2020 SCEC WORKSHOP REPORT - SCEC Award 20056
Science Workshop for the Cajon Pass Earthquake Gate Area

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Summary and Purpose of the Workshop:

SCEC defines Earthquake Gate Areas (EGA) as "regions of fault complexity conjectured to inhibit propagating ruptures, owing to dynamic conditions setup by proximal fault geometry, local material properties, distributed deformation, and earthquake history." The four primary science questions related to EGAs are:

1. How do fault intersections affect the probability of through-going earthquake ruptures?
2. How does 3D fault geometry and stress variations modulate these through-going rupture probabilities?
3. How do prior ruptures affect future rupture paths and probabilities?
4. Does the current stress field reflect recent rupture history or is it more influenced by other factors?

The purpose of this workshop was to present and discuss ongoing research in the Cajon Pass EGA, to solicit and encourage additional studies and new investigators, and to establish science priorities for the remainder of SCEC5 and beyond. 2020 is the beginning of the fourth year of SCEC5, but only the third year of the Cajon Pass Earthquake Gate initiative. Numerous projects have been funded to address the Cajon Pass EGA science plan. This workshop brought various Cajon Pass investigators together to assess what progress had been made since the first Cajon Pass workshop in 2018, and what still remained to be done.

Workshop planning:

Due to the ongoing COVID-19 pandemic, this workshop was held as a web-based Zoom conference on September 4, 2020 (https://www.scec.org/workshops/2020/cajon-ega). Anyone currently working on, or interested in, the EGA science questions was encouraged to apply to participate, especially researchers and young investigators with expertise in earthquake geology, geophysics, modeling, and the Cajon Pass region. Based on the applications received, a workshop program was developed that consisted of three science sessions of invited talks organized around field geology and remote sensing, geophysics and insights from other potential EGAs, and modeling studies. An afternoon summary discussion to address workshop recommendations ended the workshop. Prior to the workshop, invited speakers as well as anyone else with results relevant to the workshop were encouraged to provide an extended, one-page abstract that included one exemplary figure. These extended 2020 Cajon Pass workshop abstracts were compiled and made available to workshop participants. The workshop had 15 invited speakers and 61 participants.

Workshop highlights and results:

Kate Scharer presented results from a new model of ruptures on the southern San Andreas fault (**Fig. 1**), which was designed to produce the fewest (and hence largest) ruptures on the fault permissible with the available paleoseismic data (*Scharer and Yule*, 2020). The data tend to show that co-ruptures of the SAF and northern SJF are permissible, although consistency of events at Wrightwood and Pitman Canyon also argue that ruptures can continue on SAF past Cajon Pass. Ruptures in San Gorgonio Pass tend to occur when Cajon Pass sequences are not active. The model suggests that clusters of closely-timed earthquakes, followed by periods of quiescence, may be the dominant mode of seismic strain release for this part of the plate boundary system. This holds major implications for rupture forecasting and earthquake preparedness.

Alba Rodriguez Padilla presented work that shows "passenger faults" – faults which do not host large earthquakes themselves, but respond to rupture on other faults – like the Lytle Creek Ridge fault (LCRF) are very sensitive to ruptures that bridge the stepover from the SJF to the SAF. The timing of ruptures on this small fault suggests the SAF and SJF may have ruptured together 3 to 4 times in the last 2500 years, most recently in 1812 (*Rodriguez Padilla et al.*, 2019). Modeling suggests that ruptures that bridge the stepover are the only ones to trigger the characteristic normal-fault behavior of the LCRF and are more likely to propagate northwards with slip tapering abruptly in Cajon Pass, like 1812 (**Fig. 2**).

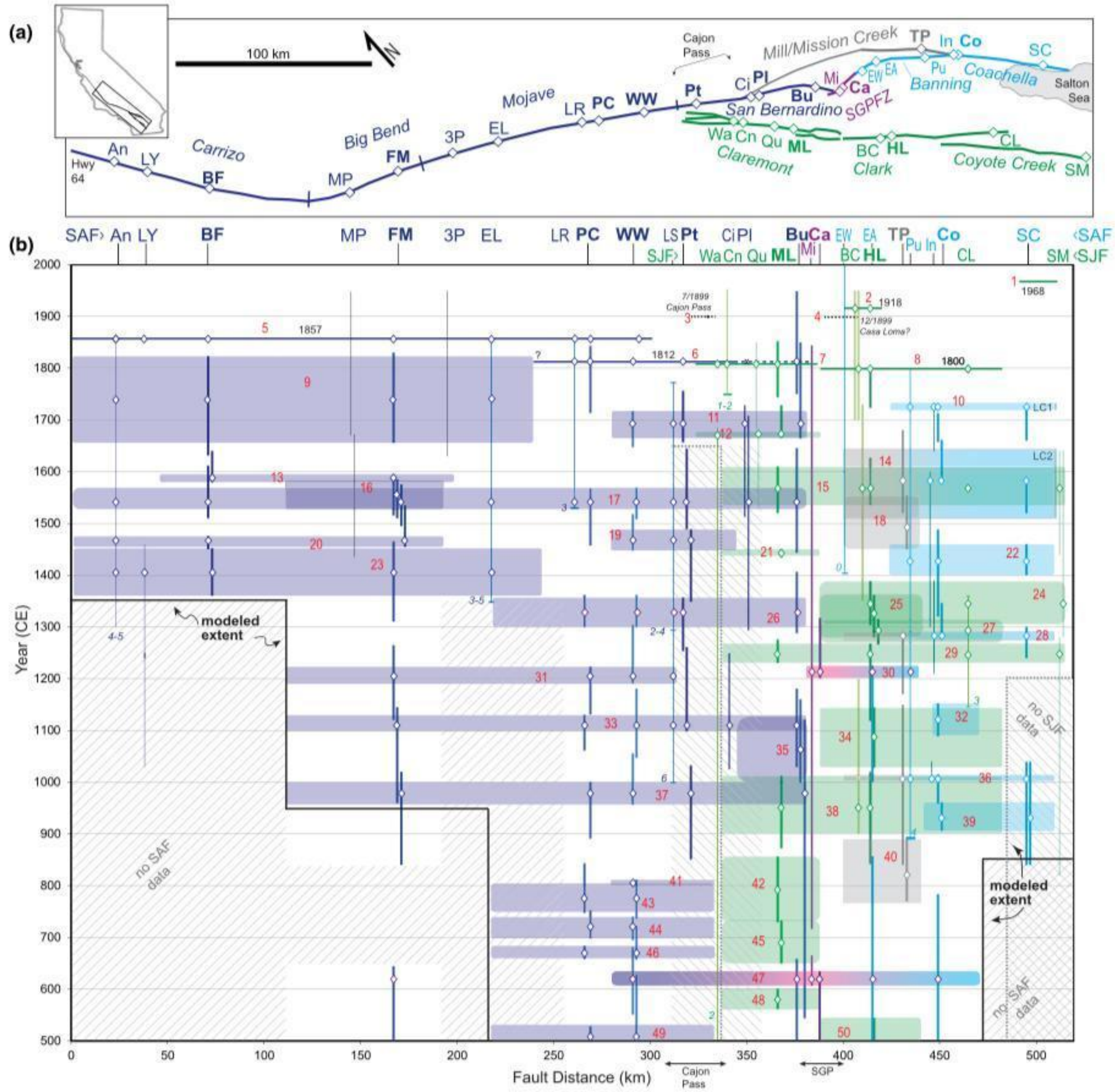

Figure 1. Maximum rupture model for SAF (dark and light blues), SJF (green), SGPFZ (purple), and Mill/Mission Creek (gray) (*Scharer and Yule*, 2020).

Nate Onderdonk presented geomorphic and paleoseismic data that indicate the Glen Helen fault has not experienced a surface rupturing event in the last 2500 years (**Fig. 3**) (*Onderdonk et al.*, 2020). This is surprising given this strand of the San Jacinto fault is seismically active at the microearthquake level, is the closest to the SAF, and hence is in a favorable location for the transfer of strain between the SJF and SAF. These new data suggest that slip on the northern San Jacinto fault zone is focused on the middle San Jacinto strand that extends northwest into upper Lytle Creek, farther than its USGS mapped surface trace, and may be the path of strain transfer between the San Jacinto and San Andreas faults in the vicinity of the LCRF.

Craig Nicholson showed that focal mechanism nodal planes of relocated hypocenters in Cajon Pass are predominantly parallel or nearly parallel to the major SAF and SJF strands, and are steeply dipping (*Nicholson et al.*, 2020). This indicates the SAF, Glen Helen and SJF are near-vertical and subparallel to depths of 15 km or more, and do not tend to merge at depth (**Fig. 4**), rather the earthquake and geologic data (*e.g.*, *Forand et al.*, 2017) tend to define a wide, subvertical viscoelastic zone of distributed right-lateral shear, which may have important implications on dynamic rupture and slip transfer through the Pass.

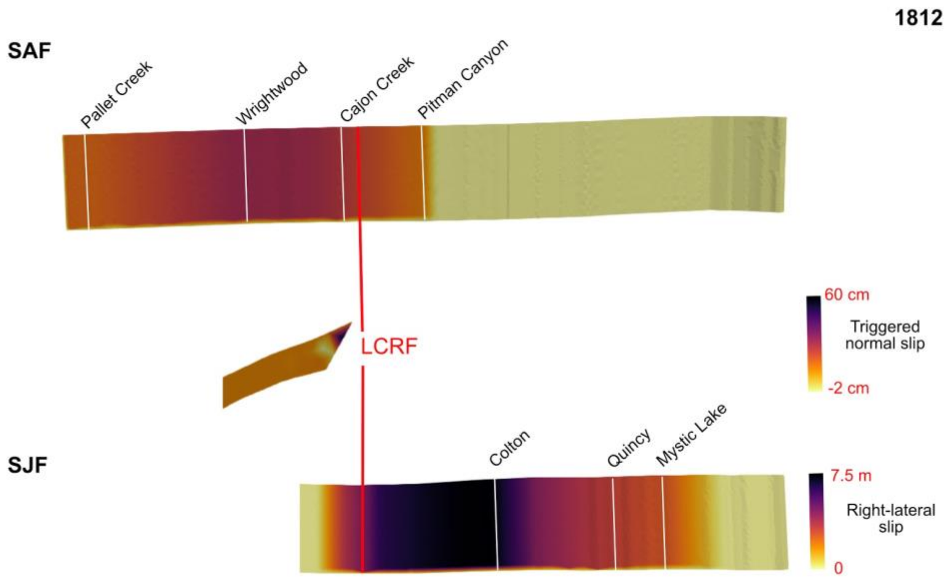

Figure 2. Rupture model for 1812 earthquake that bridges the gap between SAF and SJF, and triggers observed, characteristic normal slip on the intervening 'passenger' LCRF (*Rodriguez Padilla et al.*, 2019). Color bars indicate amounts of right-slip on SAF & SJF, and normal-slip on LCRF, respectively.

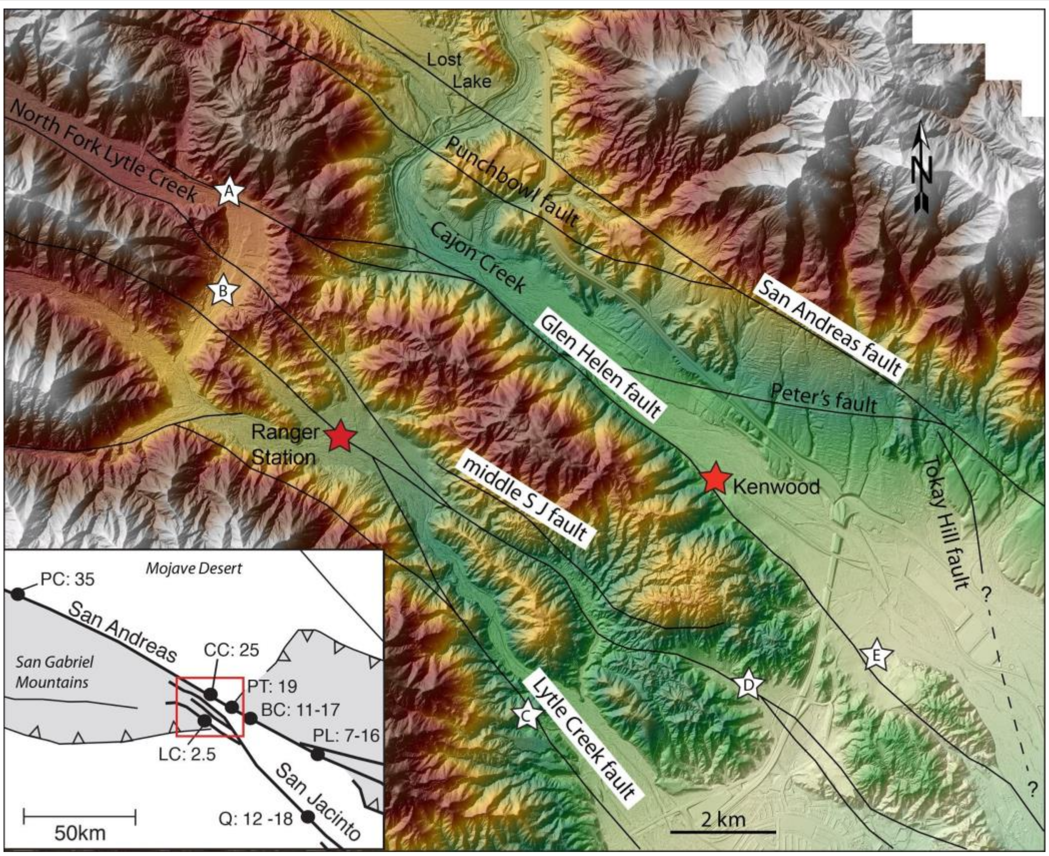

Figure 3. Lidar-derived DEM showing topography of the Cajon Pass area with faults and paleoseismic and/ or slip rate sites currently being investigated. Data from trenching at Kenwood site and site "E" show the Glen Helen fault has not experience surface rupture in the past 2000 years or more (*Onderdonk et al.*, 2020).

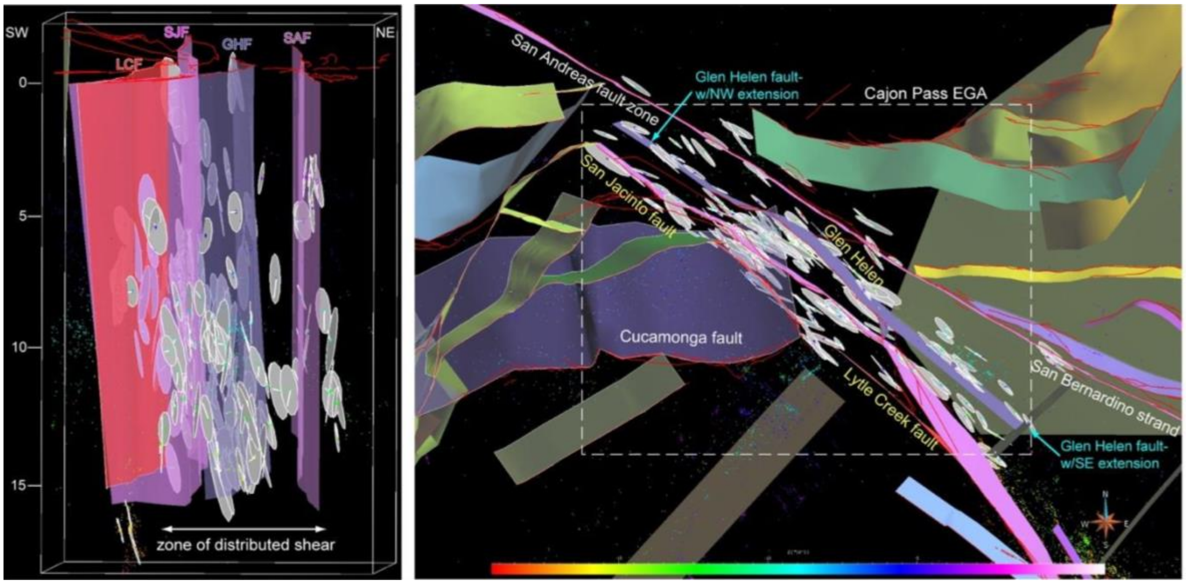

Figure 4. Focal mechanism nodal planes (circular disks) of relocated hypocenters are predominantly parallel or subparallel to SAF and SJF strands and are steeply dipping. (*left*) In cross section, active faults remain near-vertical, do not merge at depth, and together with mapped geology, define a wide, sub-vertical viscoelastic zone of distributed shear through the Pass. (*right*) Aligned nodal planes also define blind, NW and SE extensions to the Glen Helen fault beyond its mapped surface trace (*Nicholson et al.,* 2020).

Observations from other potential earthquake gate areas along the SAF (Gordon Seitz), Denali (David Schwartz) and Altyn Tagh faults (Veronica Prush) indicate that past rupture history, fault geometry and stress rotations related to fault geometry can all strongly influence rupture behavior through an earthquake gate (*e.g., Schwartz et al*., 2012*; Shao Yanxiu et al.*, 2018; *Seitz et al*., 2019).

Several studies utilized stress field orientations derived from inverting earthquake focal mechanisms to infer the presence of major stress field variations, and to model these variations for fault characteristics and potential rupture behavior. Michele Cooke demonstrated that deep normal-faulting focal mechanisms adjacent to the SJF suggest the presence of deep creep along the base of the SJF seismogenic zone (*Cooke et al.*, 2018). Karen Luttrell modeled the potential for sharp variations or rotations in maximum shear stress orientation between SAF and SJF fault segments to inhibit multi-fault ruptures (*Helgans et al.,* 2019), and Niloufar Abolfathian identified significant deviations or rotations from the regional stress regime as defined by the stress ratio, R (**Fig. 5**) in the vicinity of Cajon Pass that likely strongly influence fault behavior (*Abolfathian et al,* 2019).

Dunyun Liu presented results of dynamic rupture simulations using realistic fault geometries to investigate the effects of both the Big Bend and Cajon Pass on potential multicycle rupture histories of the SAF and SJF. The probability and frequency of large earthquakes that may break the entire system strongly depended on the maximum shear loading direction, rates, and interseismic stress evolution (*Liu and Duan*, 2020). Christos Kyriakopoulos also presented work in progress on dynamic rupture simulations incorporating the effects of the significant variation in surface topography from San Gorgonio Pass through Cajon Pass on SAF ruptures (*Kyriakopoulos and Oglesby*, 2020). These dynamic rupture modeling talks were followed by extensive discussion of possible future modeling studies, as well as what data could be collected to validate these existing studies.

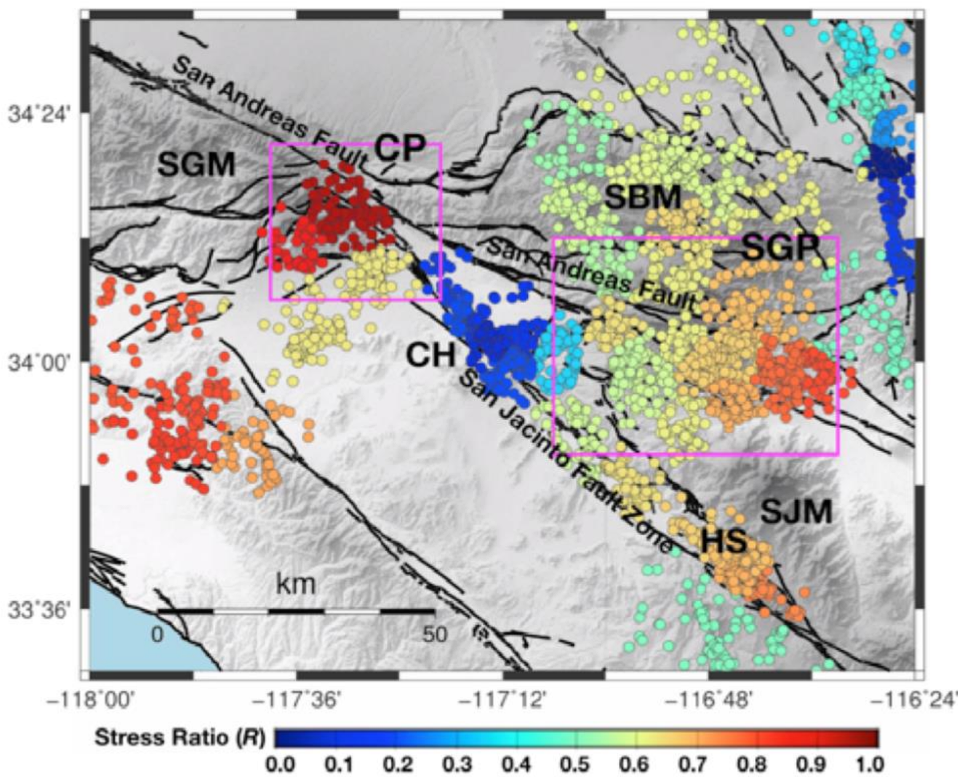

Figure 5. Declustered seismicity color-coded with values of the stress ratio, R, that varies from 0.0 (blue, normal) to 0.5 (green, strike-slip) to 1.0 (red, reverse), in the region around the South Central Transverse Ranges. The stress ratio R identifies significant variation in stress orientations along the SAF and SJF that may affect fault behavior. The two purple boxes indicate study areas near the Cajon Pass (CP) and San Gorgonio Pass (SGP).

Workshop recommendations:

1. Continue to pursue slip rate and slip history data from strands of the northern San Jacinto fault system in the Cajon Pass area. These data are needed to evaluate a wide variety of models and to test previous ideas about rupture patterns and fault interactions. Any validation of recent SJF activity in upper reaches of Lytle Creek drainages would be valuable for understanding how strain may affect secondary faults.
2. As there are significant deficits in observed fault slip rates compared to overall plate motion, it is crucial to check if these deficits are related to pervasive off-fault deformation and penetrative finite strain. Can we quantify this contribution to the strain budget by capturing such potential interseismic, inelastic deformation and its strain rate using modern geodetic techniques or evaluating rock properties?
3. Construct additional dynamic rupture models with realistic 3D fault geometry that use initial stresses determined from forward static models. Also consider constructing multi-cycle simulations to address the physics of sequences of multiple large Cajon Pass events in a short span of time.
4. Continue rupture model validation of the likelihood that ruptures would be expected to proceed from the SAF to the SJF and vice versa, stay on only one branch of the earthquake gate, or branch simultaneously onto the SAF and SJF. Also evaluate from which direction(s) these branching scenarios are more likely to occur.

References:

Abolfathian, N., P. Martinez-Garzon and Y. Ben-Zion, Spatial variations of stress patterns near the south central Transverse Ranges in Southern California, *Seismological Research Letters*, v. **90**, n. 2B, p. 1029, DOI:10.1785/0220190061(2019).

Cooke, M.L. and J.L. Beyer, Off-fault focal mechanisms not representative of interseismic fault loading suggest deep creep on the northern San Jacinto fault, *Geophysical Research Letters,* v. **45**, n. 17, p. 8976-8984, DOI:10.1029/2018GL078932 (2018).

Forand, D., J.P. Evans, S. Janecke and J. Jacobs, Insights into fault processes and the geometry of the San Andreas fault system: Analysis of core from the deep drill hole at Cajon Pass, California, *Geological Society of America Bulletin*, **130** (1-2), doi:10.1130/B3168.1, p.64-92 (2017).

Scharer, K.M. and D. Yule, A maximum rupture model for the southern San Andreas and San Jacinto faults, California, derived from paleoseismic earthquake ages: observations and limitations, *Geophysical Research Letters*, v. **47**, n. 15, DOI:10.1029/2020GL088532 (2020).

Schwartz, D.P., P.J. Haeussler, G.G. Seitz and T.E. Dawson, Why the 2002 Denali Fault rupture propagated onto the Totschunda Fault; implications for fault branching and seismic hazards, *Journal of Geophysical Research: Solid Earth*, v. **117**, n. B11, Citation B11304. DOI:10.1029/2011JB008918 (2012).

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Shao Yanxiu, J. Liuzeng, M.E. Oskin, A.J. Elliott, et al., Paleoseismic investigation of the Aksay restraining double bend, Altyn Tagh Fault, and its implication for barrier-breaching ruptures, *Journal of Geophysical Research: Solid Earth*, v. **123**, n. 5, p. 4307-4330 (2018).

2019 Cajon Pass EGA SCEC meeting abstracts:

Elston, H. M., Cooke, M. L., Marshall, S. T., & Hatch, J. L. (2019, 08). Sensitivity of regional interseismic deformation to variations in active fault configuration of the southern San Andreas fault and San Jacinto faults . Poster Presentation at 2019 SCEC Annual Meeting.

Figueiredo, P. M., Weldon, R. J., Owen, L. A., & Onderdonk, N. W. (2019, 08). Preliminary Geochronology data for Cajon Pass Terraces- implications to the regional chronosequence. Poster Presentation at 2019 SCEC Annual Meeting.

Helgans, E. C., Luttrell, K. M., Smith-Konter, B. R., & Burkhard, L. (2019, 08). Multicomponent Model of Crustal Stress at Cajon Pass, Southern California with Implications for Stress Field Heterogeneity. Poster Presentation at 2019 SCEC Annual Meeting.

Kerr, D. D., Onderdonk, N. W., & Figueiredo, P. M. (2019, 08). Late Quaternary deformation and recency of faulting of the northernmost San Jacinto fault zone, and implications for slip transfer to San Andreas fault. Poster Presentation at 2019 SCEC Annual Meeting.

Kyriakopoulos, C., Wu, B., & Oglesby, D. D. (2019, 08). The Cajon Pass Earthquake Gate: the effect of topography on dynamic rupture models. Poster Presentation at 2019 SCEC Annual Meeting.

Liu, D., & Duan, B. (2019, 08). Multi-cycle Dynamics of the San Andreas and San Jacinto Faults in Southern California. Poster Presentation at 2019 SCEC Annual Meeting.

Nicholson, C., Plesch, A., Sorlien, C. C., Shaw, J. H., Marshall, S. T., & Hauksson, E. (2019, 08). Continued Updates, Expansion and Improvements to the Community Fault Model (CFM version 5.3). Poster Presentation at 2019 SCEC Annual Meeting.

Onderdonk, N. W., Kerr, D. D., & Figueiredo, P. M. (2019, 08). Using UAV-mounted LiDAR surveys to investigate potential slip rate sites along the northernmost San Jacinto fault zone near its junction with the San Andreas fault in the Cajon Pass area, California. Poster Presentation at 2019 SCEC Annual Meeting.

Rodriguez Padilla, A., Oskin, M. E., Rockwell, T. K., Delusina, I., & Singleton, D. M. (2019, 08). Paleoseismic investigation and mechanical modeling of rupture behavior through Cajon Pass . Poster Presentation at 2019 SCEC Annual Meeting.

2020 Cajon Pass EGA SCEC meeting abstracts:

Gonzalez-Huizar, H., & Douilly, R. (2020, 08). Investigating the Role of Seismic Waves on Multi-fault Rupturing. Poster Presentation at 2020 SCEC Annual Meeting.

Kyriakopoulos, C., Wu, B., & Oglesby, D. D. (2020, 08). The Cajon pass earthquake gate: clues from synthetic and realistic topography dynamic rupture models . Poster Presentation at 2020 SCEC Annual Meeting.

Liu, D., & Duan, B. (2020, 08). Observation-constrained multicycle dynamic models of southern San Andreas fault and the San Jacinto fault: the effect of the Big Bend and Cajon Pass on rupture dynamics. Poster Presentation at 2020 SCEC Annual Meeting.

Nicholson, C., Plesch, A., Sorlien, C. C., Shaw, J. H., & Hauksson, E. (2020, 08). Updates, Evaluation and Improvements to the Community Fault Model (CFM version 5.3). Poster Presentation at 2020 SCEC Annual Meeting.

Onderdonk, N. W., Kerr, D. D., & Figueiredo, P. M. (2020, 08). Geomorphic and paleoseismic trenching evidence that the Glen Helen fault has not experienced surface rupture in the past 2000 years, and implications for slip transfer between the San Andreas and San Jacinto fault zones. . Poster Presentation at 2020 SCEC Annual Meeting.

Shearer, P. M., & Abercrombie, R. E. (2020, 08). Calibrating Spectral Decomposition of Local Earthquakes using Borehole Seismic Records---Results for the 1992 Big Bear Aftershocks in Southern California. Poster Presentation at 2020 SCEC Annual Meeting.