Project Report 20150: Refining the timing and mechanics of San Jacinto-San Andreas joint rupture through Cajon Pass

Summary

Large, multi-fault earthquakes increase the threat of strong ground-shaking and reshape event probabilities across a system of faults. Fault junctions act as conditional barriers, or earthquake gates, that stop most earthquakes but permit junction-spanning events when stress conditions are favorable. Constraining the physical conditions that favor multi-fault earthquakes requires information on the frequency of isolated events versus events that activate faults through the junction. Measuring this frequency is challenging because dating uncertainties limit the correlation of paleoseismic events at different faults, requiring a direct approach to measuring rupture through an earthquake gate. We proposed to dig a paleoseismic trench of the Lytle Creek Ridge Fault, a small aseismic low-angle normal fault located within the releasing step-over between the San Andreas and the San Jacinto faults at Cajon Pass. We show that co-rupture of the San Andreas and San Jacinto faults through the Cajon Pass earthquake gate occurred at least three times in the past 2000 years, most recently in the historic 1812 earthquake. We supplement our paleoseismic dataset with quasistatic finite element models of the 1812 and the 1857 events to determine what mechanical conditions favor rupture linkage through Cajon Pass. We found that gate-breaching events taper steeply and halt abruptly as they transfer slip between faults. Comparison to independent chronologies showed that the San Andreas and the San Jacinto faults co-rupture with a frequency of 0.25 to 0.30, making multi-fault events a relatively common occurrence at Cajon Pass.

Intellectual merit

Physical modeling and modern observations show that multiple faults can link up in surprising ways to produce unexpectedly large earthquakes. This is an acute challenge to forecasting seismic hazard because it affects both the frequency and extent of large, damaging, surface-rupturing earthquakes. Up until now, it has remained impossible to concretely show that faults ruptured together in a pre-historic earthquake. In this contribution, we show that the two highest-hazard faults in southern California, the San Andreas and the San Jacinto faults, ruptured together three times in the past 2000 years, most recently in the historical 1812 earthquake, relying on the slip history of an aseismic secondary fault. We estimate the San Andreas and the San Jacinto faults co-rupture with a frequency of 0.25 to 0.30 and a recurrence interval of ~660 years. The relatively common occurrence of gap-bridging events at this location provides crucial information for long-term hazard estimates for the state of California. The approach of combining paleoseismic chronologies with modeling triggered secondary fault slip has never been applied before and has the potential to be used at other junctions of hazardous faults worldwide.

Broader impacts

This project contributes directly to understanding the frequency of multi-fault earthquakes through the densely populated LA Basin, a key component of long-term hazard assessment models for the state of California. This project provided research fellowship support for University of California, Davis graduate student Alba M. Rodriguez, including travel to research conferences and analyses that will contribute to one research publication (submitted).

Technical report

Collectively, the San Andreas fault and San Jacinto fault carry the majority of Pacific-North America plate motion through southern California and produce frequent, large, surface-rupturing earthquakes[1,2]. The San Jacinto fault terminates in a 3.5km wide releasing step-over with the San Andreas fault at Cajon Pass, where their surface traces do not intersect[3]. The potential for rupture transfer through this step-over has been demonstrated through dynamic modeling and by synthetic earthquake catalogs[4,5], but previously lacked direct observational constraints. Earthquake chronologies from paleoseismic sites are available for the San Andreas fault[6,7] and the San Jacinto fault[8,9]. However, the alignment of the northernmost San Jacinto fault with major river canyons draining the eastern San Gabriel Mountains presents a challenging geomorphic setting for recording earthquake event chronologies within the earthquake gate.

We identified and mapped the Lytle Creek Ridge Fault (LCRF), a low angle normal fault that bridges the releasing step-over between the San Jacinto and the San Andreas faults (Figure 1). The LCRF strikes west over a distance of at least 3 km and dips north at 25-30°. McCalpin and Hart[10] previously identified scarps on the LCRF as a sackung formed by collapse of the nearby ridge line. However, based on its gentle dip, and because its map trace crosses over the ridge crest, we interpret the LCRF as a low-angle normal fault that roots into the San Andreas fault at a shallow depth (~1 km). Located within the Transverse Ranges regime of overall north-south contraction[11], normal slip on the LCRF requires strong, local extension, produced by earthquake ruptures that jump the step-over. Thus, while the LCRF is too shallow and short to be seismogenic on its own or to act directly to transfer slip dynamically, triggered slip on this fault provides a field test for joint San Andreas-San Jacinto ruptures through Cajon Pass.

Paleoseismic event timing results from the LCRF establish the timing of past joint rupture of the San Jacinto fault and San Andreas fault through the Cajon Pass earthquake gate. By documenting the amount of triggered slip observed in each event, we also constrain the amount of slip that occurred on these faults when mechanical conditions favored linkage. The chronology of LCRF slip events, based on ^{14}C ages and pollen analysis of invasive species**,** shows that at least three earthquakes have bridged the Cajon Pass earthquake gate in the past 2000 years (Figure 2). These events exhibit displacements in the 50cm-1m range, distributed between a low-angle master normal fault and a graben system of minor faults that root into the LCRF, which is exposed at the contact with bedrock at the bottom of the hanging wall stratigraphic sequence. The oldest event exposed in the trench ruptures to the top of unit 150, a 2 meter-thick angular gravel and cobble debris flow deposit, and is capped by gravelly sand unit 144 which thickens across the fault zone in response to increased accommodation space towards the principal fault splay. Our Bayesian model of radiocarbon ages using the program Oxcal places this event before 300AD. The penultimate event in the trench ruptures to the top of layer 140 and is capped by the growth strata of layers 135 and 130; radiocarbon ages yield a range of 600-900AD. The most recent fault rupture reaches the top of layer 60B, with infilling above this event horizon by unit 60A and by a colluvial wedge contributing material from the footwall. Pollen analyses of samples from the stratigraphic sequence reveals that a significant portion of the pollen is invasive to California. Samples in layers 45 and 60A accumulated in the time interval between 1848, the first appearance in the sequence of the invasive species Spartium junceum (Spanish broom) and 1890, the first appearance of Salsola tragus (Russian thistle). Samples from underlying units (60B-150) were presumably deposited before 1839 because they do not contain evidence for Tamarix ramosissima (Tamarisk). This suggests that the most recent event to rupture through Cajon Pass and induce slip on the LCRF corresponds to the 1812 earthquake on the San Andreas fault, and correlates to the most recent large earthquake recorded at the Mystic Lake paleoseismic site on the San Jacinto fault, also interpreted to be 1812[8].

We compare our chronology of LCRF events with the existing chronologies for the southern San Andreas and northern San Jacinto to constrain the timing of other possible joint ruptures, and the relationship of these to prior events that did not breach the Cajon Pass earthquake gate (Figure 3). This allows establishing the relative frequency of shared events between the San Andreas, the San Jacinto, and the LCRF. The LCRF has hosted three events in the past ~2000 years, resulting in a recurrence interval of ~660 years. The probability density functions reflecting the ages of the two older events in the LCRF are too broad to enable direct comparison to the well-established chronologies in Wrightwood[7] and Mystic Lake[8], north and south of Cajon Pass on the San Andreas and the San Jacinto, respectively (Figure 3). It is possible, however, to compare the frequency of events at these paleoseismic sites with the total number of events at the LCRF to establish the probability of shared events. This approach suggests that 25% and 30% events are shared, respectively, between the San Andreas fault and the San Jacinto fault. The most recent event to have bridged the step-over is the 1812 historical earthquake, which is present in the paleoseismic sites of Pallet Creek and Wrightwood on the San Andreas fault, and at Mystic Lake on the San Jacinto fault, and is now confirmed to have bridged the gap as recorded by the LCRF.

We compare our results to the most recent Uniform California Earthquake Rupture Forecast[5], which accounts for the possibility of joint rupture of the San Jacinto-San Andreas faults through Cajon Pass. UCERF3 predicts an annual rate of shared events comparable to the frequency of events recorded by the LCRF (1.5 events per 1000 years) (Figure 3), but does not match the frequency of events on the San Jacinto fault from paleoseismic studies[8]. Scharer and Yule[12] developed a 1500yr maximum rupture model for the San Andreas and the San Jacinto faults based on radiocarbon ages and slip measurements from paleoseismic trenches throughout California. Their model is compatible with our findings, and when considered together with our results (Figure 3), shows that joint ruptures of the San Andreas fault with the San Jacinto fault occurred as frequently as ruptures that breach the San Gorgonio Pass stepover on the southern San Andreas fault.

Because the LCRF is too short and shallow to be seismogenic on its own, large slip events on the LCRF must be driven by strains imposed by rupture events on the San Andreas or San Jacinto faults. We use the 1812 and 1857 historical events as case examples to understand the conditions that induce slip on the LCRF. We rely on these two events because there are slip distributions available from prior studies and the induced slip on the LCRF may be compared to our slip measurements from trench and geomorphic studies.

Based on correlation with sparse paleoseismic data and historic reports of damage to Spanish California Missions, Lozos[4] modeled the ~M7.5 1812 earthquake as a multi-fault event that originated around the Mystic Lake paleoseismic site on the San Jacinto fault and propagated northwards, breaching the Cajon Pass step-over and transferring slip onto the San Andreas fault. We perform a finite element model to test potential slip distributions for the northern San Jacinto fault in the 1812 event. We impose slip on the San Andreas fault and the San Jacinto fault based on the preferred model outcomes from the Lozos[4] dynamic simulations. We keep the San Andreas fault slip distribution and the San Jacinto fault slip distributions consistent with the Lozos[4] result from Mystic Lake to Colton, the northernmost paleoseismically verified point in the model. From this point northward, we test over thirty slip distributions for the northern San Jacinto fault entering the Cajon Pass step-over.

Model results are assessed based on the amount of slip they trigger on the LCRF. Plausible slip distributions trigger between 50cm and 1m of slip on the LCRF, consistent with the slip measured in the trench for the most recent event. Models that impose slip comparable to observations require at least 5 m of San Jacinto fault slip north of the Colton site, tapering steeply within Cajon Pass, losing about 1m of slip per km of fault length approaching the step-over, and halting abruptly 1-3 kilometers north of the LCRF (Figure 4). This result is consistent with prior observations that steep slip gradients and abruptly-halting ruptures promote linkage across stepovers[13,14].

To explore the possibility that the 1857 earthquake on the San Andreas fault also triggered slip on the LCRF, we model the 1857 event based on the surface displacements documented by Sieh[15] and Zielke et al.[16]. The slip distribution of Sieh[15], which places the southern terminus of the rupture north of Pitman Canyon, imposes little to no slip (<0.1cm) on the LCRF. Zielke et al.[16] report several slip measurements south of where Sieh[15] placed the end of the 1857 rupture. We consider only the slip measurements classified as high quality by Zielke et al.[16], which impose ~10cm of slip on the LCRF (Figure 4). The slip measurements in Sieh[15] and Zielke et al.[16] are not age-constrained and could combine slip from the 1812 and 1857 events north of Cajon Pass, and thus serve as the upper bound for slip on the 1857 event. Nevertheless, both slip distributions trigger negligible slip on the LCRF. Together with the pollen data, the modeling supports that the most recent event to overcome the Cajon Pass earthquake gate was the 1812 historical earthquake, not the 1857 Fort Tejon earthquake, which likely remained confined to the San Andreas fault.

Heterogeneous stress fields resulting from prior events exert a first-order control of the initiation, arrest, and propagation of the next earthquake[17]. This behavior is particularly crucial at step-overs, where residual stresses from prior events may determine whether the next rupture is able to overcome the gap, ultimately regulating the behavior of the earthquake gate over multiple earthquake cycles [18]. The high slip and steep taper we model for the 1812 event suggests that it released residual stress built up from prior events that terminated on the San Jacinto fault.

The chronology of rupture events recorded by the LCRF stratigraphic sequence establishes that the San Andreas and the San Jacinto have ruptured together at least three times in the past 2000 years, most recently in the historical 1812 earthquake, preceded by events at 611-896 AD and 452 BC-622 AD. The frequency of events recorded by the LCRF suggests that approximately one quarter of events on the adjacent San Andreas fault and San Jacinto fault may be joint ruptures through the Cajon Pass earthquake gate. Mechanical modeling of 0.5-1 meter-scale slip on the LCRF in 1812 shows that slip on the San Jacinto fault must have tapered steeply and halted abruptly within 3 km of our trench site. Conversely, the 1857 earthquake triggers no more than 10cm of slip on the LCRF, confirming that this event did not jump to the San Jacinto fault. The relatively common occurrence of gap-bridging events spanning the junction of the San Andreas fault and San Jacinto fault provides crucial information for long-term hazard estimates for the state of California. The approach of combining paleoseismic chronologies with modeling triggered secondary fault slip could be applied at other suspected locations of gate-like rupture behavior.

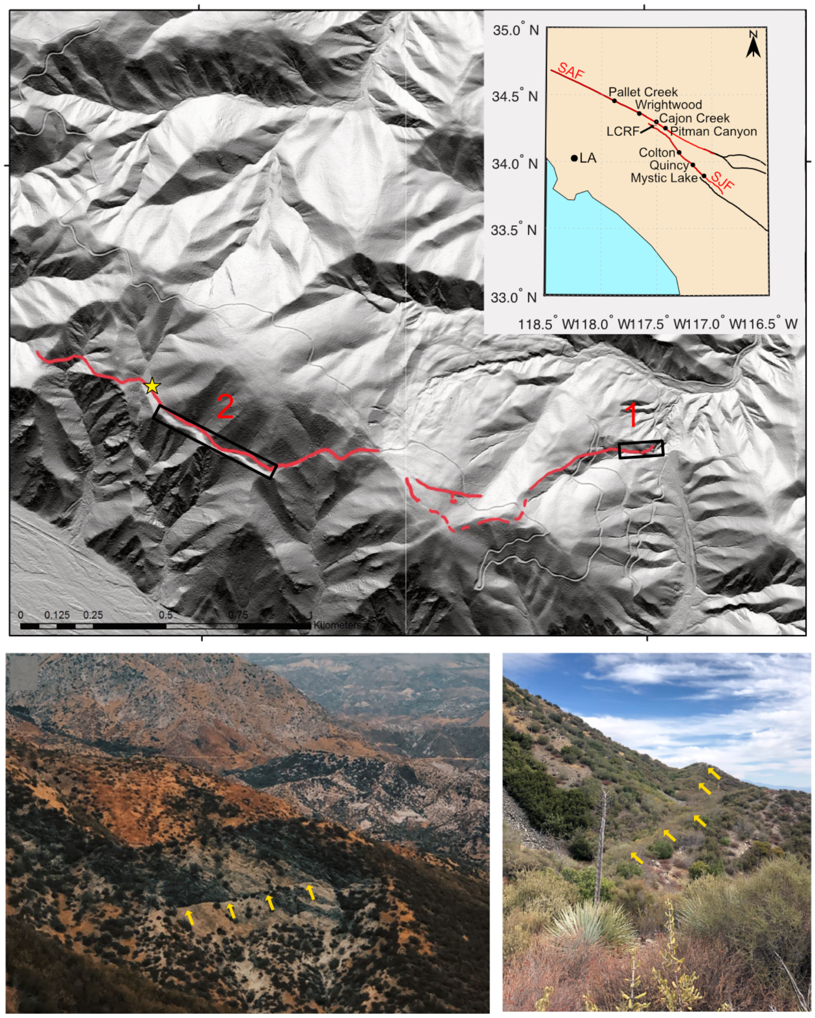

Fig. 1. Top: Lidar hillshade map of the Lytle Creek Ridge Fault (LCRF) in Cajon Pass. The star denotes the location of the paleoseismic trench. The inset shows the San Andreas and the San Jacinto faults in Southern California with paleoseismic sites. Bottom left: Bedrock exposure of the LCRF cutting the Pelona Schist. Bottom right: uphill facing scarp of the LCRF cutting through Lytle Creek Ridge.

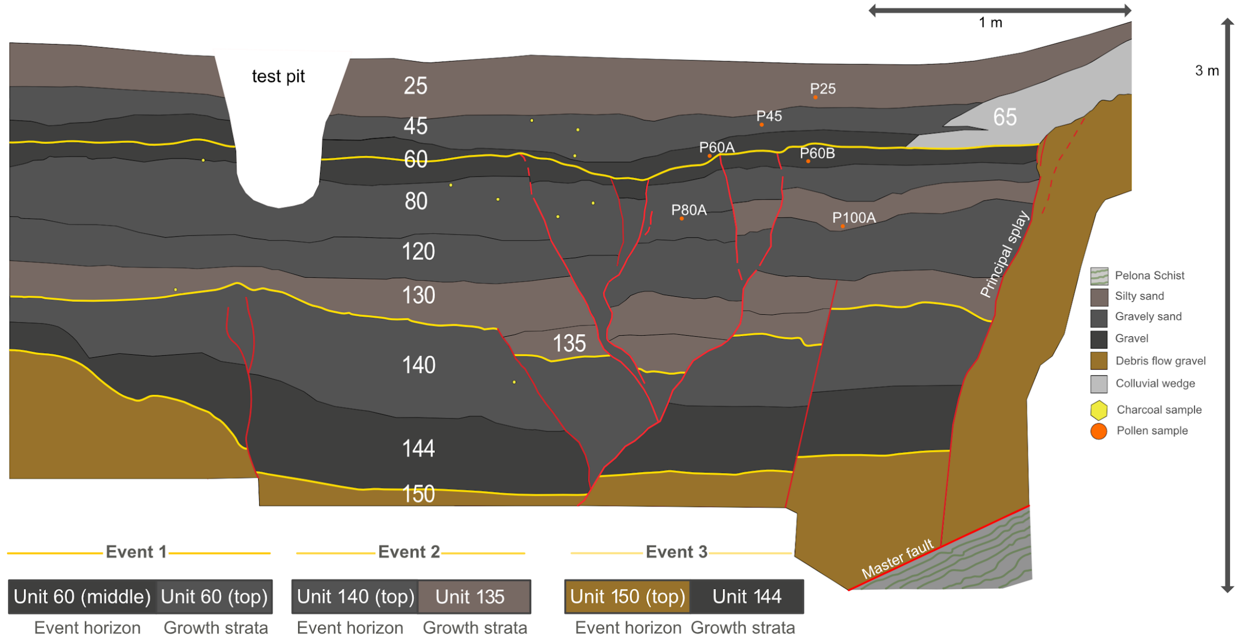

Fig. 2. Trench log showing the structure of the southern wall. Event horizons and growth strata are listed under the log, and layers are color coded by grain size.

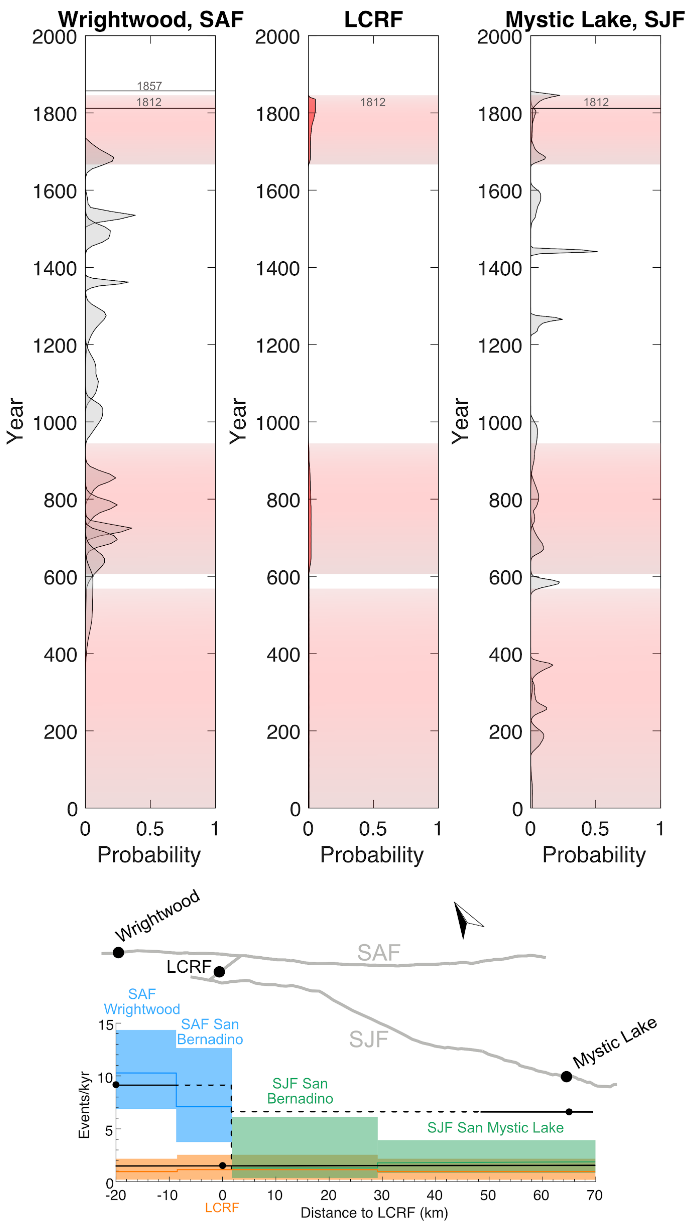

Fig. 3. Top: Comparison of event histories recorded at paleoseismic neighboring sites at the northern San Jacinto and San Andreas faults. The red rectangles outline the area spanned by the probability density functions of events recorded in the LCRF trench. The Wrightwood chronology is from Scharer et al. [9] and the Mystic Lake chronology is from Ordendonk et al. [10]. Bottom: Comparison between event rates from the paleoseismic record and UCERF3. The black lines indicate paleoseismic event rates from Wrightwood, Mystic Lake, and the LCRF; Black dots denote trench locations. Colored lines represent UCERF3 event rates for the San Andreas fault (blue), the San Jacinto fault (green), and shared (orange). Shaded areas represent the model range. Faults are divided into segments as defined in UCERF3.

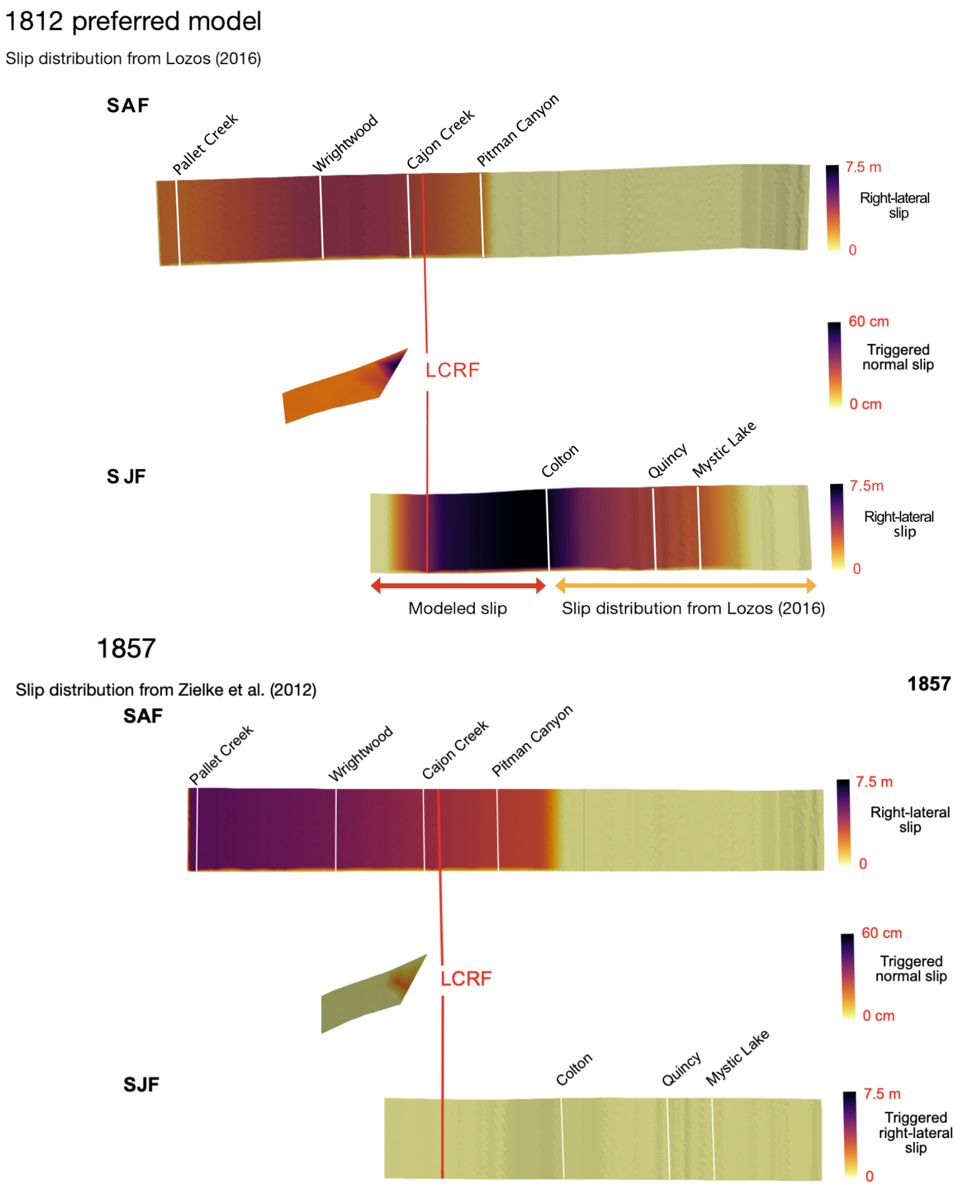

Fig. 4. Slip models for the 1812 and 1857 earthquakes through Cajon Pass. Top: Preferred slip model for the 1812 event. Right-lateral slip imposed on the San Jacinto and the San Andreas is based on the final slip distributions in the preferred model in Lozos [2]. Slip north of the Colton paleoseismic site on the San Jacinto fault is based on the model that triggers the amount of slip measured in the LCRF trench from a suite of tests (Supplement figure S6). Bottom: 1857 event model based on the slip distributions in Zielke et al. [17]

References

1. Fialko, Y. Interseismic strain accumulation and the earthquake potential on the southern San Andreas fault system. (2006) doi:10.1038/nature04797.
2. Rockwell, T., Scharer, K. M. & Dawson, T. E. *Earthquake geology and paleoseismology of major strands of the San Andreas fault system*. vol. 26 (2016).
3. Morton, D. M., Miller, F. K., Cossette, P. M. & Bovard, K. R. Geologic map of the San Bernardino and Santa Ana 30' x 60' quadrangles, California Digital preparation by Geology and Description of Map Units, version 1.0.
4. Lozos, J. C. A case for historic joint rupture of the San Andreas and San Jacinto faults. *Sci. Adv.* **2**, e1500621 (2016).
5. Field, E. H. *et al.* Long-Term Time-Dependent Probabilities for the Third Uniform California Earthquake Rupture Forecast (UCERF3). doi:10.1785/0120140093.
6. Biasi, G. P. *et al. Paleoseismic Event Dating and the Conditional Probability of Large Earthquakes on the Southern San Andreas Fault, California*. *Bulletin of the Seismological Society of America* vol. 92 2761–2781 http://pubs.geoscienceworld.org/ssa/bssa/article-pdf/92/7/2761/2713311/2761_927_00605.pdf (2002).
7. Scharer, K. M., Ii, R. J. W., Fumal, T. E. & Biasi, G. P. A New Method for Evaluating Paleoseismic Evidence and Earthquake Horizons. *Bull. Seismol. Soc. Am.* **97**, 1054–1093 (2007).
8. Onderdonk, N., McGill, S. & Rockwell, T. A 3700 yr paleoseismic record from the northern San Jacinto fault and implications for joint rupture of the San Jacinto and San Andreas faults. *Geosphere* **14**, 2447–2468 (2018).
9. Rockwell, T. K., Dawson, T. E., Young Ben-Horin, J. & Seitz, G. A 21-Event, 4,000-Year History of Surface Ruptures in the Anza Seismic Gap, San Jacinto Fault, and Implications for Long-term Earthquake Production on a Major Plate Boundary Fault. *Pure Appl. Geophys.* **172**, 1143–1165 (2015).
10. McCalpin, J. P. & Hart, E. W. RIDGETOP SPREADING FEATURES AND RELATIONSHIP TO EARTHQUAKES, SAN GABRIEL MOUNTAINS REGION, SOUTHERN CALIFORNIA -- PART A: DISTRIBUTION AND DESCRIPTION OF RIDGETOP DEPRESSIONS (SACKUNGEN). 75.
11. Hardebeck, J. L. & Hauksson, E. Crustal stress field in southern California and its implications for fault mechanics. *J. Geophys. Res. Solid Earth* **106**, 21859–21882 (2001).
12. Scharer, K. M. & Yule, D. A Maximum Rupture Model for the Southern San Andreas and San Jacinto Faults, California, Derived From Paleoseismic Earthquake Ages: Observations and Limitations. *Geophys. Res. Lett.* **47**, e2020GL088532 (2020).
13. Scholz, C. H. & Lawler, T. M. Slip tapers at the tips of faults and earthquake ruptures. *Geophys. Res. Lett.* **31**, n/a-n/a (2004).
14. Elliott, A. J., Dolan, J. F. & Oglesby, D. D. Evidence from coseismic slip gradients for dynamic control on rupture propagation and arrest through stepovers. *J. Geophys. Res.* **114**, B02313 (2009).
15. Sieh, K. E. *SLIP ALONG THE SAN ANDREAS FAULT ASSOCIATED WITH THE GREAT 1857 EARTHQUAKE*. *Bulletin of the Seismological Society of America* vol. 68 1421–1448

http://pubs.geoscienceworld.org/ssa/bssa/article-pdf/68/5/1421/2701526/BSSA0680051421.pdf?casa_token=OdumYQmZkfIAAAAA:m2jLN-AfcBI3-RrkOZN46wX5N (1978).
16. Zielke, O., Arrowsmith, R., Ludwig, L. G. & Akciz, S. O. High-Resolution Topography-Derived Offsets along the 1857 Fort Tejon Earthquake Rupture Trace, San Andreas Fault. doi:10.1785/0120110230.
17. Harris, R. A., Archuleta, R. J. & Day, S. M. Fault steps and the dynamic rupture process: 2-D numerical simulations of a spontaneously propagating shear fracture. *Geophys. Res. Lett.* **18**, 893–896 (1991).
18. Wang, H., Liu, M., Duan, B. & Cao, J. Rupture propagation along stepovers of strike-slip faults: Effects of initial stress and fault geometry. *Bull. Seismol. Soc. Am.* **110**, 1011–1024 (2020).