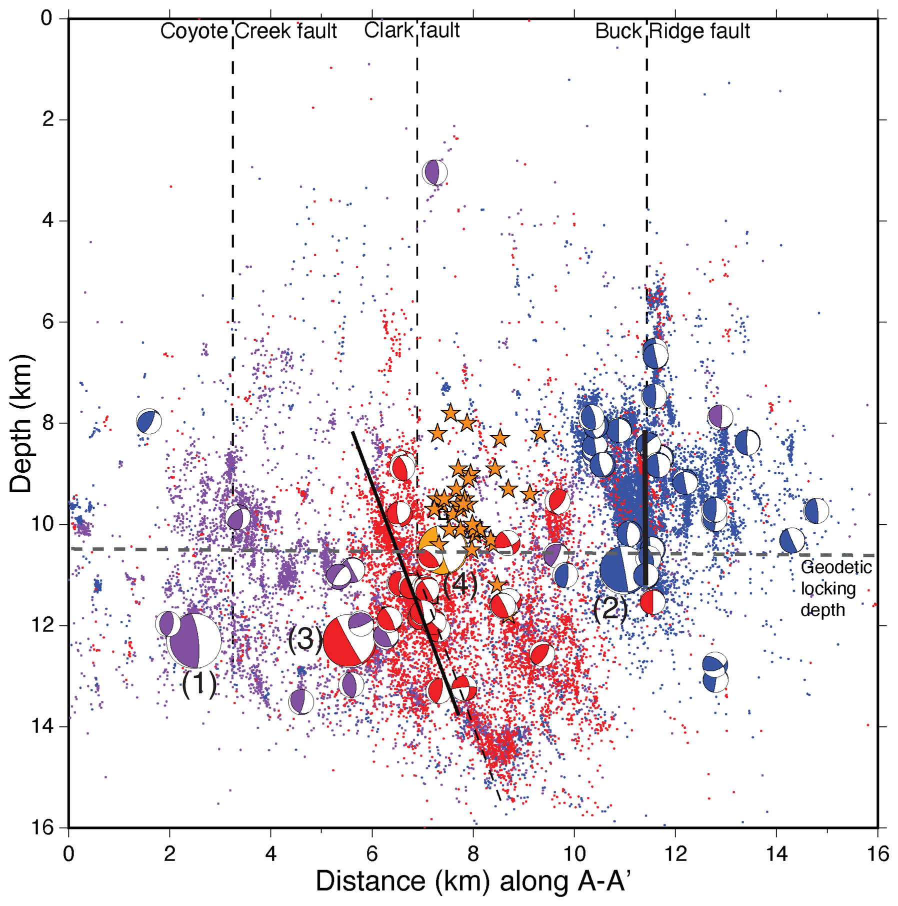
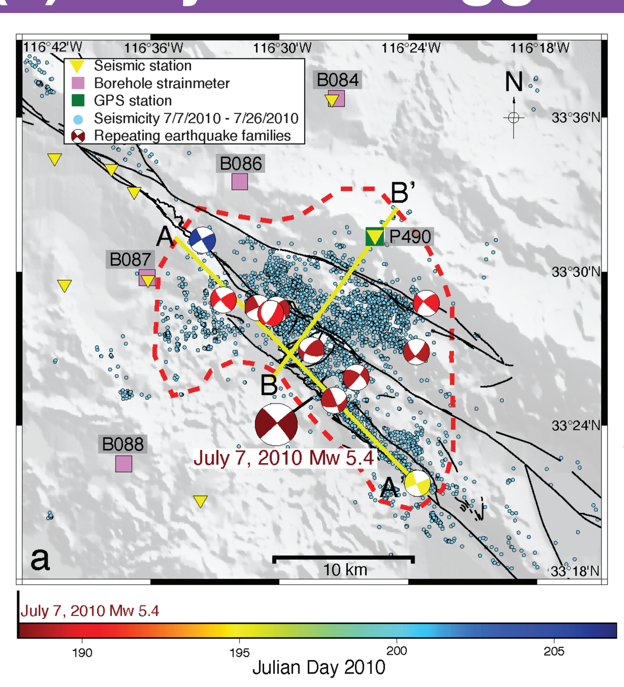
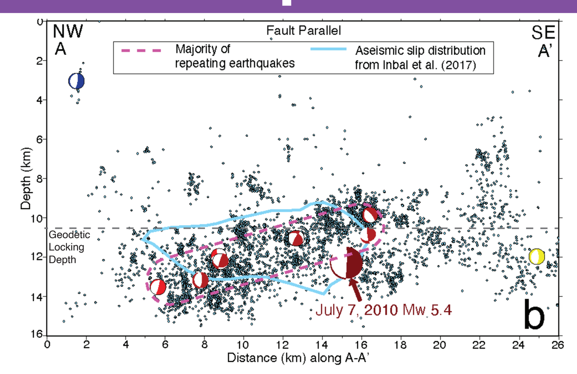


Figure 4. Fault perpendicular cross-section of seismicity and repeating earthquakes within 15 km of A-A' on Fig. 1 during each triggered slow slip transient. Repeating earthquakes and seismicity during the 2010, 2013, and 2016, triggered slow slip transients are shown as smaller focal mechanisms and small filled circles, respectively. Repeating earthquakes during the 2020 triggered slow slip transient are shown as orange stars. The Coyote Creek, Clark, and Buck Ridge fault projections from the surface expressions are shown as black dashed lines. The dip of the 2013 and 2016 rectangular Okada dislocations are shown as solid black lines.

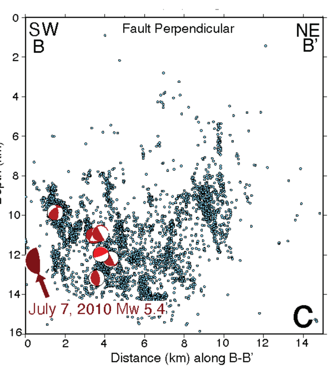
Individual Events

(1) July 2010 triggered slow slip transient





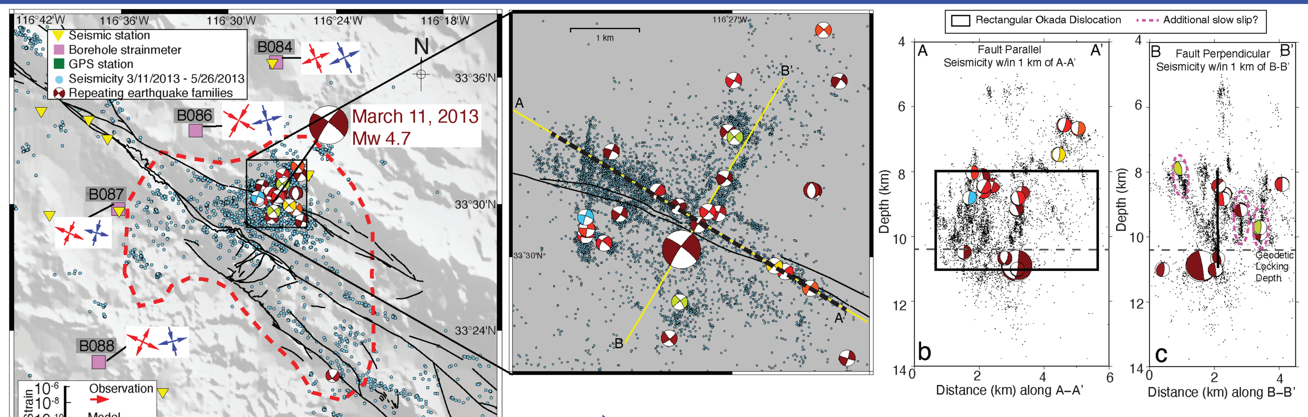
Mw 5.8 slow slip transient previously identified by Inbal et al. (2017)



Slow slip distribution based on burst-type repeating earthquake locations is similar to the model by Inbal et al. (2017)

Can use burst-type repeating earthquakes to delineate slow slip and identify transients not clearly detected with BSMs

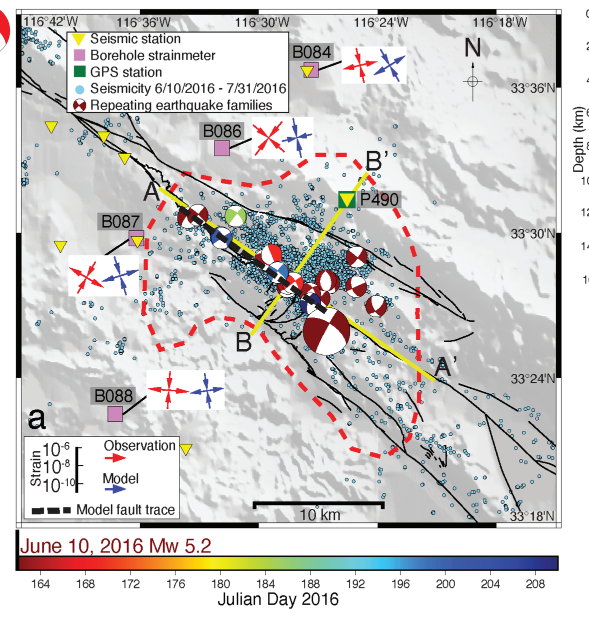
(2) March 2013 triggered slow slip transient

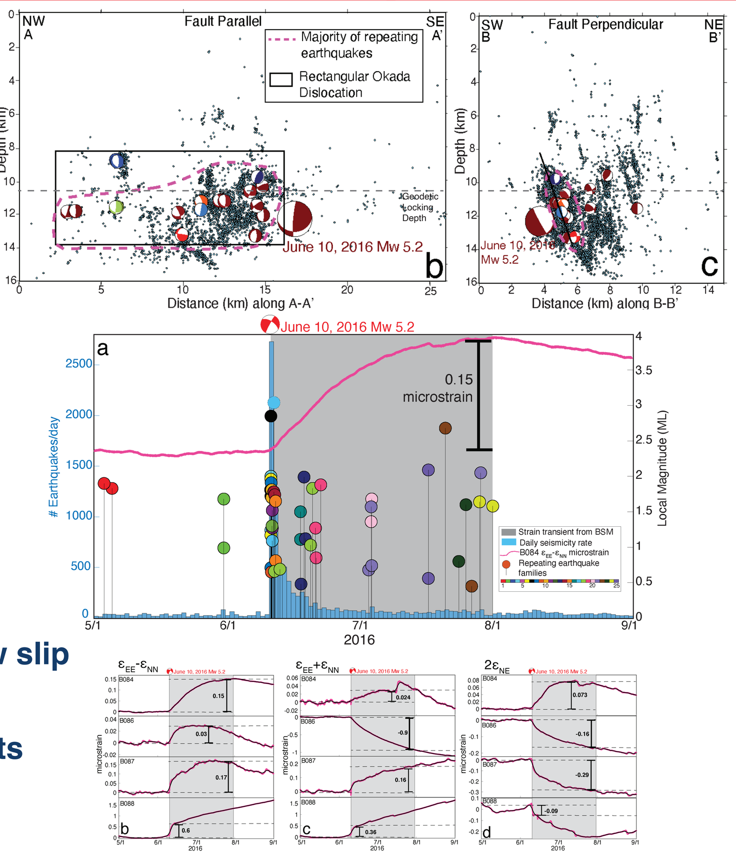


Mw 5.3 triggered slow slip transient

Additional slow slip on several small vertical faults

(3) June 2016 triggered slow slip transient

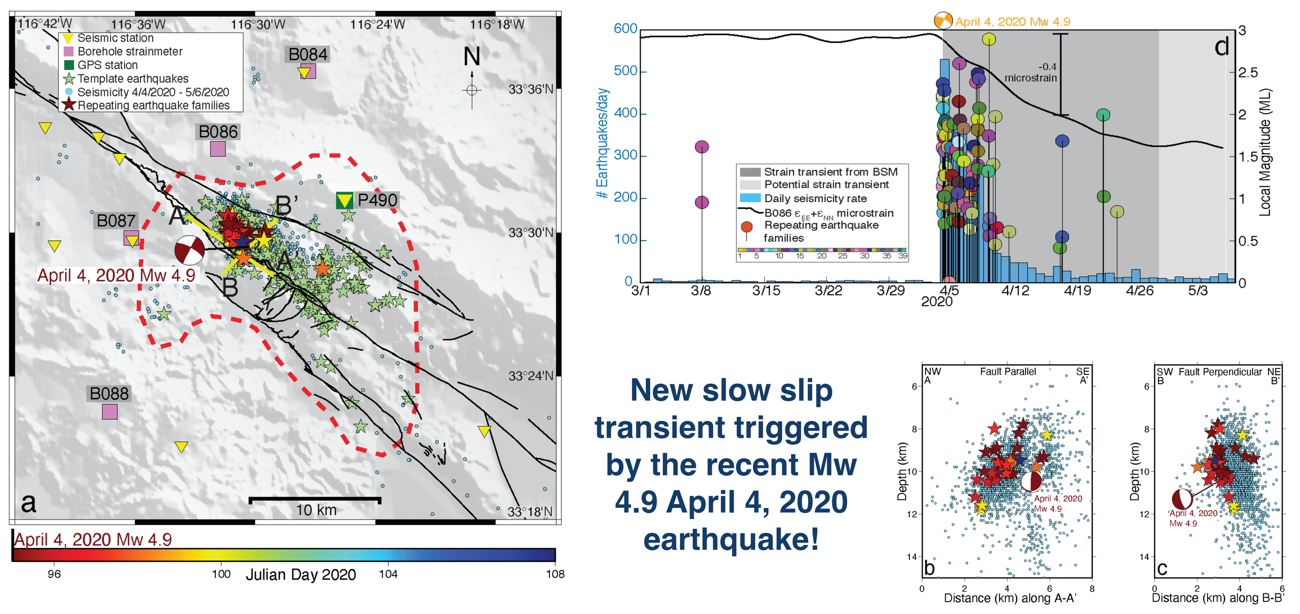




New Mw 5.6 locally triggered slow slip transient on the Clark fault

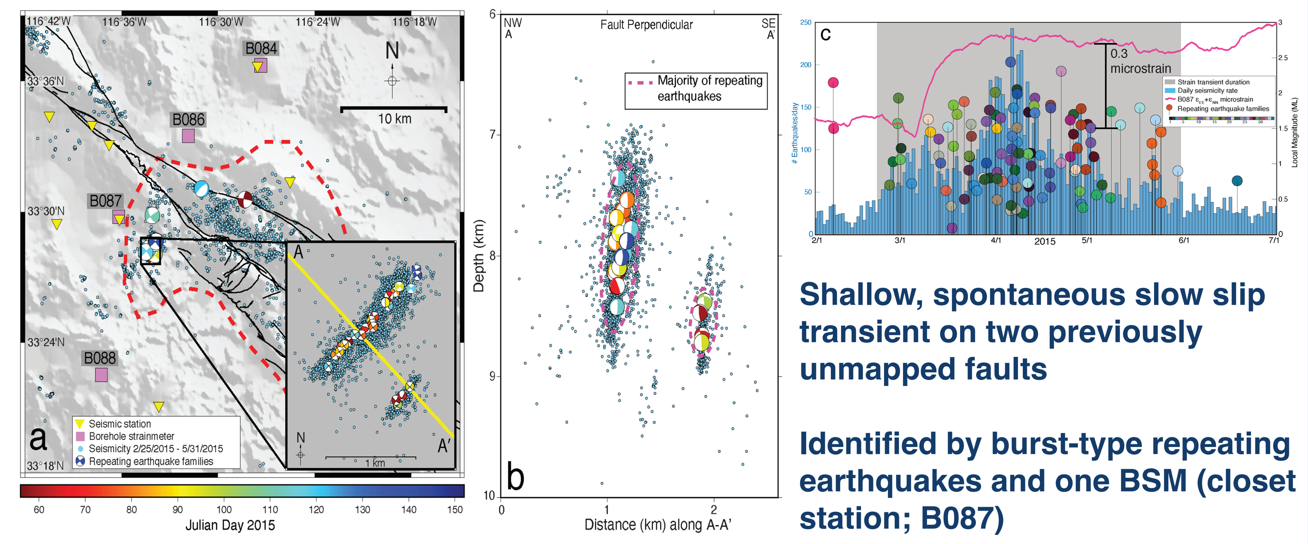
Additional slow slip on minor faults within damage zone

(4) April 2020 triggered slow slip transient



New slow slip transient triggered by the recent Mw 4.9 April 4, 2020 earthquake!

March 2015 spontaneous transient



Shallow, spontaneous slow slip transient on two previously unmapped faults

Identified by burst-type repeating earthquakes and one BSM (closet station; B087)

CONCLUSIONS

1a. New triggered slow slip transients identified following the Mw 5.2 June 10, 2016 & Mw 4.9 April 4, 2020 earthquakes.

1b. First evidence of spontaneous slow slip in the region from burst-type repeating earthquakes on two minor faults in 2015.

2. All Mw > 4.5 earthquakes in the study region and period (2010-2016) trigger deep to moderate-depth slow slip transients with moments greater than the mainshock. Triggered slow slip occurs on several fault segments both on and off the triggering earthquake fault.

3. Burst-type repeating earthquakes, like low-frequency earthquakes in tremor, indicate intermittent periods of slow slip.

4. Our observations support a model where deep microseismicity is located in a transitional region at the bottom of the seismogenic zone with spatially heterogeneous frictional properties that produces frequent slow slip transients.

References

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Acknowledgments

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