Off-fault Seismicity Suggests Deep Creep on the Northern San Jacinto Fault

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Key Points:

- Crustal deformation models demonstrate the plausibility of deep creep along the northern San Jacinto fault to account for nearby enigmatic normal slip mechanisms
- Microseismicity that records off-fault deformation may record stresses that differ from interseismic loading of the primary fault surfaces
- Where faults exhibit creep at any crustal level, caution should be used in the inversion of nearby focal mechanisms for interseismic fault loading

Abstract

Within the San Bernardino basin, focal mechanisms show normal slip events that are inconsistent with the interseismic strike-slip loading of the nearby San Jacinto and San Andreas faults. The discrepancy may owe to deep (> 10 km depth), creep along the northern San Jacinto fault. The enigmatic normal slip events occur to the northeast of the fault and primarily below 10 km depth, consistent with off-fault deformation due to spatially non-uniform deep creep rates. Consequently, if these normal slip events are included in stress inversions from the seismic catalog, the results may provide inaccurate information about fault loading. Here, we show that models with deep creep on the northern San Jacinto fault that match first-order pattern of observed normal slip focal mechanisms in the basin and that this deep creep cannot be detected with GPS data due to the proximity of the San Andreas fault.

Plain Language Summary

Over the past 36 years, seismic stations have recorded the style of deformation from thousands of small earthquakes in the San Bernardino basin, California. Within this basin, many earthquakes below 7.5 depth show deformation that doesn't match what we expect for this region during the current period between large damaging earthquakes along the San Jacinto and San Andreas faults. Rather than showing expected horizontal slip, many of these earthquakes show vertical movement. We use crustal deformation models to show that vertical movement can be produced in the basin if the northern portion of the San Jacinto fault creeps at depth; this portion of the fault is constantly moving rather than locked, like the San Andreas. Traditional GPS-based approaches to detect deep creep don't work here because the faults are too close to one another. The findings of this study demonstrate that small earthquakes that occur adjacent to and between faults can have very different style of deformation than the large ground rupturing earthquakes produced along active faults. This means that scientists should not use the information recorded by these small earthquakes in the San Bernardino basin to predict loading of the San Andreas and San Jacinto faults.

1 Introduction

The assumption built into seismic hazard assessments, such as Unified California Earthquake Rupture Forecast (Field et al., 2014), is that the seismic catalog collected over the past several decades accurately represents the loading of active faults within California. This assumption is challenged by the limited duration of the seismic catalog compared to the 100-1000 year recurrence intervals along most faults within California. For example, during the recording of the seismic catalog, the San Andreas fault (SAf) south of Cajon Pass has had fewer earthquakes than smaller nearby faults (e.g. Yang et al., 2012). Although this fault has the greatest potential for large earthquakes in southern California (e.g. Field et al., 2014), it is relatively under-sampled within the seismic catalog. Furthermore, small earthquakes in the crust may record off-fault deformation rather than slip along the primary slip planes of active faults (Cheng et al., 2018). Where off fault deformation differs from loading of the primary faults, the stress state inferred from microseismicity may not accurately reflect the interseismic loading of the major active faults capable of producing ground rupturing earthquakes.

While we might expect the focal mechanisms from recorded microseismicity along the southern SAf system to reveal that dextral deformation dominates this system, Yang et al. (2012) show that some regions, such as the San Bernardino basin, produce predominantly normal-slip events (Fig. 1a). These focal mechanisms contrast the observations of long-term strike-slip along the nearby SAf (e.g. McGill et al., 2013; McGill et al., 2015) and San Jacinto fault (SJf) (e.g. Anderson et al., 2004; Onderdonk et al., 2015). The normal slip focal mechanisms also disagree with crustal deformation models of the region that show dextral interseismic loading (e.g. Johnson, 2013; Fig. 1b; Loveless and Meade, 2011; Smith-Konter et al., 2011). This discrepancy suggests that the seismicity in the San Bernardino basin is not consistent with the loading of the SAf and SJf flanking the basin.

Some of the normal slip events that occur just to the northeast of the northern San Jacinto fault, have been associated with secondary normal faults reveal by geophysical imaging of the top of basement (Anderson et al., 2004). Small normal faults trend sub-parallel to the SJf and bound the edges of a local basement low that developed where the SJf changes strike (Fig. 1c). While co-seismic slip along the SJf could promote extension of this basin, the production of normal slip earthquakes during the interseismic period when these faults are presumed to be locked throughout the seismogenic crust remains enigmatic. Furthermore, the occurrence of normal slip earthquakes extends beyond the geophysically imaged extensional basin. The San Bernardino basin is expected to have dextral loading between large earthquake events on the SAf and SJf (Fig. 1b).

Slip gradients along strike-slip faults, such as near the tips of earthquake ruptures, can produce off-fault stresses and subsequent aftershocks that differ from the loading of the faults (e.g. Hardebeck, 2014; Oppenheimer, 1990). Yang et al. (2012) report temporary changes in focal mechanism slip sense after large magnitude earthquakes in southern California. Cheng et al. (2018) report off-fault aftershocks that have distinct slip sense from the events that occur along the Anza segment of the San Jacinto fault, to the south of the study area of this study. Because the San Bernardino basin has not experienced a large event during the catalog record, we propose that spatially non-uniform creep at depth along the northern SJf may drive the observed normal slip microseismicity in the San Bernardino basin. Consequently, the microseismicity in our multi-decadal catalog may record both interseismic dextral loading of the region as well as off-fault deformation associated with deep creep on the northern SJf. We use crustal deformation models to show the potential for slip to produce off-fault microseismicity that obfuscates our interpretation of fault loading from the seismic catalog.

2. Methods

2.1 Reliable catalog of focal mechanisms in the San Bernardino basin

We analyze the three-dimensional distribution of focal mechanisms in the San Bernardino basin to assess the spatial pattern of the enigmatic normal slip events. A catalog of relocated southern California focal mechanisms from January 1981 through September 2016 are

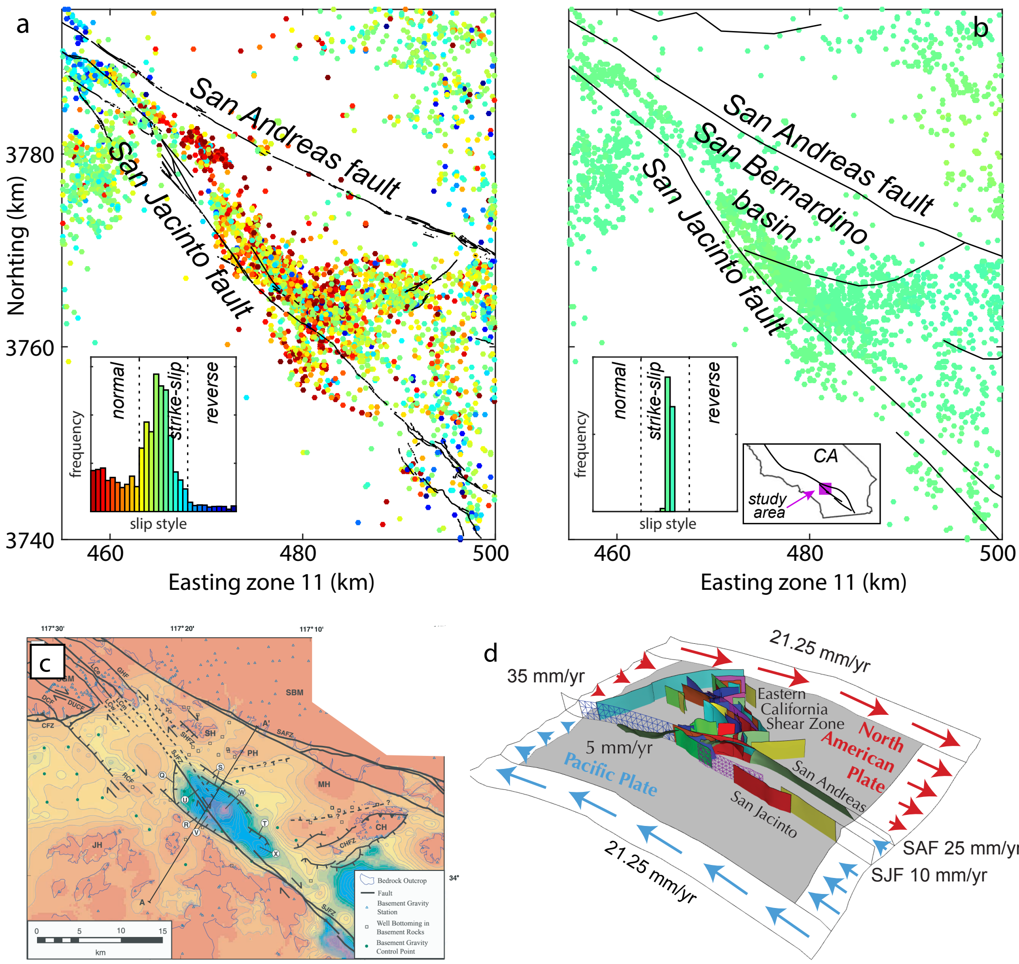

Figure 1. a) High quality focal mechanisms (nodal plane uncertainty < 45˚) from 1981 through September of 2016 in the relocated catalog of (Hauksson et al., 2012) with traces of faults active within the last 15 ka (USGS & CGS, 2006). Colors show slip sense with tangent of slip rake scaled to the 0-3 range of Aϕ slip sense (Simpson, 1997). b) Slip sense predicted by interseismic crustal deformation model of D at locations of the seismic events recorded in the catalog. Traces of modeled faults shown in black. Insets show histograms of slip sense. The normal slip events within the San Bernardino basin are not expected from loading between large earthquakes. c). Basement depth inverted from gravity data shows secondary normal faults that flank the San Jacinto fault (taken from Anderson et al., 2004). The normal slip focal mechanisms extend beyond the interpreted graben. d) Model of 63 active faults in the region used to build the steady state and interseismic models of crustal deformation. The lateral edges of the horizontal crack are loaded with plate velocities to simulate the regional tectonic loading (taken from Beyer et al., in revision).

available from the Southern California Earthquake Center database (Hauksson et al., 2012). We limit the analysis to high-quality events, with nodal plane uncertainty < 45˚ (Yang et al., 2012). Figure 2a shows the 6081 high-quality events between Easting 455000 and 500000 meters UTM zone 11 and Northing 3740000 and 3795000 meters. In this region, the mean slip sense assessed with a 600-event moving window remains around $A\phi = 1.2$ during the time period of the catalog, indicating overall normal and strike-slip events (black line on Fig. 2a).

Excluding earthquakes smaller than the magnitude completeness limit eliminates bias of including small events that are recorded because they occur close to seismic instruments. The completeness limit of the San Bernardino basin seismic catalog improves with time as seismic stations are added to the network. We calculate the evolving magnitude completeness limit using the maximum curvature method (Wiemer and Wyss, 2000) for a moving window of 600 events advanced in increments of 100 events. The magnitude completeness improves around 2002 and 2012 so that we can define three epochs of magnitude completeness limits (red line on Fig. 2b). To determine a reliable catalog of events that exceed completeness, we exclude earthquakes smaller than M2 for epoch1 (1981 – 2001), smaller than M1.5 for epoch2 (2002-2011), and smaller than M1.0 for epoch3 (2012 – September 2016). The resulting catalog of 3920 reliable events shows consistent slip sense ($A\phi = 1.2$) throughout the 36-year catalog, suggesting that the catalog is not significantly impacted by transient changes, such as stress changes from nearby large earthquakes or anomalous periods of enhanced normal faulting (Fig. 2c).

2.2 Steady-state and interseismic crustal models of the region

To simulate the stresses in the San Bernardino basin that drive interseismic microseismicity, we have developed 3D Boundary Element Method stressing rate models that simulate interseismic loading between earthquakes using a two-step approach. For the first step, multiple earthquake cycles are simulated in a steady-state model where all portions of the fault surfaces slip. The second step of the approach implements a back-slip approach to simulate the interseismic loading of the faults, where the slip distribution from the steady-state model is applied to faults below the locking depth (e.g. Marshall et al., 2009).

For the first stage of interseismic model development, we produce a steady-state model of crustal deformation over many earthquake cycles. The model incorporates active faults surfaces of the region based on the SCEC Community Fault Model v. 4.0 and re-meshed for more uniform triangular element size and coincident nodes along fault intersections (Fig. 1d). The fault geometry used in this study follows that of the preferred model of Beyer et al. (in revision) with revised resolution of the San Jacinto fault (average element length ~ 2.6 km). Within the 3D models, faults are extended to 35 km depth, where they merge with a horizontal crack. Deformation along this crack simulates distributed deformation below the seismogenic crust. Following Beyer et al. (in revision) this study applies a plate tectonic movement equivalent to 47.5 mm/yr at 322.5˚ (e.g. DeMets et al., 2010) to the sides of the model that parallel plate velocity and a velocity gradient along the sides of the model perpendicular to plate velocity. Where faults meet the lateral edges of the model, the applied velocity has a step and

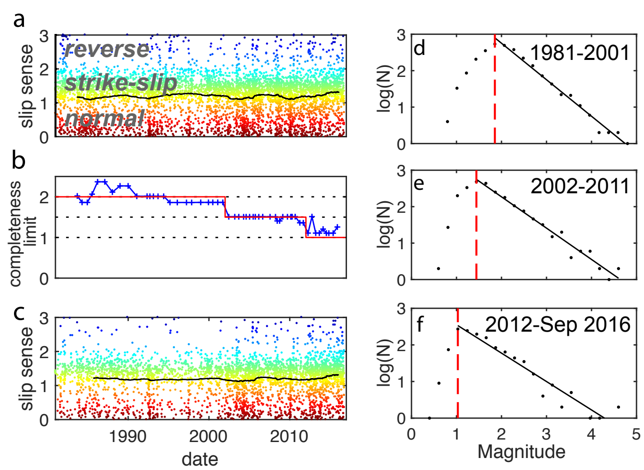

Figure 2. a) Focal mechanisms from Hauksson et al. (2012) within the region of Figure 1. The average slip sense for moving window of 600 events shown with black line. Warm colors are normal events, cool colors are reverse events, and green are strike-slip events. b) Magnitude completeness limit for a moving window of 600 events advanced in 100 event increments shown in blue. The stepped red line shows the three stages of magnitude completeness during the record. C) The 3920 events that exceed the three-phased magnitude completeness limit have mean Aϕ of 1.2 ± 0.04, indicating limited variation in slip sense during the record. (d-e) The log of frequency demonstrates the completeness of the catalog for each epoch: 1981 through 2001 (d), 2002 through 2011 (e) and after 2012 (f). The completeness limit (red dashed line) decreases in each successive epoch.

corresponding slip rates are applied to the endmost patch of the fault to avoid slip rates going to zero at these artificial fault tips (Fig. 4a). The shear traction-free faults in the center of the model slip in response to tectonic loading and interaction with each other. This low shear traction simulates dynamic conditions when most of the fault slip occurs.

To simulate interseismic loading between large earthquakes, the interseismic models apply slip rates from the long-term model below a prescribed locking depth. Using this approach, these interseismic models can simulate deep creep. To avoid a sharp step between slipping and locked regions, fault elements within a 2.5 km high transitional band above the locking depth are prescribed 50% of the slip rate values of the long-term model. We explore the impact of varying locking depth from 7.5 to 20 km along the San Jacinto fault while all other faults have a 20 km locking depth. In all the models, stress tensors are sampled at points in the model corresponding to the locations of reliable focal mechanisms. This allows the model results to be directly compared to the observed seismicity.

3. Focal mechanism distribution supports deep creep along the northern San Jacinto fault

Three aspects of the three-dimensional distribution of interseismic events in the San Bernardino basin are consistent with deep creep along the northern SJF. Firstly, the contrast of high rate of microseismicity along the SJF compared to the quiet nearby SAF (Fig. 3a). Observations of abundant microsiesmicity adjacent to creeping faults (e.g. Harris, 2017) support the inference that the SJF could have active creep whereas the SAF is currently locked. Secondly, projecting the focal mechanisms of the reliable catalog into a north-south profile reveals that most of the enigmatic normal slip events of the San Bernardino basin occur below ~7.5 km depth (Fig. 3b). If the creep is contributing to the off-fault normal slip microseismcity, then the fault below this depth may be creeping. Along the Anza section of the San Jacinto fault, south of this study area, normal slip microsiesmicity also occurs near the SJf at depths of 10-13 km (Cheng et al., 2018). The discrepancy between locking depth of the Anza section of the SJf and base of seismicity have led to inference of creep below 10 km along this section of the SJf (Wdowinski, 2009), consistent with the depths of off-fault normal microseismicity.

The third aspect of the focal mechanism distribution that supports deep creep is that the normal slip focal mechanisms are primarily located northeast, and not southwest, of the SJF (Fig. 3a). This pattern is consistent with the results of steady-state crustal deformation models of the region that simulate deformation over multiple earthquake cycles (Resor et al., 2018; Fig. 4b). This model shows a southward increasing dextral slip rate along the northern San Jacinto fault that produces a region of positive dilation (increased mean normal tension) within the San Bernardino basin. This long-term dilation can promote normal slip events by unclamping potential slip surfaces relative to those outside of the basin. The location of off-fault dilation correlates to the location of slip rate gradient along the SJf (Fig. 4b). Consequently, deep dilation consistent with the occurrence of normal slip events below ~7.5 km in the San Bernardino basin may be associated with creep along the SJf below ~7.5 km. Taken together, the three-

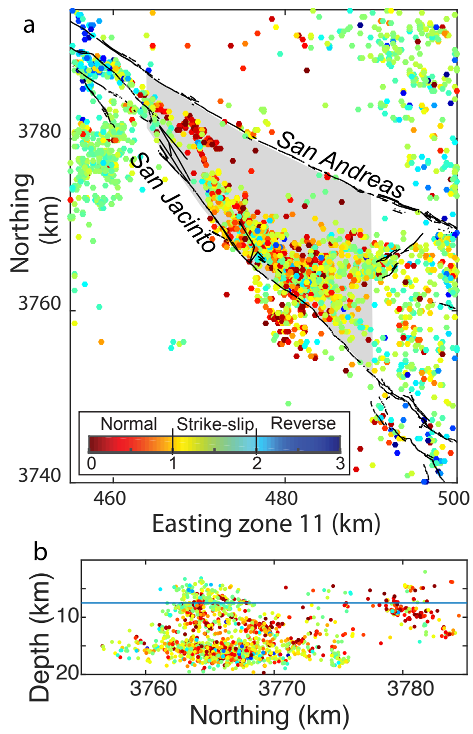

Figure 3. a) Map view of reliable focal mechanisms that pass the completeness test colored by slip sense. Enigmatic normal slip events occur within the San Bernardino basin, between the San Andreas and San Jacinto faults. Dashed fault traces are the graben bounding normal faults imaged by Anderson (2004) in Fig. 1C. b) Focal mechanisms of the San Bernardino basin (grey region of a) projected into a N-S profile. Slip sense color same as in a. The normal slip focal mechanisms within the San Bernardino basin occur predominantly below 7.5 km depth

dimensional distribution of focal mechanisms within the San Bernardino basin is consistent with southward increasing creep rate along the northern SJF at depth.

4. Simulating deep creep on the northern San Jacinto fault

To investigate the impact of deep interseismic creep on the northern San Jacinto fault, we investigate the sensitivity of focal mechanism slip sense within the San Bernardino basin to locking depth along the northern SJf (San Bernardino and San Jacinto Valley segments). The interseismic models apply 20 km locking depth on all other faults, consistent with the general base of seismicity of the region (e.g. Yang et al., 2012). The overall slip sense of microseismicity within the San Bernardino basin (grey region in Fig. 5a) is best matched by interseismic models with locking depth < 12.5 km along the northern SJF (Fig. 5b). Results for locking depths of 7.5 and 10 km show similar fit within 1σ. The interseismic model with 10 km locking depth produces normal slip events that are spatially consistent with the observed enigmatic normal slip focal mechanisms within the San Bernardino basin (Fig. 5a). The normal slip events in the interseismic model occur to the northeast of the San Jacinto fault near the gradient in dextral slip rate along the fault.

While creep below 10-13 km has been inferred along the southern San Jacinto fault from geodetic evidence of shallow locking depths (Fialko, 2006; Smith-Konter et al., 2011; Wdowinski, 2009), geodetic inversions for the northern San Jacinto fault suggest a deep (~20 km) locking depth (Smith-Konter et al., 2011). Because the San Jacinto and San Andreas faults approach within 10 km of each other at the San Bernardino basin, the inversions of geodetic data for locking depth in this region may not distinguish the independent locking depths of the SJf and SAf. To explore this, we compare the interseismic velocities at GPS sties from two models: one that has 15 km locking depth on all faults and another that has 10 km locking depth on the northern SJf and 20 km on all other faults. The station velocities from the two models cannot be distinguished from the observed GPS station velocities determined by Herbert at al. (2014) (Fig. 5c). Consequently, geodetic data cannot eliminate deep creep on the northern San Jacinto fault as a potential mechanism for the off-fault normal slip microseismicity within the San Bernardino basin.

5. Discussion

Some differences in the predicted interseismic slip sense at locations of microseismicity and observed slip sense reveal aspects of the model that may not adequately capture the 3D complexity of active deformation along the San Jacinto fault. Within the model, normal slip microseismity occurs within a narrow band adjacent to the SJf with strike-slip and reverse events outside of this band where the catalog records a combination of normal and strike-slip focal mechanisms. The nature of fault surface discretization within the model leads to artificially linear and abrupt transitions from slipping to transitional (1/2 long term slip rate) to locked portions of the fault. These abrupt transitions may produce a more localized pattern of normal slip microseismicy than observed. Furthermore, the model does not consider host rock

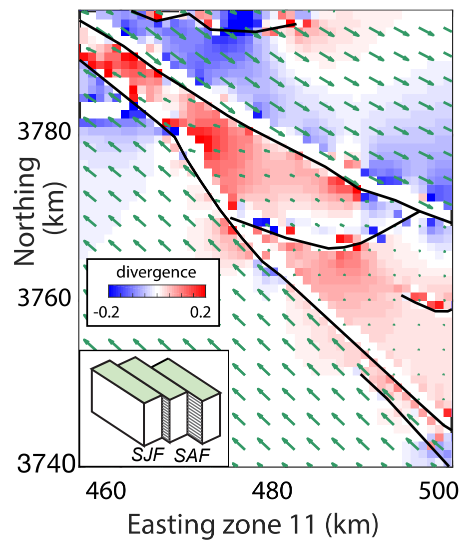

Figure 4. Green arrows show the velocities from the steady state model that simulates many earthquake cycles. The divergence of this velocity field reveals regions of overall contraction (negative dilation blue) and extension (positive dilation red) due to slip distribution along the faults. Inset cartoon shows the set-up of the steady-state model.

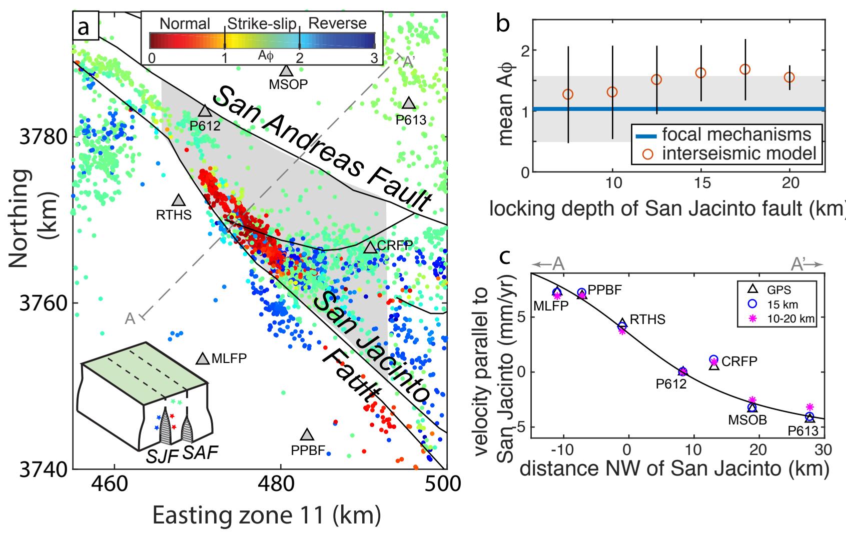

Figure 5. a) Slip sense at locations of microseismicity from the interseismic model with shallow locking depth (10 km) on the San Jacinto fault to simulate deep creep. The locking depth on all other faults is 20 km. Inset cartoon shows the set-up of the interseismic model. Normal slip events occur within the San Bernardino basin. GPS stations shown with labeled triangles. b) Mean interseismic slip sense for events within light grey region of A shown with 1σ vertical bars. Models with SJf locking depth < 12.5 km better match the mean slip sense of focal mechanisms in the San Bernardino Basin. c) Transect along A-A' (shown in A) of GPS station velocity parallel to the San Jacinto fault (Herbert et al., 2014), and velocity predictions from the interseismic model with a shallow locking depth on the SJf (pink star, same as results shown in a) and interseismic model with a 15 km locking depth on all faults (blue circle). The surface velocities cannot resolve deep slip on the SJf because of its proximity to the SAf.

heterogeneities and deformation along secondary faults (e.g. Anderson et al., 2004) that could act to promote interseismic normal slip microseismicity over a wider region. For example, deep creep along strands parallel to the modeled San Jacinto fault would broaden the predicted zone of off-fault normal faulting.

Deep creep along the northern San Jacinto fault may impact seismic hazard estimates on this fault. Both the accommodation of slip along the fault and the accommodation of off-fault deformation within the adjacent crust via microseismicity and aseismic pervasive deformation mechanisms may reduce the interseismic loading on the deeper portion of the northern SJf, thereby reducing seismic hazard. We might also expect moderate or large earthquake to nucleate at the transition between creeping and locked portions (Harris, 2017). Shallow sections of the northern SJf may have increased loading due to deep creep and greater potential for large earthquakes.

The correlation between the slip sense of focal mechanism in the San Bernardino basin and patterns of off-fault stressing rate from interseismic models with shallow locking depth on the San Jacinto fault suggests that the interseismic microseismicity of the basin records a component of permanent distributed off-fault deformation in the basin. This result is consistent with a recent study of normal slip focal mechanisms along the Anza section of the SJf (Cheng et al., 2018). If the focal mechanisms of the basin were inverted to estimate interseismic stresses on the SJf and SAf, they would predict normal loading contrary to the long-term slip record of these faults. Using microseismicity that records this off-fault deformation may produce erroneous estimates of interseismic fault loading. Within the San Bernardino basin, the errors of focal mechanism inversions for fault stressing rate are compounded by the under-sampling of strike-slip events along the relatively quiet SAf. This study suggests that where faults creep, spatially non-uniform creep rates may produce non-representative off-fault focal mechanisms. This non-representation is similar to that of aftershocks near rupture ends that have different focal mechanisms than the rupture (e.g. Hardebeck, 2014; Oppenheimer, 1990). Hence, where faults exhibit creep at any crustal level, caution should be used in the inversion of nearby focal mechanisms for interseismic fault loading.

Acknowledgments, Samples, and Data

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Figure Captions

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Figure 3. a) Map view of reliable focal mechanisms that pass the completeness test colored by slip sense. Enigmatic normal slip events occur within the San Bernardino basin, between the San Andreas and San Jacinto faults. Dashed fault traces are the graben bounding normal faults imaged by Anderson (2004) in Fig. 1c. b) Focal mechanisms of the San Bernardino basin (grey region of a) projected into a N-S profile. Slip sense color same as in a. The normal slip focal mechanisms within the San Bernardino basin occur predominantly below 7.5 km depth.

Figure 4. Green arrows show the velocities from the steady state model that simulates many earthquake cycles. The divergence of this velocity field reveals regions of overall contraction

(negative dilation blue) and extension (positive dilation red) due to slip distribution along the faults. Inset cartoon shows the set-up of the steady-state model.

Figure 5: a) Slip sense at locations of microseismicity from the interseismic model with shallow locking depth (10 km) on the San Jacinto fault to simulate deep creep. The locking depth on all other faults is 20 km. Inset cartoon shows the set-up of the interseismic model. Normal slip events occur within the San Bernardino basin. GPS stations shown with labeled triangles. b) Mean interseismic slip sense for events within light grey region of A shown with 1σ vertical bars. Models with SJf locking depth < 12.5 km better match the mean slip sense of focal mechanisms in the San Bernardino Basin. c) Transect along A-A’ (shown in A) of GPS station velocity parallel to the San Jacinto fault (Herbert et al., 2014), and velocity predictions from the interseismic model with a shallow locking depth on the SJf (pink star, same as results shown in A) and interseismic model with a 15 km locking depth on all faults (blue circle). The surface velocities cannot resolve deep slip on the SJf because of its proximity to the SAf.