Afterslip and Spontaneous Aseismic Slip on the Anza Segment of the San Jacinto Fault Zone, Southern California

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Abstract Understanding the interplay of seismic and aseismic slip is key in seismic hazard evaluation. It is particularly important to know if the same or nearby fault segments can host different slip modes and understand the transition between modes of slip. We investigate this in the trifurcation zone of the Anza segment of the San Jacinto fault where deep creep driving seismicity below the geodetic locking depth has been proposed. We focus on periods following local moderate-sized earthquakes by combining the occurrence of highly correlated families of earthquakes (i.e., closely spaced or partially overlapping events) that we describe here as near-repeating earthquakes, seismicity, and borehole strainmeter data. We find that all \( M_w > 4.5 \) earthquakes between 2010 and 2020 triggered afterslip with coplanar families of near-repeating earthquakes and off-fault microseismicity. These observations include newly detected afterslip following the June 10, 2016 \( M_w 5.2 \) and April 4, 2020 \( M_w 4.9 \) local earthquakes. Afterslip geometries defined by the near-repeating earthquake families are consistent with strain change observations. We conclude that families of near-repeating earthquakes, similar to low-frequency earthquakes within tremor, can be useful indicators of aseismic slip transients and can reveal faulting complexities during aseismic slip. Further, we identify the first evidence of spontaneous aseismic slip in the Anza region from near-repeating earthquake families on two minor faults in 2015. Taken together, 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 produce frequent aseismic slip transients near Anza.

Plain Language Summary Slip on faults occurs as a spectrum ranging from continuous sliding, where motion is too slow to radiate seismic waves (aseismic creep), to rapid movement during earthquakes (seismic slip). Within the fault slip spectrum lies the transient release of stress through aseismic slip. We investigate the interplay of these various slip modes near the Anza segment of the San Jacinto fault by combining observations of seismicity and borehole strainmeter data. We test the hypothesis that transient slip drives intervening small strong patches to failure generating near-repeating earthquakes (i.e., highly correlated events located very close in space). We find that all moderate-sized \( (M_w > 4.5) \) local earthquakes between 2010 and 2020 triggered transient slip events and coplanar families of near-repeating earthquakes. We use the locations of near-repeating earthquake families to define transient slip geometries and find that they are largely consistent with strain change observations. Transient slip occurs on main fault strands and minor structures. We also identify the first evidence of spontaneous transient slip in the Anza region from near-repeating earthquake families and strainmeter data.

1. Introduction

Falt slip occurs as a spectrum, ranging from stably sliding (i.e., aseismic creep) to rapid seismic ruptures (i.e., earthquakes/stick-slip events). Within the fault slip spectrum are transient events of slow, aseismic slip that occur in conditionally stable frictional regimes, often interpreted as the transition between velocity-strengthening (aseismic creep) and velocity-weakening (stick-slip) zones (Bürgmann, 2018; Scholz, 1998; Schwartz & Rokosky, 2007). Understanding the interplay of seismic and aseismic slip is key in seismic hazard evaluation since this can determine the largest earthquake a fault can host. Transient aseismic slip can be spontaneous, quasi-periodic events commonly referred to as slow slip events (Beroza & Ide, 2011;
Dragert et al., 2001; Peng & Gomberg, 2010; Schwartz & Rokosky, 2007), which may include precursory slow slip leading up to a large earthquake (Ito et al., 2013; Kato et al., 2012; Kato & Nakagawa, 2014; Ruiz et al., 2014). It may also be postseismic afterslip relieving static coseismic stress increases aseismically adjacent to an earthquake rupture (Avouac, 2015, and references therein), or aseismic slip triggered by static or dynamic stress changes from earthquakes not adjacent to ruptures (Araki et al., 2017; Taira et al., 2014; Työufeyeva et al., 2019; Wallace et al., 2017; Wei et al., 2015).

Tectonic tremor is considered to be the seismic manifestation of the same process as slow slip and has therefore been used to infer the presence and location of slow slip where it occurs (Annoura et al., 2017; Bartlow et al., 2011; Shelly et al., 2007; Walter et al., 2013; Wech & Creager, 2011). Tectonic tremor is likely made up of repeating low-frequency earthquakes (LFEs) that are driven to failure by slow slip on the surrounding fault (Shelly et al., 2006). LFEs are grouped into families that repeatedly rupture a small patch (∼1 km²) (Sweet et al., 2014), with individual LFEs within a family having variable sizes and likely rupturing multiple (3–10) subpatches within the larger family patch (Chestler & Creager, 2017a, 2017b). Similarly, repeating “regular” earthquakes, often referred to as “characteristic” (Nadeau & McEvilly, 1999) or “continual-type” (Igarashi et al., 2003), are events with nearly identical waveforms driven to failure quasi-periodically by continuous tectonic loading (i.e., aseismic creep) on the surrounding fault and have therefore been used to estimate creep rates on plate boundary faults (Chen et al., 2008; Igarashi et al., 2003; Nadeau & McEvilly, 1999; Uchida et al., 2004). However, there are important differences; repeating earthquakes have a constant magnitude, regular repeat interval, and are thought to repeatedly rupture the exact same fault asperity (Nadeau & Johnson, 1998; Nadeau & McEvilly, 1999; Uchida & Bürgmann, 2019).

Sequences of nearly identical events have also been observed in short-term (minutes to months), irregularly repeating bursts (Igarashi, 2010; Igarashi et al., 2003; Kimura et al., 2006; Lenglîné & Marsan, 2009; Li et al., 2018; Nadeau et al., 1995; Templeton et al., 2008; Waldhauser & Ellsworth, 2002; Yao et al., 2017). These highly correlated events have been referred to as short-term (Lenglîné & Marsan, 2009; Nadeau et al., 1995) or “burst-type” (Igarashi, 2010; Igarashi et al., 2003; Kimura et al., 2006; Shaddox & Schwartz, 2019; Templeton et al., 2008) repeating earthquakes and have been observed during aftershock sequences or afterslip following large magnitude events (Igarashi, 2010; Igarashi et al., 2003; Kimura et al., 2006; Li et al., 2018; Templeton et al., 2008; Yao et al., 2017). These short-term repeating earthquakes have also been observed during migrating slow slip episodes preceding large earthquakes (Kato et al., 2012; Meng et al., 2015).

Nadeau et al. (1995) first identified families or clusters of short-term repeating earthquakes with aperiodic repeat intervals of minutes to days near characteristic repeating earthquake families on the San Andreas fault (SAF) near Parkfield, California. Based on hypocenter locations they estimated that short-term repeating earthquakes within clusters were located 100–200 m apart. They proposed that these events were occurring on distinct asperities, triggered either by rapid, transient aseismic slip on the surrounding fault or short-distance triggering of closely spaced asperities. Lenglîné and Marsan (2009) also identified short-term repeating earthquakes near Parkfield and found that the locations of events within families were not as tightly clustered as characteristic repeating earthquake families. They proposed that short-term repeating earthquakes could be due to partial rupture of the same asperity after the preceding earthquake did not rupture the entire asperity, or events within clusters rupturing very near but distinct asperities. Shaddox and Schwartz (2019) found these short-term repeating earthquakes at the northern Hikurangi margin coincident with tremor on an upper-plate fracture network above a subducted seamount after an Mw 6.8 offshore slow slip event. Based on the colocation with tremor, they concluded that the short-term repeating earthquake families were driven by transient aseismic slip, possibly triggered by fluids migrating from over-pressed sediments down-dip of the seamount into the upper plate fracture network during the interplate slow slip event.

Short-term repeating earthquakes may rupture closely spaced or partially overlapping asperities and are different from characteristic repeating earthquakes in source (i.e., repeated rupture of exact same asperity) and therefore mechanism (i.e., loading by steady aseismic creep). Instead of creep, short-term repeating earthquakes have been associated with transient aseismic slip, including afterslip (Igarashi, 2010; Igarashi et al., 2003; Kimura et al., 2006; Li et al., 2018; Templeton et al., 2008; Yao et al., 2017), precursory slow slip (Kato et al., 2012; Meng et al., 2015), and aseismic slip triggered by fluid migration (Shaddox & Schwartz, 2019). In this study, we refer to families of closely spaced earthquakes (within 200 m)
as “near-repeating” earthquakes, owing to their highly correlated waveforms, aperiodic repeat intervals, and variable magnitudes, to make the distinction from characteristic repeating earthquakes and previously identified short-term/burst-type repeating earthquakes that likely rupture the same asperity or partially overlapping asperities. We propose that sequences of near-repeating earthquake families concentrated in time and space are more similar in source and mechanism to clusters of LFE families: near-repeating earthquakes likely rupture asperities within family patches and are driven to failure by transient aseismic slip on the surrounding fault. However, unlike LFEs, near-repeating earthquakes are not devoid of high-frequency energy. Some prior studies have successfully used tremor and LFE detections as timing and location indicators to guide the identification of aseismic transient signals in GNSS (Bartlow, 2020; Frank et al., 2015; Rousset et al., 2019) and strainmeter data (Delbridge et al., 2020; Hawthorne, Bostock, et al., 2016). We propose that similar to LFEs, near-repeating earthquakes can be useful spatiotemporal seismic indicators of transient aseismic slip that can be combined with geodetic observations to model aseismic slip transients.

To demonstrate the utility of near-repeating earthquakes as a proxy for transient aseismic slip, we investigate the occurrence of near-repeating earthquake families during aseismic transients independently detected by borehole strainmeter data that are too small to be robustly detected using GNSS data in the trifurcation area of the San Jacinto fault (SJF) zone near Anza in southern California (Figure 1). We find that all three $M_w > 4.5$ earthquakes occurring in this region during the time period studied (2010–2016) have afterslip signals on borehole strainmeter data and are accompanied by near-repeating earthquakes and elevated seismicity rates. We use the location of near-repeating earthquakes to infer the geometry of faults.
hosting afterslip and find that afterslip occurs at depths between 6 and 14 km, on all three major strands of the SJF zone, and on several different fault segments both on and off the mainshock fault. A local $M_w 4.9$ earthquake occurred in April 2020, at the conclusion of our study, and we use this event to validate our hypothesis that afterslip accompanied by near-repeating earthquakes follows all moderate magnitude earthquakes in this region. We also identify and locate a spontaneous aseismic slip transient in 2015 using near-repeating earthquakes and a strain signal on the nearest borehole strainmeter station. This demonstrates that aseismic slip in this region is not restricted to afterslip and that near-repeating earthquakes can be generated by spontaneous as well as triggered aseismic slip (i.e., afterslip). We conclude that like LFEs, near-repeating earthquakes can be a useful proxy for aseismic slip transients. This is particularly useful in regions that are not tremorgenic. In addition, detecting and analyzing near-repeating earthquakes following local moderate-sized events can provide insight into whether aseismic slip occurs on main fault strands or on splay faults within damage zones.

2. Anza Segment of the San Jacinto Fault Zone

The southern SAF system consists of three main faults: the SAF, the SJF, and the Elsinore fault, with a total of 35–40 mm/year of right-lateral strike-slip motion accommodated across these faults (Bennett et al., 1996). The SJF is the most seismically active fault in southern California, with slip of approximately 19 mm/year (Lindsey & Fialko, 2013). 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 ($\sim M_w 7$) earthquake (Sanders & Kanamori, 1984). Determining the locking depth of the SJF in this region is important in constraining the size of a potential large earthquake in the Anza seismic gap, and future earthquake rupture of the Anza seismic gap is likely to start on either end of the gap zone where stress buildup is greatest, thus it is important to understand fault behavior just outside of the Anza seismic gap. Southeast of the Anza seismic gap in the trifurcation area the SJF splays into three semi-parallel strands: the Coyote Creek fault (CCF), the Clark fault (CF), and the Buck Ridge fault (BRF) (Figure 1). From 2000 to 2016, 12 $M_w > 4$ local earthquakes have occurred in the trifurcation area. Three $M_w > 4.5$ earthquakes occurred in the trifurcation area during our study period (2010–2016): the July 7, 2010 $M_w 5.4$ Collins Valley earthquake on the CCF, the March 11, 2013 $M_w 4.7$ earthquake on the BRF, and the June 10, 2016 $M_w 5.2$ Borrego Springs earthquake on the CF (Figure 1). In addition, an $M_w 4.9$ earthquake occurred toward the conclusion of this study on April 4, 2020 (Figure 1).

Seismicity in the trifurcation area of the SJF extends to 17 km depth (Ross et al., 2019), 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). However, characteristic repeating earthquakes have not been commonly identified in this region as expected in a primary velocity strengthening deep creep zone containing distinct velocity weakening seismic asperities (Jiang & Fialko, 2016). 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 aseismic slip transients below the locked zone (Jiang & Fialko, 2016; Wei et al., 2013). In this scenario, characteristic repeating earthquakes would not be expected, although near-repeating earthquakes might occur. Anomalously large aftershock zones with logarithmic expansion rates following deep (>12 km) $M_w > 4$ earthquakes in the study area have been interpreted as deep afterslip (Meng & Peng, 2016) and provide additional evidence for deep, intermittent aseismic slip transients. Further, following the 2010 and 2016 local earthquakes, the magnitudes of the largest aftershocks were smaller than expected; in fact, the largest aftershock of nearly all the magnitude $M_w > 4.5$ earthquakes in this region was $\sim M_w 3.5$, smaller than expected (Kilb & Vernon, 2020). This is possibly due to the complexity of the fault system limiting the maximum magnitude of the largest aftershock (Kilb & Vernon, 2020). However, smaller than expected aftershocks could also be consistent with seismicity driven by afterslip. Another interpretation for the deep microseismicity that does not require aseismic slip is that it is mostly caused by off-fault activity in broad and deep damage zones between the primary SJF strands (Cheng et al., 2018; Ross, Hauksson, et al., 2017).

Inbal et al. (2017) found deep, triggered aseismic slip in the study region following the remote April 4, 2010 $M_w 7.2$ El Mayor-Cucapah earthquake and the local July 7, 2010 $M_w 5.4$ Collins Valley earthquake using Plate Boundary Observatory (PBO) borehole strainmeter (BSM) data and local microseismicity. The
triggered aseismic slip transient following the El Mayor-Cucapah earthquake lasted up to 94 days and likely triggered two local earthquakes on June 13, 2010 ($M_w 4.45$ and $M_w 4.2$), followed by the $M_w 5.4$ Collins Valley local earthquake on July 7, 2010. From their joint microseismicity and BSM inversion with rate and state friction they conclude that aseismic slip and seismicity are not coplanar, but deep (>10 km) aseismic slip on the main fault strand drives off-fault seismicity at shallower depth. We find these transients to be associated with both increased seismicity which may be outside of the plane of aseismic slip as concluded by Inbal et al. (2017), and near-repeating earthquakes which are thought to be driven by surrounding aseismic slip.

The intermittent and distributed nature of the creep provides strong support for a model with a spatially heterogeneous transition from locked to freely slipping between 6 and 14 km below the SJF trifurcation region.

3. Detecting and Locating Transient Aseismic Slip

To demonstrate the utility of near-repeating earthquakes as a proxy for transient aseismic slip, we combine observations of near-repeating earthquake families, seismicity patterns, and strain changes across BSM stations. The instrumentation available near the Anza segment of the SJF enables the combination of these observations. Four BSM stations border the study area to the west, 12 consistently operational seismometers from the Anza Seismic Network and Southern California Seismic Network are within 30 km of the study area, and an excellent seismic catalog covers this region (Figure 1; Ross et al., 2019). The 2010–2016 study period was selected to evaluate three moderate-sized ($M_w > 4.5$) local earthquakes that occurred since the BSMs were installed (2006–2007) and had adequate settling time. During this time the high-resolution seismicity catalog was available. The specific study area within the greater region of the SJF was chosen based on the concentration of microseismicity.

3.1. Near-Repeating Earthquakes and General Seismicity

We evaluate seismicity patterns using the Quake Template Matching (QTM) catalog (Ross et al., 2019) during our study period: January 1, 2010 to December 31, 2016. The magnitude of completeness of the QTM catalog is around 0.3. Seismicity in the study area during this period is bimodally concentrated around 8 and 10 km depth, and drops off significantly at 14.6 km but extends down to 17 km depth (Figure S1).

We perform template matching to identify near-repeating earthquakes. We select template earthquakes from the QTM catalog with a local magnitude $\geq 1.5$ (Figure 1) for a total of 1,103 template earthquakes.

We chose template earthquakes with local magnitude $\geq 1.5$ based on the average spectral amplitudes for these events generally exceeding noise levels above 3 Hz (Figure S2). Depths of the template events are concentrated between 6 and 14 km. The template earthquakes are cut to 5-s-long windows around the P-phase arrival (0.15-s pre-pick) and mostly include the S-phase arrivals. Template events are then filtered using a 3–10 Hz zero-phase band-pass filter. This band-pass is selected due to noise below 3 Hz (Figure S2), and to detect near-repeating earthquakes that have variable magnitudes ($\sim M_0–M_3$) and therefore different frequency content. This is particularly important because near-repeating earthquakes are likely closely spaced (<200 m) or partially overlapping asperities, rather than the exact same asperity. We therefore chose parameters to maximize the detection of closely spaced events. We performed template matching in higher frequency bands and find fewer near-repeating earthquake families with more uniform magnitudes, as expected. However, the spatiotemporal distribution of near-repeating earthquakes in all frequency bands is similar and does not affect our interpretations (see Supporting Information for further discussion of chosen parameters). Template matching is performed from January 1, 2010 through December 31, 2016 using the open-source Python package EQcorrscan (Chamberlain et al., 2017) on the vertical components of the seismometers. The procedure is similar to that outlined in Shaddox and Schwartz (2019). We use 10 seismic stations from the Anza seismic network (AZ) and 2 from the Southern California Seismic Network (SCSN). Templates that yield a cross-correlation coefficient of 0.90 at 4–12 stations (average of 9 stations used) are considered near-repeating earthquakes.

A sample near-repeating earthquake detection seismogram is included in Figure S3, and a list of near-repeating earthquakes found are listed in Supporting Information Datasets S1 and S2. These are near-repeating earthquakes with high cross-correlation coefficients in the band-pass selected (3–10 Hz). Generally,
events with this high level of similarity are located within one-quarter of the dominant wavelength (Geller & Mueller, 1980). The dominant frequency in this band-pass is the 10 Hz cutoff frequency used. Assuming a P-wave velocity potentially ranging from 4 to 6 km/s, the dominant wavelength is 400–600 m. Thus, any potential near-repeating earthquake pairs detected are likely separated by less than 100–150 m. Further, most of the near-repeating earthquakes within families were located in the QTM catalog and have locations 130 m or less from each other. Based on the local magnitudes of near-repeating earthquakes ranging from 0.09 to 3.18, with an average magnitude of 1.3, near-repeating earthquake pairs within 130 m of each other may be completely overlapping, partially overlapping, or closely spaced seismic asperities. This is consistent with our definition of near-repeating events as potentially closely spaced (<200 m) rather than completely overlapping asperities. Focal mechanisms for most of the near-repeating earthquakes within families were obtained from the Yang et al. (2012) catalog.

3.2. Borehole Strainmeter Data
We use 5-min level 2 processed strain data calibrated using earth tides (Hodgkinson et al., 2013) from the PBO network for four BSM stations located west of the study region (Figure 1) to identify strain transient signals. The strain gauge data is converted to three strain components: differential (pure) shear strain, areal strain, and engineering (simple) shear strain. Then the strain components are corrected for tidal effects, earthquake offsets and other large static offsets, long-term borehole trends from settling, and barometric pressure using the level 2 corrections provided by PBO. The trend from the prior month is first removed, and then strain offsets were manually selected based on best estimates of stable offsets. The expectation of a logarithmic dependence on time as well as the timing from near-repeating earthquake families were used to help guide the time windows of strain offsets.

3.3. Afterslip Distribution
To determine the slip direction and average magnitude of afterslip following a moderate-sized local earthquake we approximate fault slip using a rectangular Okada dislocation model (Beauducel, 2020; Okada, 1985). We identify the orientation and dimension (strike, dip, and center) of the afterslip fault plane using the location of the majority of near-repeating earthquake families, and perform a grid search using the three strain components from the BSM stations (Figure 1) and minimum mean squared error to determine the optimal fault length, width (in the dip direction), slip and rake. Since we assume a uniform half-space model, our modeled dislocation depth and slip amplitude may be biased. More compliant shallow layers will generally lead to our estimated depths being too shallow and slip amplitudes being too large (Savage, 1998; Segall, 2010). A near-fault compliant zone could amplify these biases if the BSMs are inside the compliant zone, or have the opposite biases if the BSMs are outside the compliant zone (Segall, 2010). Depth biases are likely in the range of 5%–20% (Savage, 1998). It should also be noted that since we are modeling afterslip on one fault plane, if afterslip is simultaneously occurring on multiple minor faults that are not oriented similarly to the modeled fault plane, the moment will likely be underestimated.

4. Results
4.1. Previously Identified Afterslip/Triggered Aseismic Slip Transients
Following the $M_w$ 5.4 July 7, 2010 Collins Valley ("2010 earthquake") and $M_w$ 4.7 March 11, 2013 ("2013 earthquake") local earthquakes (focal mechanism symbols in Figures 1 and 2), there is a sharp increase in seismicity, increase in near-repeating earthquake activity above the background rate (Figure 2, Supporting Information Dataset S1), and a logarithmic transient signal on the strain data across BSM stations and components (Figures 2, S4, and S5), consistent with previous studies identifying afterslip or aseismic transients following these earthquakes (Agnew, 2017; Hodgkinson, 2013; Inbal et al., 2017; Meng & Peng, 2016). A remotely triggered aseismic slip transient identified in BSM and seismicity data following the 2010 El Mayor-Cucapah earthquake (Figure 2; Inbal et al., 2017) is not evident in the near-repeating earthquake time series.
Near-repeating earthquake families following the 2010 and 2013 earthquakes have short and irregular repeat intervals and variable magnitudes (Figures S4 and S5), consistent with prior observations of short-term/burst-type repeating earthquakes (Igarashi, 2010; Igarashi et al., 2003; Lengliné & Marsan, 2009; Nadeau et al., 1995; Shaddox & Schwartz, 2019; Templeton et al., 2008). We propose that these families of near-repeating earthquakes can be used to infer the location, distribution, and temporal migration of transient afterslip.

Inbal et al. (2017) modeled the triggered aseismic slip transient (or afterslip) following the 2010 earthquake using a joint inversion of strain and seismicity data. They found an $M_w$ 5.8 event with afterslip distributed...
along the CCF at depths between 10 and 14 km, as shown in Figure 3b, as well as northwest of the Anza Gap. We find near-repeating earthquakes along strike of the CCF (Figure 3b), consistent with the model of Inbal et al. (2017). However, near-repeating earthquakes also located on what appears to be a dipping structure between the CCF and CF (Figure 3c), suggesting that afterslip may also be occurring on faults between the main SJF strands, likely within deep damage zones.

Although a strain transient was previously identified on BSM data following the 2013 earthquake on the BRF (Agnew, 2017; Hodgkinson, 2013), there is no published model for this event. We identified 28 families of near-repeating earthquakes following this event that are mostly shallower (7–11 km depth) than the mainshock earthquake (10.9 km depth) and indicate a shallow temporal migration (Figure 4b). We use the location of the majority of near-repeating earthquakes to define a plane (strike, dip, and center) hosting afterslip and model the resulting strain changes for comparison to the BSM data for general consistency.

There are several vertical fault planes defined by the locations of near-repeating earthquakes that host afterslip. We use the plane on the steeply dipping BRF (Figure 4c), with a strike defined by near-repeating earthquakes, for dislocation modeling. The resulting model and fit to the data is shown in Figure 4a and has the following parameters: 301° strike, 90° dip, a rake of 150°, 9.5 km center depth, 5 km fault length, 3 km fault width (8–11 km depth), and slip of 26 cm (Figure 4a, Table S1). These faulting parameters yield afterslip with $M_w = 5.3$ and predict 3 mm vertical, 0.5 mm north, and 1 mm east displacements at nearby cGPS station P490 (Figure 4), which is too small to robustly detect, consistent with a lack of visibly observable signal at this instrument. It is also important to note that our models are far from unique, and other models that fit the BSM data may easily be found which predict even smaller GPS displacements, so the lack of detection by GPS instruments is not considered surprising. Therefore, afterslip with $M_w = 5.3$ following the 2013...
earthquake on the mapped BRF with a shallow temporal migration is consistent with both the observations of surface strain changes and the timing and location of the majority of near-repeating earthquake families. However, additional afterslip on minor vertical structures off of the BRF may also be occurring based on the location of additional near-repeating earthquakes. The cumulative seismic moment from seismicity in the study region during the approximate afterslip timing (starting on March 11, 2013 16:56:06 directly following the 2013 earthquake and continuing through May 26, 2013) is less than 1% of the seismic moment of the modeled $M_w 5.3$ 2013 afterslip.

4.2. Newly Detected Afterslip

The $M_w 5.2$ June 10, 2016, Borrego Springs earthquake (“2016 earthquake”) on the CF (focal mechanism symbol in Figures 1 and 2) propagated unilaterally to the northwest (Ross, Kanamori, et al., 2017). Following this earthquake there is a sharp increase in seismicity (Figures 2a and 5a), an increase in near-repeating earthquake activity (Figures 2b and 5a, Supporting Information Dataset S1), and a logarithmic transient signal on the strain data across BSM stations and components (Figures 2c and 5b–5d) similar to the 2010 and 2013 previously identified transients. This is evidence of newly detected afterslip following a moderate-sized local earthquake. The depth of seismicity following the earthquake ranges from 8 to 15 km, but is most concentrated at 11–12 km depth (Figure S1), similar to the 2010 event.

Based on the locations of 23 near-repeating earthquake families following the 2016 earthquake, afterslip extends at least 14 km to the northwest of the hypocenter at a strike of 305° along the CF, from approximately 8 to 14 km depth with a dip of 70° to the northeast (Figure 6). There also appears to be a northwest temporal migration of near-repeating earthquake families (Figures 6a and 6b). Additional afterslip on faults within
the damage zone between the CF and BRF is also likely based on the location of several near-repeating earthquake families on small splay faults (Figure 6c).

Using a fault plane defined by the location of the majority of near-repeating earthquake families with the strike constrained to be on the mapped CF (305° strike, 70° northeast dip, centered at 11 km depth; Figure 6), we perform a grid search to determine a slip of 11 cm, a fault length of 14 km, a width of 6 km (8.2–13.8 km depth), and a rake of 174° that best fit the observed surface strain changes (Figure 6a, Table S1). These faulting parameters yield afterslip with $M_w = 5.6$. Our model is also consistent with the observation that cGPS station P490 (Figure 6a) did not detect postseismic afterslip, as the model predicts vertical (2.5 mm) and horizontal (0.54 mm north; 3.1 mm east) displacements beneath the detection threshold of this single instrument. Therefore, deep, $M_w = 5.6$ afterslip migrating northwest apparently along the CF following the 2016 earthquake is consistent with both the observations of near-repeating earthquake families and surface strain changes. Similar to the 2010 and 2013 earthquakes, the moment of afterslip is larger than for the local mainshock earthquake. The cumulative seismic moment from seismicity in the study region during the approximate afterslip timing (starting on June 10, 2016 08:04:39 directly following the 2016 earthquake and continuing through July 31, 2016) is less than 1% of the seismic moment of the modeled $M_w = 5.6$ 2016 afterslip.

Figure 5. Timing of the 2016 afterslip. (a) Seismicity rate (in study area; see Figure 1), near-repeating earthquakes, and strain transient timing from BSM data (indicated in gray). Near-repeating earthquakes plotted by local magnitude and colored according to family (25 total families; 23 during afterslip). Differential shear strain from BSM station B084 is plotted as the magenta line. (b–d) 5-min corrected strain data (b: differential shear strain, c areal strain, d engineering shear strain) for BSM stations B084, B086, B087, and B088 (see Figure 1) with the trend of the month before the earthquake removed is shown in magenta, 1-week running average shown in black. Observed strain change (microstrain) during afterslip is indicated in red, modeled strain change is indicated in blue. Approximate timing of afterslip from BSM data and near-repeating earthquakes is highlighted in gray. Timing (in UTC) of the $M_w = 5.2$ June 10, 2016 Borrego Springs earthquake is indicated at the top of each panel.
From February to May 2015 there is a notable increase in near-repeating earthquake activity above the background rate and a moderate increase in seismicity (Figures 2 and 7c). These increases are much more gradual than what is observed for 2010, 2013, and 2016 transients, and there is not an obvious regional or local moderate-sized earthquake. The majority of near-repeating earthquake families and microseismicity during this time period are located on two previously unmapped adjacent (0.75 km separation) but unconnected 0.5–1.5 km long faults, trending northeast and approximately orthogonal to the main fault strands, at depths of 7–9 km, which is shallower than most of the seismicity associated with afterslip (Figures 7a and 7b and Figure S1). A strain transient signal is observed on the areal and engineering shear strain components of the nearest BSM station, B087, located approximately 4 km northwest of these faults. The cumulative slip from microseismicity on the two northeast-trending splay faults from February 25, 2015 to May 31, 2015 (approximate timing of strain transient signal) would result in strain at B087 that is over 1000× less than what is observed. Therefore, the strain transient signal is not due to cumulative strain from microseismicity alone. The near-repeating earthquake families, microseismicity increase, and strain transient signal on B087 are evidence of a spontaneous aseismic slip transient occurring on two separate faults only detected on the nearest BSM station.
5. Discussion

5.1. Afterslip of the 2010, 2013, and 2016 Earthquakes

The moment released by afterslip following the 2010, 2013, and 2016 earthquakes was larger than the main-shock moments. The cumulative seismic moment from earthquakes in the study area during afterslip is 1%
or less of the afterslip moment of each event. This indicates that the strain transient signals observed across BSM stations are from aseismic rather than seismic slip.

The 2010 and 2016 earthquakes both have hypocentral depths near 12 km (SCSN catalog). Afterslip is mostly deep (>10 km) on major fault strands beneath the geodetic locking depth of ~10 km (Lindsey et al., 2014). However, near-repeating earthquakes during afterslip of both events locate off-fault, in the damage zone between primary fault strands (Figure 8), suggesting that afterslip may also have occurred on minor off-fault structures. The majority of near-repeating earthquakes during the 2016 afterslip define a plane dipping 70° to the northeast, consistent with previous work documenting a change in dip of the main faults in the trifurcation area from near vertical to 70° near a depth of 10 km (Ross, Hauksson, et al., 2017) (Figure 8). Near-repeating earthquakes during the 2013 afterslip appear to define a near-vertical plane apparently coplanar with and shallower than the mainshock and on the BRF, as well as on multiple minor vertical faults (Figure 8). Most of the afterslip is shallower than the geodetic locking depth. Afterslip is likely occurring on several planes, both on and off the major faults from 6 to 14 km depth (Figure 8), providing support for a model with a spatially heterogeneous transition from locked to freely slipping between 6 and 14 km depth. Our afterslip models for 2013 and 2016 (based on the location of near-repeating earthquakes) are generally not coplanar with the majority of seismicity; indicating that afterslip likely drives off-fault microseismicity.
Although we refer to the transient, aseismic slip observable on local BSMs directly following the 2010, 2013, and 2016 earthquakes as afterslip, it is important to note that afterslip has generally been defined as occurring on the mainshock fault, in regions adjacent to coseismic slip (Avouac, 2015 and references therein). Since we propose that afterslip following these earthquakes occurs on both the mainshock fault and on several other minor faults within the damage zone, it may be appropriate to more broadly characterize these transients as triggered aseismic slip, consistent with terminology adopted by Inbal et al. (2017), Agnew (2017), and Hodgkinson (2013).

5.2. Near-Repeating Earthquakes as a Proxy for Transient Aseismic Slip

By defining rectangular afterslip planes based on the locations of the majority of near-repeating earthquake families, we were able to model strain changes largely consistent with observations at the four nearest BSM stations for the 2013 and 2016 afterslip. However, the observed strain changes are likely influenced by unmodeled details including additional afterslip on minor structures, which may account for disparities between the model and observations. Still, the overall general consistency provides confidence that near-repeating earthquakes are coplanar with afterslip and can be used to not only detect aseismic slip transients, but also to reveal aseismic slip geometry. Further, the temporal migration of near-repeating earthquake families can be used in some cases to identify the migration of afterslip. A northwest temporal migration of near-repeating earthquake families during the 2016 afterslip and a shallow temporal migration during the 2013 afterslip are examples of this.

Aftershocks can be driven primarily by afterslip rather than from coseismic stress changes (Avouac, 2015; Hsu et al., 2006; Perfettini et al., 2005; Perfettini & Avouac, 2004; Schaff et al., 1998; Yu et al., 2013). Aftershocks that are loaded by afterslip can be coplanar with afterslip (Yu et al., 2013), occur on adjacent segments of the fault (Hsu et al., 2006; Perfettini et al., 2005), or be located on adjacent faults (Inbal et al., 2017). We believe that the near-repeating earthquakes during the 2010, 2013, and 2016 afterslip are coplanar with afterslip. They may be ruptures of nearby or partially overlapping asperities that are loaded or partially reloaded by transient afterslip. These near-repeating earthquakes are aftershocks, but with unique characteristics, in particular, they occur very close together and are coplanar with afterslip. There are additionally many off-fault aftershocks, consistent with deep transient aseismic slip driving off-fault aftershocks reported by Inbal et al. (2017) following the 2010 earthquake.

We were able to find the first evidence of spontaneous aseismic slip near Anza on two minor faults in 2015 from a notable increase in near-repeating earthquake activity above the background rate. This activity was accompanied by a modest increase in seismicity and a strain transient signal on the closest BSM. The seismicity on these two minor faults is swarm-like, that is, earthquakes are clustered in both space and time without a clear mainshock (Vidale & Shearer, 2006). The driving mechanisms of swarms are thought to be aseismic, including fluid flow (Chen et al., 2012; Shelly et al., 2015; Shelly, Hill, et al., 2013; Shelly, Moran, et al., 2013; Vidale & Shearer, 2006; Waite & Smith, 2002), transient aseismic slip (Lohman & McGuire, 2007; Ozawa et al., 2007; Roland & McGuire, 2009), or a combination where pore pressure changes from fluid migration trigger aseismic slip that then drives swarm activity (Bourouis & Bernard, 2007; Hainzl, 2004). The strain signal on the closest BSM—1000× greater than what would be expected from the swarm seismicity alone—is evidence that this swarm was driven by aseismic slip, possibly an episodic event or triggered by fluid migration.

The 2015 transient is evidence that near-repeating earthquakes can be indicative of spontaneous aseismic slip in addition to triggered aseismic slip (i.e., afterslip). These findings are similar to Shaddock and Schwartz (2019) that found near-repeating earthquakes spatiotemporally coincident with tremor and concluded that this seismicity was driven by fluid-included aseismic slip on minor faults. Without the notable increase in near-repeating earthquake activity, the 2015 swarm-like seismicity may not have been noticed. Thus, near-repeating earthquakes can be useful to identify and locate spontaneous transient aseismic slip.

We have demonstrated that near-repeating earthquakes are a useful proxy for triggered and spontaneous transient aseismic slip. This is particularly useful in the absence of tremor and LFEs. Few studies have identified tremor near Anza on the SJF. Triggered tremor composed of 12 LFEs was identified at ~13 km depth northwest of our study region near Anza during the Love-wave arrival of the 2002 $M_w$ 7.8 Denali earthquake.
However, triggered tremor was not identified following 43 other $M_w > 7.4$ teleseismic events analyzed from 2001 to 2011 (Wang et al., 2013), indicating that a high peak shear stress is required to trigger tremor near Anza. Hutchison and Ghosh (2017) found five discrete short-duration episodes of ambient tremor in June 2011 located near the Wang et al. (2013) triggered tremor at 13–24 km depth. In an attempt to identify LFEs associated with the aseismic slip transients triggered by the remote 2010 $M_w 7.2$ El Mayor-Cucapah earthquake and the local 2010 earthquake identified by Inbal et al. (2017) we selected the 12 LFEs during the 300 s triggered tremor episode from Wang et al. (2013) as templates and performed template matching for 2010 using 8 seismometers and similar methodology described in Section 3.1. We did not find any LFE detections. Other recent work similarly used these LFEs as templates and performed template matching from 2002 to 2016 and did not find LFE activity (Bürgmann et al., 2019). This work additionally attempted to identify LFEs within the ambient tremor detected by Hutchison and Ghosh (2017) to use as additional templates but were unsuccessful (Bürgmann et al., 2019). Further, they did not find transient signals above the noise level using a geodetic matched filter analysis on the local GPS network, other than a signal potentially related to the July 2010 aseismic transient identified by Inbal et al. (2017). In general, tremor episodes are infrequent in the Anza region or the anthropogenic noise level is too high for detection of ambient or triggered tremor. Further, the 2013 and 2016 afterslip were not large enough to be detectable with the local GPS network. The combined analysis of near-repeating earthquakes and BSM data allowed for the identification and analysis of these aseismic slip transients.

5.3. Deep Slip in the Trifurcation Area

The 2015 aseismic slip transient is the first evidence of any spontaneous aseismic slip in the trifurcation area near Anza. Although we find no direct evidence of other spontaneous or continuous creep events, $M_w > 4.5$ earthquakes have occurred at semi-regular intervals of every 3–5 years between 2001 and 2020. These fairly regular moderate-sized events might be loaded by deep creep that is not detected by BSMs and does not drive characteristic repeating earthquakes. The moderate-sized earthquakes themselves trigger aseismic slip transients near the locking depth that do drive near-repeating earthquakes. It is possible that the loading rate from afterslip is high enough to both drive near-repeating earthquakes and generate a noticeable strain change signal.

The afterslip following the 2010, 2013, and 2016 earthquakes is evidence that deep and moderate-depth transient aseismic slip can occur on each of the main fault strands of the trifurcation area, and on minor structures in the off-fault damage zone. This aseismic slip drives coplanar near-repeating earthquakes and abundant off-fault microseismicity. The 2015 aseismic slip transient is evidence that spontaneous aseismic slip can occur on small faults within the larger damage zone, mostly beneath the detection threshold of nearby BSM stations. It also provides evidence for aseismic slip within the seismogenic zone at a depth of 7–9 km. These observations favor a model where deep microseismicity is located in a transitional region at the bottom of the seismogenic zone with spatially heterogeneous frictional properties. Such an environment could produce frequent and sporadic aseismic slip transients of various sizes, potentially including many too small to drive numerous near-repeating earthquakes and beneath the detection threshold of nearby BSM stations.

5.4. Afterslip of Moderate-Sized Earthquakes

In general, afterslip following large earthquakes ($M_w > 7.5$) have moments equal to 10%–40% of the coseismic moment (Avouac, 2015; Bürgmann et al., 2002; Lin et al., 2013). The more limited observations of afterslip following small to moderate-sized earthquakes find a larger ratio of postseismic to coseismic moment, often with afterslip moment comparable to the mainshock moment (Alwahedi & Hawthorne, 2019; Bell et al., 2012; Fattahi et al., 2015; Freed, 2007; Furuya & Satyabala, 2008; Hawthorne, Simons, et al., 2016; Murray-Moraleda & Simpson, 2009; Taira et al., 2014). The large afterslip moments observed may reflect observational limitations; smaller afterslip is difficult to observe. Further, most of these observations are on terrestrial strike-slip faults with near-field land GPS networks and available InSAR data.

There have been several observations of large afterslip moments following moderate-sized earthquakes on the SAF. Taira et al. (2014) identified a year-long $M_w 5.22$ triggered slow slip transient following the $M_w 5.1$
1998 earthquake on the San Juan Bautista segment of the SAF using BSM data, GPS data, and repeating earthquakes. The 2004 $M_w$ 6 Parkfield earthquake-triggered afterslip with $M_w = 6.3$ (Freed, 2007) and the 2007 $M_w$ 5.4 Alum Rock earthquake on the Calaveras fault near the junction with the Hayward fault triggered afterslip with a comparable moment to the mainshock (Murray-Moraleda & Simpson, 2009). Using 12 BSMs near the San Juan Bautista and Parkfield segments of the SAF, Alwahedi and Hawthorne (2019) analyzed the coseismic and postseismic (1.5 days following the mainshock) moments of 11 local moderate-sized ($M_w$ 4–5) earthquakes and found the median postseismic moment is 0.45 times the coseismic moment. Although Alwahedi and Hawthorne (2019) are using a much smaller postseismic time frame for analysis than the previously mentioned work, it is still consistent with other observations of larger afterslip following moderate-sized earthquakes than large earthquakes.

During the study period of 2010–2016, we find that all $M_w > 4.5$ earthquakes in the trifurcation area southeast of Anza triggered moderate to deep afterslip or aseismic slip transients on different fault strands, each with a larger moment than the mainshock. This is consistent with other observations of moderate-sized earthquakes triggering large afterslip. It is therefore possible that in general, moderate-sized earthquakes trigger afterslip or aseismic slip transients of a comparable or larger moment than the mainshock. Another possibility is that these observations of moderate-sized earthquakes triggering large afterslip occur in unique locations. The trifurcation area on the Anza segment of the SJF is complex, splaying into three main fault strands with numerous smaller faults within fault-bounded damage zones. Further, the trifurcation area is located in a transitional coupling zone, southeast of the locked Anza seismic gap, and is the most seismically active fault zone in southern California. Similarly, the San Juan Bautista and Parkfield segments of the SAF where large afterslip has been well-documented following moderate-sized earthquakes (Alwahedi & Hawthorne, 2019; Taira et al., 2014), form the transition zones between locked and creeping segments of the SAF. In addition, the 2007 Alum Rock earthquake triggered comparable magnitude afterslip near the junction of the Calaveras and Hayward faults (Murray-Moraleda & Simpson, 2009). The frictional heterogeneity and transitional/partial locking in all of these locations may be the reason for the significant afterslip and strong coupling of seismic and aseismic slip. The interplay of seismic and aseismic slip in these locked to creeping transition zones is of particular interest because they have the greatest fault stressing rates and are likely points for nucleation of future large earthquakes.

5.5. April 2020 Earthquake and Triggered Aseismic Slip

On April 4, 2020, toward the conclusion of this study, a magnitude 4.9 earthquake occurred on the CF (Figures 1 and 9), northwest of the 2016 earthquake that also ruptured the CF. Although this earthquake occurred after our initial study period (2010–2016) and after creation of the QTM catalog, it is within our study region and provides an opportunity to validate our premise that all moderate-sized earthquakes in this region trigger aseismic slip accompanied by near-repeating earthquakes. We therefore performed a cursory analysis of near-repeating earthquakes, earthquake catalog data, and BSM data approximately 4 weeks before and after this earthquake to determine whether this moderate-sized earthquake-triggered aseismic slip.

We performed template matching similar to 2010–2016 using templates in the study region from March 1 to May 6, 2020 from the SCSN standard catalog (Hutton et al., 2010) with a local magnitude $\geq 1.5$ (237 templates) as well as templates with the same magnitude criteria from June 1 to July 31, 2016 (137 templates) from the QTM catalog that occurred during the 2016 slip transient also on the CF. We performed template matching using the 374 template earthquakes (Figure 9) from March 1 to May 6, 2020.

We find that following the 2020 earthquake there is a sharp increase in seismicity (Figures 9a and 9d; SCSN standard catalog), an increase in near-repeating earthquake activity (Figures 9a and 9d, Supporting Information Dataset S2), and a logarithmic transient signal on the strain data across the three nearest BSM stations (B086, B087, and B088; B084 was non-operational) and components (Figures 9d and S6) similar to the 2010, 2013, and 2016 triggered aseismic slip transients. This appears to be a newly detected triggered aseismic slip transient or afterslip following a moderate-sized local earthquake. At the time of writing, it appears that the largest strain changes on BSM stations occurred from April 4 to April 28, 2020 (Figures 9d and S6) and that the triggered aseismic slip transient has finished or has slowed significantly. However, it is too early to know if the aseismic slip transient may continue further in time. Since B084 was non-operational during
the aseismic slip transient, and B087 had significant outages before and during the aseismic slip transient, we did not model the triggered aseismic slip transient.

The depth of seismicity following the 2020 earthquake is most concentrated at 8–12 km depth (Figure S1), with most near-repeating earthquakes at 8.5–11 km depth (Figures 9a–9c). Few of the 2016 templates used detected near-repeating earthquakes, indicating that a different part of the CF was activated following the 2020 earthquake. The 2020 template earthquakes from the SCSN catalog have not been relocated with a 3D

Figure 9. Spatial distribution of the 2020 aseismic slip transient. (a) Seismicity map during the aseismic slip transient (April 4, 2020 to May 6, 2020), template earthquakes (green stars), near-repeating earthquake families (stars colored according to Julian day indicated on the color bar [also on b, c]), and the focal mechanism of the Mw 4.9 April 4, 2020 local earthquake. The study area is outlined with the red dashed line; faults are shown as black lines. (b) Fault parallel cross-section of seismicity and near-repeating earthquake families in the study area within 5 km of A-A’ during the aseismic slip transient. The majority of near-repeating earthquakes are outlined by the dashed magenta line. (c) Fault perpendicular cross-section of seismicity and near-repeating earthquake families in the study area within 5 km of B-B’ during the triggered aseismic slip transient. The Clark fault (CF) is indicated by a black dashed line. The geodetic locking depth (Lindsey et al., 2014) is indicated by the dashed gray line. The majority of near-repeating earthquakes are outlined by the dashed magenta line. (d) Seismicity rate (in study area outlined in a), near-repeating earthquakes, strain transient timing from BSM data (dark gray), potential timing of strain transient continuation (light gray), and one-week running average of BSM station B086 εEE+εNN component (black line). Near-repeating earthquakes are plotted by local magnitude and colored according to family.
velocity model or using waveform similarity and have error estimates of less than 3 km. Further, focal mechanisms are not yet available to help determine plane geometry of near-repeating earthquakes. However, we can still make a general estimate of an aseismic afterslip plane defined by the location of the majority of near-repeating earthquakes (Figures 8 and 9). It appears that aseismic slip occurs parallel to but off of the main CF, dipping at 75° to the northeast, and centered around the geodetic locking depth of 10 km. Overall, this appears to be newly detected moderate-depth triggered aseismic slip transient that drives coplanar near-repeating earthquakes and off-fault microseismicity. Agnew (2017) identified strain transients on the long baseline strainmeter at the Pinon Flat Observatory following the local events in 2010 and 2013 discussed here. He also reported very similar signals following two $M_{w} 5.0$ earthquakes near Anza in 2001 and 2005. This provides further support for our contention that all moderate-sized earthquakes in this region trigger aseismic slip transients accompanied by near-repeating earthquakes.

6. Conclusions

We find that all moderate-sized ($M_{w} > 4.5$) earthquakes in the Anza region of the SJF between 2010 and 2016 triggered deep to moderate-depth afterslip with larger moment than the mainshocks. This includes newly identified $M_{w} 5.6$ afterslip following the 2016 local earthquake. Following the 2010, 2013, and 2016 earthquakes, families of near-repeating earthquakes defined a dominant afterslip geometry consistent with strain change observations at nearby BSM stations. Their locations revealed that afterslip occurred on each of the main fault strands of the trifurcation area and on minor structures in the off-fault damage zone. We conclude that near-repeating earthquakes, similar to LFEs that make up tremor, are useful indicators of spontaneous and triggered aseismic slip transients and can identify the geometric complexities of these events. Further, the Anza region does not appear to be tremorgenic and aseismic slip transients are not consistently detected by the local GPS network; the combined analysis of near-repeating earthquakes and strainmeter data allowed for the identification and analysis of these aseismic slip transients. Serendipity allowed us to successfully use the April 4, 2020 $M_{w} 4.9$ local earthquake on the CF, that occurred at the termination of this study, to validate our expectation that all moderate-sized earthquakes in this region trigger afterslip or aseismic slip transients accompanied by near-repeating earthquakes.

The 2010, 2013, and 2016 moderate-to-deep afterslip add to a growing body of evidence that moderate-sized earthquakes generally trigger large afterslip. However, it is possible that observations of afterslip following moderate-sized earthquakes are biased toward larger signals, and large afterslip has been documented in unique locations. The trifurcation area of the SJF is located in a transitional coupling zone southeast of the Anza seismic gap with complex faulting. Similarly, the San Juan Bautista and Parkfield segments of the SAF and the junction of the Calaveras and Hayward faults where large afterslip has occurred are located in transition zones between locked and creeping segments. The frictional heterogeneity and transitional locking in all of these locations may be the reason for the significant afterslip observed and strong coupling of seismic and aseismic slip.

Finally, we report the first evidence of spontaneous aseismic slip near Anza from near-repeating earthquake families on two minor faults in 2015. This aseismic slip transient is evidence that spontaneous aseismic slip can occur on small faults within the larger damage zone, mostly beneath the detection threshold of nearby BSM stations. Although we find no direct evidence of other spontaneous or continuous creep events, it is possible that the fairly regular moderate-sized events that trigger large aseismic slip transients (i.e., afterslip) are loaded by deep creep. Taken together, our observations favor a model where deep microseismicity is located in a transitional region near the bottom of the seismogenic zone with spatially heterogeneous frictional properties. Such an environment could produce frequent and sporadic aseismic slip transients of various magnitude, some that are beneath the detection threshold of nearby BSM stations.

Data Availability Statement

Waveform data used in this study are available at the Incorporated Research Institutions for Seismology Data Management Center and the Southern California Data Center (https://doi.org/10.7914/SN/AZ; https://doi.org/10.7914/SN/CI). Borehole strainmeter data are available from the Plate Boundary Observatory Borehole Seismic Network (no DOI is registered for this network). The hypocentral locations and
best fit double couple solutions for the moderate-size triggering earthquakes are collected by the Southern California Seismic Network and publicly available at the Southern California Earthquake Data Center (2013) (scedc.caltech.edu). Maps and cross-sections were produced with the Generic Mapping Tools. Late Quaternary faults are from the U.S. Geological Survey and California Geological Survey.

Acknowledgments

The authors acknowledge support from the Southern California Earthquake Center (SCEC) Stress and Deformation Over Time (SDOT) Award #18160. The authors wish to thank Brent Delbridge and two anonymous reviewers who helped to improve the content and clarity of this manuscript. We are grateful to Kathleen Hodgkinson for assistance with the borehole strainmeter data.

References

Agnew, D. C. (2017). Understanding triggering of repeated aseismic strain changes in the Anza Gap. (Final Technical Report No. G14AP00071). United States Geological Survey.

Alwahedi, M. A., & Hawthorne, J. C. (2019). Intermediate-magnitude postseismic slip follows intermediate-magnitude (M 4 to 5) earthquakes in California. Geophysical Research Letters, 46(7), 3676–3687. https://doi.org/10.1029/2018GL081001

Annoura, S., Hashimoto, T., Kamaya, N., & Katsumata, A. (2017). Shallow episodic tremor near the Nankai Trough axis off southeast Mie prefecture, Japan. Geophysical Research Letters, 44(8), 3564–3571. https://doi.org/10.1002/2017GL073006

Araki, E., Saffer, D. M., Kopf, A. J., Wallace, L. M., Kimura, T., Machida, Y., et al. (2017). Recurring and triggered slow-slip events near the trench at the Nankai Trough subduction megathrust. Science, 356(6343), 1157–1160. https://doi.org/10.1126/science.aan3120

Avouac, J.-P. (2015). From geodetic imaging of seismic and aseismic fault slip to dynamic modeling of the seismic cycle. Annual Review of Earth and Planetary Sciences, 43(1), 233–271. https://doi.org/10.1146/annurev-earth-060614-105302

Bartlow, N. M. (2020). A long-term view of episodic tremor and slip in Cascadia. Geophysical Research Letters, 47(3), e2019GL085303. https://doi.org/10.1029/2019GL085303

Bartlow, N. M., Miyazaki, S. i., Bradley, A. M., & Segall, P. (2011). Space-time correlation of slip and tremor during the 2009 Cascadia slow slip event. Geophysical Research Letters, 38(18). https://doi.org/10.1029/2011GL048714

Beauducel, F. (2020). Okada: Surface deformation due to a finite rectangular source. March 4, 2020. Retrieved from https://www.mathworks.com/matlabcentral/fileexchange/25982-okada-surface-deformation-due-to-a-finite-rectangular-source

Bell, J. W., Amelung, F., & Henry, C. D. (2012). InSAR analysis of the 2008 Reno-Mogul earthquake swarm: Evidence for westward migration of Walker Lane style dextral faulting. Geophysical Research Letters, 39(18). https://doi.org/10.1029/2012GL052795

Bennett, R. A., Rodi, W., & Reilinger, R. E. (1996). Global Positioning System constraints on fault slip rates in southern California and northern Baja, Mexico. Journal of Geophysical Research, 101(B10), 21943–21960. https://doi.org/10.1029/96jb02488

Beroza, G. C., & Ide, S. (2011). Slow earthquakes and nonvolcanic tremor. Annual Review of Earth and Planetary Sciences, 39(1), 271–296. https://doi.org/10.1146/annurev-earth-040809-152531

Bourouis, S., & Bernard, P. (2007). Evidence for coupled seismic and aseismic fault slip during water injection in the geothermal site of Soultz (France), and implications for seismic processes at intermediate to great seismic events. Geophysical Journal International, 169(2), 723–732. https://doi.org/10.1111/j.1365-246X.2006.03325.x

Bürgmann, R. (2018). The geophysics, geology and mechanics of slow fault slip. Earth and Planetary Space Science, 495, 112–134. https://doi.org/10.1016/j.epsl.2018.04.062

Bürgmann, R., Ergintav, S., Segall, P., Hearn, E. H., McClusky, S., Reilinger, R. E., et al. (2002). Time-dependent distributed after-slip on and deep below the Izmit earthquake rupture. Bulletin of the Seismological Society of America, 92(1), 126–137. https://doi.org/10.1785/0220000833

Bürgmann, R., Frank, W., & Rouset, B. (2019). Multidisciplinary exploration for slow aseismic slip and low-frequency earthquakes in the Anza Gap (San Jacinto fault zone) (Report for SCEC Award #18014). Southern California Earthquake Center.

Chestler, S. R., & Creager, K. C. (2017b). Evidence for a scale-limited low-frequency earthquake source process. Journal of Geophysical Research, Solid Earth, 122(4), 3099–3114. https://doi.org/10.1002/2016JB017177

Delbridge, B. G., Carmichael, J. D., Nadeau, R. M., Shelly, D. R., & Bürgmann, R. (2020). Geodetic measurements of slow-slip events southeast of Parkfield, CA. Journal of Geophysical Research: Solid Earth, 125(5), e2019JB019059. https://doi.org/10.1029/2019JB019059

Dragert, H., Wang, K., & James, T. S. (2001). A silent slip event on the deeper Cascadia subduction interface. Science, 292(5521), 1525–1528. https://doi.org/10.1126/science.1000152

Fattahi, H., Amelung, F., Chaussard, E., & Wdowinski, S. (2015). Coseismic and postseismic deformation due to the 2007 M5.5 Ghazaband fault earthquake, Balochistan, Pakistan. Earth and Planetary Science Letters, 429, 3305–3312. https://doi.org/10.1016/j.epsl.2015.08.021

Furuya, M., & Satyabala, S. P. (2008). Slow earthquake in Afghanistan detected by InSAR. Geophysical Research Letters, 35(6). https://doi.org/10.1029/2008GL039155

Geller, R. J., & Mueller, C. S. (1980). Four similar earthquakes in central California. Geophysical Research Letters, 7(10), 821–824. https://doi.org/10.1029/GL007i010p00821

Hainzl, S. (2004). Seismicity patterns of earthquake swarms due to fluid intrusion and stress triggering. Geophysical Journal International, 158(3), 1090–1096. https://doi.org/10.1111/j.1365-246X.2004.02463.x

Hawthorne, J. C., Bostock, M. G., Boyer, A. A., & Thomas, A. M. (2016). Variations in slow slip moment rate associated with rapid tremor reversals in Cascadia. Geochemistry, Geophysics, Geosystems, 17(12), 4899–4919. https://doi.org/10.1002/2016GC006489
Hawthorne, J. C., Simons, M., & Ampuero, J. P. (2016). Estimates of aseismic slip associated with small earthquakes near San Juan Bautista, CA. *Journal of Geophysical Research: Solid Earth*, 121(11), 8254–8275. https://doi.org/10.1002/2016JB013120

Hodgkinson, K. (2013). Strainmeters capture strain transients following the M4.7 March 2013 Anza earthquake. February 24, 2020, Retrieved from https://www.unavco.org/highlights/2013/anza.html

Hodgkinson, K., Langbein, J., Henderson, B., Mencin, D., & Borsa, A. (2013). Tidal calibration of plate boundary observation borehole strainmeters. *Journal of Geophysical Research: Solid Earth*, 118(1), 447–458. https://doi.org/10.1002/2012JB009653

Hsu, Y.-J., Simons, M., Avouac, J.-P., Galetzka, J., Sieh, K., Chlieh, M., et al. (2011). Frictional afterslip following the 2005 Nias-Simeulue earthquake, Sumatra. *Science*, 332(5872), 1921–1926. https://doi.org/10.1126/science.1126960

Hutchison, A. A., & Ghosh, A. (2017). Ambient tectonic tremor in the San Jacinto fault, near the Anza gap, detected by multiple multi-seismic arrays. *Bulletin of the Seismological Society of America*, 107(5), 1985–1993. https://doi.org/10.1785/0120160385

Hutton, K., Woesner, J., & Hauksson, E. (2010). Earthquake monitoring in Southern California for seventy-seven years (1932-2008). *Bulletin of the Seismological Society of America*, 100(2), 423–446. https://doi.org/10.1785/120090130

Igarashi, T. (2010). Spatial changes of inter-plate coupling inferred from sequences of small repeating earthquakes in Japan. *Geophysical Research Letters*, 37(20). https://doi.org/10.1029/2010GL044609

Igarashi, T., Matsuzawa, T., & Hasegawa, A. (2003). Repeating earthquakes and interplate aseismic slip in the northeastern Japan subduction zone. *Journal of Geophysical Research*, 108(BS). https://doi.org/10.1029/2002JB001920

Inbal, A., Ampuero, J.-P., & Avouac, J.-P. (2017). Locally and remotely triggered aseismic slip on the central San Jacinto Fault near Anza, CA, from joint inversion of seismicity and strainmeter data. *Journal of Geophysical Research: Solid Earth*, 122(4), 3033–3061. https://doi.org/10.1002/2016JB013499

Ito, Y., Hino, R., Kido, M., Fujimoto, H., Osada, Y., Inazu, D., et al. (2013). Episodic slow slip events in the Japan subduction zone before the 2011 Tohoku-Oki earthquake. *Tectonophysics*, 600(Suppl C), 14–26. https://doi.org/10.1016/j.tecto.2012.08.022

Jiang, J., & Filcko, Y. (2016). Reconciling seismicity and geodetic locking depths on the Anza section of the San Jacinto fault zone. *Nature Geoscience*, 9(10), 699–704. https://doi.org/10.1038/ngeo940

Kimura, H., Kasahara, K., Igarashi, T., & Hirata, N. (2006). Repeating earthquake activities associated with the Philippine Sea plate subduction in the Kanto district, central Japan: A new plate configuration revealed by interplate aseismic slips. *Tectonophysics*, 417(1–2), 101–118. https://doi.org/10.1016/j.tecto.2005.06.013

Lengliné, O., & Marsan, D. (2009). Inferring the coseismic and postseismic stress changes caused by the 2004 Mw = 6 Parkfield earthquake from variations of recurrence times of microearthquakes. *Journal of Geophysical Research*, 114(B10). https://doi.org/10.1029/2008JB006118

Li, C., Peng, Z., Yao, D., Guo, H., Zhan, Z., & Zhang, H. (2018). Abundant aftershock sequence of the 2015 Mw 7.5 Hindu Kush intermediate-depth earthquake. *Tectonics*, 37(6), 2611–2628. https://doi.org/10.1002/2017TC004352

Lin, Y. N., Sladen, A., Ortega-Culaciati, F., Simons, M., Avouac, J.-P., Fielding, E. J., et al. (2013). Coseismic and postseismic slip associated with the 2010 Maule earthquake, Chile: Characterizing the Arauco Peninsula barrier effect. *Journal of Geophysical Research: Solid Earth*, 118(6), 3142–3159. https://doi.org/10.1002/jgrb.50207

Lindsay, E. O., & Filcko, Y. (2013). Geodetic slip rates in the southern San Andreas fault system: Effects of elastic heterogeneity and fault geometry. *Journal of Geophysical Research: Solid Earth*, 118(2), 689–697. https://doi.org/10.1002/jgrb.500935

Lindsay, E. O., Sahakian, V. J., Filcko, Y., Rock, Y., Barbot, S., & Rockwell, T. K. (2014). Intersieve strain localization in the San Jacinto fault zone. *Pure and Applied Geophysics*, 171(11), 2997–3014. https://doi.org/10.1007/s00246-013-0753-z

Lehman, R. B., & McGuire, J. J. (2007). Earthquake swarms driven by aseismic creep in the Salton Trough, California. *Journal of Geophysical Research*, 112(B4). https://doi.org/10.1029/2006JB004596

Meng, L., Huang, H., Bürgmann, R., Ampuero, J. P., & Strader, A. (2015). Dual megathrust slip behaviors of the 2014 Iquique earthquake sequence. *Earth and Planetary Science Letters*, 411, 177–187. https://doi.org/10.1016/j.epsl.2014.11.041

Meng, X., & Peng, Z. (2016). Increasing lengths of aftershock zones with depths of moderate-size earthquakes on the San Jacinto Fault zone. *Journal of Geophysical Research: Solid Earth*, 121(11), 8254–8275. https://doi.org/10.1002/2016JB013120

Murray-Moraleda, J. R., & Simpson, R. W. (2009). Geodetically inferred coseismic and postseismic slip due to the M 5.4 31 October 2007 Alum Rock earthquake. *Bulletin of the Seismological Society of America*, 99(5), 2784–2800. https://doi.org/10.1785/0120090007

Nadeau, R. M., Foxall, W., & McEvilly, T. V. (1995). Clustering and periodic recurrence of microearthquakes on the San Andreas fault at Parkfield, California. *Science*, 267(5217), 503–507. https://doi.org/10.2307/2886200

Nadeau, R. M., & Johnson, L. R. (1998). Seismological studies at Parkfield VI: Moment release rates and estimates of source parameters for small repeating earthquakes. *Bulletin of the Seismological Society of America*, 88(3), 790–814.

Nadeau, R. M., & McEvilly, T. V. (1999). Fault slip rates at depth from recurrence intervals of repeating microearthquakes. *Science*, 285(5428), 718–721. https://doi.org/10.1126/science.285.5428.718

Okada, Y. (1985). Surface deformation due to shear and tensile faults in a half-space. *Bulletin of the Seismological Society of America*, 75(4), 1135–1154.

Ozawa, S., Suito, H., & Tobita, M. (2007). Occurrence of quasi-periodic slow-slip off the east coast of the Boso peninsula, Central Japan. *Earth, Planets and Space*, 59(12), 1241–1245. https://doi.org/10.1186/B11817

Peng, Z., & Gomberg, J. (2010). An integrated perspective of the continuum between earthquakes and slow-slip phenomena. *Nature Geoscience*, 3(9), 599–607. https://doi.org/10.1038/NGEO940

Perfettini, H., & Avouac, J.-P. (2004). Postseismic relaxation driven by brittle creep: A possible mechanism to reconcile geodetic measurements and the decay rate of aftershocks, application to the Chi-Chi earthquake, Taiwan. *Journal of Geophysical Research*, 109(B2). https://doi.org/10.1029/2003JB002488

Perfettini, H., Avouac, J.-P., & Ruegg, J.-C. (2005). Geodetic displacements and aftershocks following the 2001 Mw=8.4 Peru earthquake: Implications for the mechanics of the earthquake cycle along subduction zones. *Journal of Geophysical Research*, 110(B9). https://doi.org/10.1029/2004JB003522
Yang, W., Hauksson, E., & Shearer, P. M. (2012). Computing a large refined catalog of focal mechanisms for Southern California (1981-2010): Temporal stability of the style of faulting. Bulletin of the Seismological Society of America, 102(3), 1179–1194. https://doi.org/10.1785/0120110311

Yao, D., Walter, J. I., Meng, X., Hobbs, T. E., Peng, Z., Newman, A. V., et al. (2017). Detailed spatiotemporal evolution of microseismicity and repeating earthquakes following the 2012 Mw 7.6 Nicoya earthquake. Journal of Geophysical Research: Solid Earth, 122(1), 524–542. 2016JB013632. https://doi.org/10.1002/2016JB013632

Yu, W.-C., Song, T.-R. A., & Silver, P. G. (2013). Repeating aftershocks of the great 2004 Sumatra and 2005 Nias earthquakes. Journal of Asian Earth Sciences, 67–68(68), 153–170. https://doi.org/10.1016/j.jseaes.2013.02.018