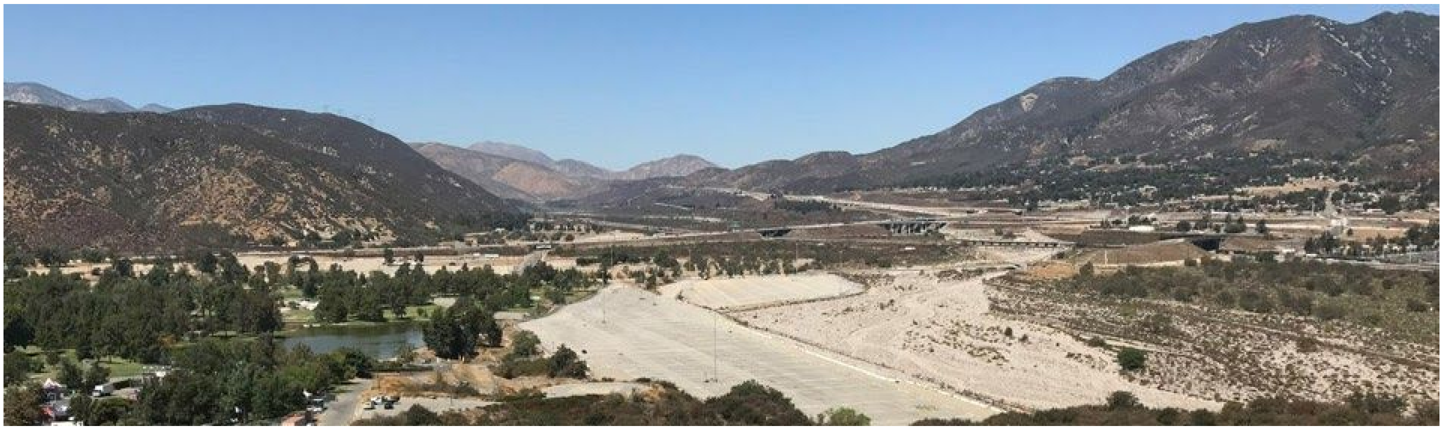


SCEC Cajon Pass Earthquake Gate Area: Progress and Future Plans

Friday, September 4 (08:45-15:00 Pacific Time or UTC-7) www.scec.org/workshops/2020/cajon-ega

Agenda Outline

08:45 Julian Lozos

Session 1 (Julian Lozos)
09:00 Kate Scharer
09:15 Devin McPhillips
09:30 Alba Rodriguez Padilla
09:45 Drake Kerr
10:00 Nate Onderdonk
10:15 Moderated Discussion
10:30 *Break***

Session 2 (Nate Onderdonk)
11:00 Craig Nicholson
11:15 Gordon Seitz
11:30 Chris Milliner
11:45 Veronica Prush
12:00 Greg De Pascale
12:15 Moderated Discussion
12:30 *Break***

Session 3 (Craig Nicholson)
13:00 Michele Cooke
13:15 Christos Kyriakopoulos
13:30 Dunyu Liu
13:45 Karen Luttrell
14:00 Niloufar Abolfathian
14:15 Moderated Discussion

14:30 Summary Discussion
15:00 *Adjourn***

Each session has a moderator, whose responsibility is to introduce presenters and facilitate productive discussions and report the outcomes.

The **invited talks** will be presented during the scheduled timed via shared screen. The meeting participants will be able to ask questions and provide comments through the chat window or by voice/video by raising hands and being called on by the moderator.

Time is allotted in each session for a **moderated discussion** which will follow some brief Q&A for the presentations. The discussion will be led by the session moderator, who is responsible for gathering input from the session audience and guiding the group discussion. A session reporter may be assigned to capture important discussion points or action items; and submits these items to the workshop conveners to include in the final workshop report recommendations.

Speakers and moderators will be supported by two session facilitators (Tran Huynh and Edric Pauk) who will manage the online platform and help ensure broad audience interaction and accessibility.

*** During break times, the Zoom room will remain open for attendees use for informal chats and exchanges.*

Presentation Abstracts

Maximum rupture model for Cajon Pass from paleoearthquake data on the San Andreas and San Jacinto Faults

Kate Scharer and Doug Yule

We summarize a recent study (Scharer and Yule, GRL 2020) that compiled paleoearthquake ages from the southern San Andreas and San Jacinto Faults to derive a model of the longest and fewest ruptures permitted in the last 1500 years. For this workshop, we highlight four features of the study; first, that the study includes a compilation of earthquake ages from each contributing site plus the age and rupture extent of the modeled ruptures for use in numerical studies of earthquake behavior. Second, we review the ruptures around Cajon Pass. In this area, where the northern San Jacinto Fault converges with the San Bernardino section of the San Andreas Fault, there are six periods in which contemporaneous rupture on both faults is permitted by the earthquake ages, which we term Cajon Pass sequences. Based on the paleoseismic site locations, co-rupture would involve 40 km of both the northern San Jacinto Fault and the southern end of the San Bernardino section of the San Andreas Fault. We argue such behavior is unlikely as in a global dataset (Biasi and Wesnousky, 2016) co-rupture along a splay always arrests in less than 15 km, though Lozos (2016) argues this is possible for the 1812 quake. Assuming these are statically driven sequences rather than dynamic co-rupture, Coulomb modelling may provide insight into the most probable order (e.g., Anderson et al., 2003), but a range of fault geometries and stress conditions should be evaluated. Third, we note that the model produces a pattern in which ruptures in the San Gorgonio Pass Fault Zone occur when the Cajon Pass sequences are not active. Finally, while the model is an end member that provides the longest possible ruptures through the region, it compares well to offset estimates from slip-per-event studies and could be used to guide infrastructure mitigation planning.

New Be-10 Surface Exposure Ages and Fault Slip Rates, Cucamonga Fault, Southern California

Devin McPhillips, Katherine M. Scharer

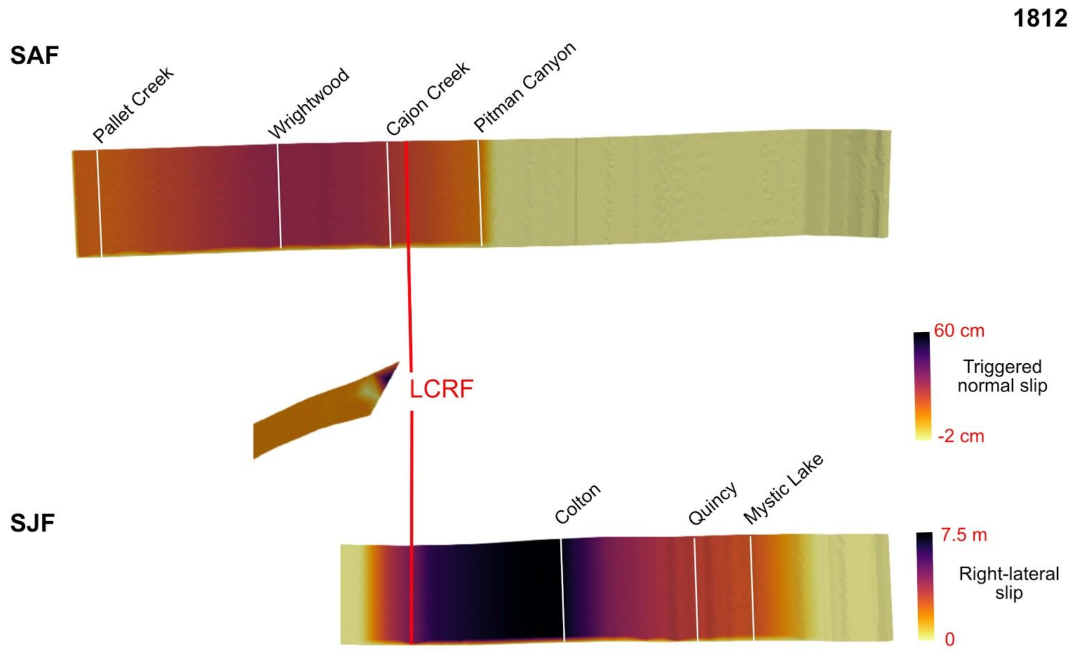
Several generations of alluvial fans at Day Canyon host some the best preserved scarps of the Cucamonga Fault. This fault is part of the Sierra Madre fault system on the southern border of the Transverse Ranges, which has generated damaging historical earthquakes in the Los Angeles, California region. In addition, the Cucamonga Fault is located at the apparent junction of the Sierra Madre fault system, San Andreas Fault, and San Jacinto Fault. Here, we report two new 10Be exposure ages from the surfaces of alluvial fans mapped as Qyf2 and Qyf3. The degree of soil development and clast weathering patterns indicate that these units are younger than the fan mapped as Qyf1, where previous exposure ages yield an average value of 38 ka. A clean and consistent depth profile in the Qyf2 deposit yields an age of 27±2 ka. The depth profile in the Qyf3 deposit shows a jump in 10Be concentration at a depth of ~1.2 m, which is coincident with our observations of a change in the degree of soil development. We interpret this contact to be the boundary between the inset Qyf3 deposit and an older alluvial fan surface. The three 10Be concentrations located in the pit above this horizon, as well as a single boulder-top measurement nearby, yield exposure ages of ~15 ka. As for the scarps preserved in the Qyf2 and Qyf3 fan surfaces, previous work has demonstrated considerable dispersion in the vertical separation along the strike of the Cucamonga Fault at Day Canyon. Despite this dispersion, preliminary time-averaged slip rate estimates yield values in the range of 1 to 2 mm/yr for both Qyf2 and Qyf3, which are consistent with estimates derived from the older Qyf1 alluvial fan. These data add to the growing literature of Sierra Madre fault system behavior through time and help to better quantify the regional soil chronostratigraphy.

The power of passenger faults as passive recorders: refining the timing and mechanics of San Andreas-San Jacinto joint rupture through Cajon Pass

Alba M Rodriguez Padilla, Michael E Oskin, Thomas K Rockwell, Irina Delusina, Drake Singleton

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. Dynamic earthquake rupture models demonstrate the potential for multifault events, yet physical records of linkage where the faults come together at Cajon Pass remain elusive. The Lytle Creek Ridge Fault (LCRF) is a newly discovered low angle normal fault uniquely positioned and mechanically favored to record ruptures that bridge the step-over, providing the first opportunity to assess the rupture behavior of this junction from field observations, and providing a valuable data point for mechanical models. Combining a paleoseismic dataset of the LCRF with analysis of invasive pollen species, we show that the San Andreas and the San Jacinto have ruptured together three to four times in the past 2500 years, most recently in 1812. Comparison to other paleoseismic records shows that ~1/4 of events involve both faults with a recurrence interval of 625-830 years. Finite element models based on slip distributions on the San Andreas and the San Jacinto from the 1812 and 1857 events, and field data from the LCRF trench, suggest that earthquakes that bridge the step-over are preferably north-traveling ruptures that taper steeply (losing 1 meter of slip per kilometer of fault length) and halt abruptly as they transfer faults at Cajon Pass. The recurrence interval of joint ruptures together with the characteristics of Earthquake-Gate-breaching events fill a crucial gap in current long-term hazard models for the state of California.

Figure: Preferred slip model for the 1812 earthquake involving the San Andreas and the San Jacinto faults. Slip on the San Andreas Fault (SAF) is imposed based on the Lozos (2016) preferred slip distribution matching paleoseismic data. Slip on the southern San Jacinto Fault (SJF, up to the Colton paleoseismic site) is based on the Lozos (2016) preferred model. We test thirty slip distributions for the northern SJF and show our preferred model, chosen based on the triggered slip on the Lytle Creek Ridge Fault (LCRF) and calibrated with slip data measured in the trench.



Tectonic-geomorphic mapping along the northernmost San Jacinto fault zone and implications for slip distribution

Drake Kerr, Nate Onderdonk

Paleoseismic and geologic data on the southern San Andreas fault zone (SAFZ) show that there is a significant difference in earthquake recurrence and slip rate on the fault north and south of Cajon Pass. Transfer of slip from the SAFZ to the San Jacinto fault zone (SJFZ) is the likely cause of the decrease in slip rate, and paleoseismic data suggest some ruptures on the SAFZ have diverted down the SJFZ. A better understanding of the fault structure and distribution of slip across the northern SJFZ are needed to test these hypotheses. To better understand where slip is transferred between the SAFZ and the SJFZ in the Cajon Pass area, we present mapping of tectonic-geomorphic features along the three major strands of the SJFZ from where it exits the San Bernardino basin to its northwest termination in the San Gabriel Mountains. Field investigations were complimented by the use of LiDAR imagery, and consultant trench logs to investigate the fault structure and look for potential slip rate or paleoseismic sites. Two potential slip rates sites as well as several sites that have the potential to bracket the timing of faulting have been identified along the northern SJFZ. Results show the middle strand of the SJFZ extending the furthest northwest and displaying the strongest geomorphic evidence for recent slip. A relatively steady decrease in geomorphic evidence of slip to the northwest suggests that slip is transferred to the SJFZ gradually over a zone at least 20km long, and not at a structure linking the SJFZ to SAFZ.

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.

Nate Onderdonk, Drake Kerr, Paula Figueiredo

Paleoseismic data and modeling studies suggest that some ruptures through the Cajon Pass area in the past 2000 years have propagated from the San Jacinto fault zone to the San Andreas fault zone, or vice versa. The San Jacinto fault zone splits into three main fault strands as it approaches the San Andreas fault zone in the Cajon Pass area, with the Glen Helen fault being the strand closest to the San Andreas. The Glen Helen fault parallels the San Andreas for a distance of 10 km in lower Cajon Creek with less than 2 km separating the two faults. The proximity of the Glen Helen fault to the San Andreas makes it a strong candidate for facilitating slip transfer between the San Andreas and San Jacinto fault zones. In an effort to test the idea of coseismic slip transfer between these two fault zones, we conducted a geomorphic and paleoseismic study along the Glen Helen strand to document it's slip rate and the timing of the last few surface ruptures.

Geomorphic investigations of the Glen Helen fault showed no visible offset of several alluvial fans that cross the inferred fault trace along a linear mountain front in lower Cajon Creek. Apparent fault scarps are present, however, in two of the alluvial fans about 100 m out from the mountain front. We excavated 5 trenches (max depth of 2 m) across these scarps and across a possible lateral offset of a fan edge, but the trenches revealed no evidence for faulting. Stratigraphic relationships in the trenches and radiocarbon dating of detrital charcoal show that the apparent scarps are erosional features from Cajon Creek and that the fans propagated across older fluvial deposits of Cajon Creek around 2000 ybp. Two additional trenches were excavated across the previously-mapped Glen Helen fault at the mountain front and confirmed that these 2000 year old alluvial fans have not been disrupted by fault activity.

These unexpected results suggest that the Glen Helen fault has not accommodated coseismic slip transfer between the San Andreas and San Jacinto fault zones in the past 2000 years. Instead, slip transfer at the surface may have occurred farther to the southeast, possibly involving the Tokay Hill fault, or 10 to 20 kilometers to the northwest where the middle San Jacinto fault strand approaches the San Andreas between Cajon Pass and Wrightwood. Alternatively, slip transfer between the two fault zones during the past 2000 years was accomplished in a manner that did not involve surface rupture.

3D Fault Geometry and Coupling at the Junction of the San Andreas and San Jacinto Fault Systems, Cajon Pass

Craig Nicholson, Andreas Plesch and Egill Hauksson

Dynamic earthquake ruptures are strongly influenced by 3D fault geometry and the degree of coupling between faults, especially at major intersections where faults interact. In the Cajon Pass Earthquake Gate Area (EGA), an expanded, updated catalog of relocated hypocenters and focal mechanisms reveals several important characteristics about the subsurface 3D geometry of and coupling between the San Andreas and San Jacinto faults. Events with nodal planes parallel or nearly parallel to the major active faults (or principal slip zones) exhibit predominantly strike-slip motion on steeply dipping planes (Fig.1). This implies that the two closest, major active fault strands (San Andreas and Glen Helen faults) are steeply dipping and may not merge at depth, but are coupled instead by a sub-vertical, finite viscoelastic zone of distributed right-lateral shear. We consider this zone of coupling to be viscoelastic because it accommodates sufficient elastic strain energy to generate earthquakes, as well as more ductile, non-elastic components of pervasive, penetrative strain and finite deformation (e.g., Forand et al., 2017). An open question then becomes to what extent does the presence of this viscoelastic zone of finite width modify or modulate the long-term rupture behavior, transfer of slip, and fault interaction between the San Andreas and San Jacinto fault systems. Lastly, aligned hypocenters and nodal planes suggest the Glen Helen fault may extend in the subsurface much farther to the NW—parallel to the San Andreas fault—than it has been mapped at the surface.

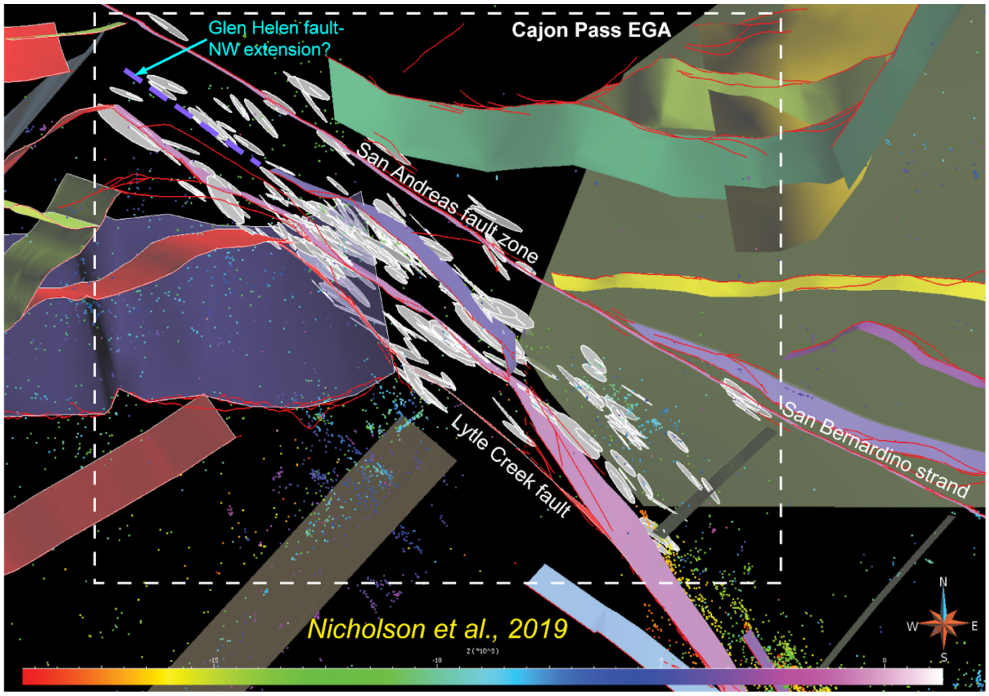


Figure 1. Oblique 3D view looking down-dip of updated Lytle Creek fault in the Cajon Pass EGA. Colored 3D fault models from SCEC CFM 5.3; red lines are mapped CGS Quaternary fault traces; seismicity colored by focal depth from Hauksson et al. (2012+updates). Nodal planes (gray disks) parallel or subparallel to San Andreas and San Jacinto faults are steeply dipping (80°–90°) and define a sub-vertical, finite viscoelastic zone of distributed right-lateral shear through the Pass. Major active strands of the San Andreas and San Jacinto faults (e.g., Glen Helen fault) do not appear to merge at depth. At upper left, nodal planes appear to define a NW extension of the Glen Helen fault (purple-dashed line) in the subsurface as compared to its mapped surface trace.

Comparing Rupture Behavior at Major San Andreas Fault Branches

Gordon Seitz

Increasingly, multi-fault ruptures have been recognized and hazard models have evolved to consider fault network behavior rather than that of individual faults. The San Andreas Fault (SAF) has major fault branches with the San Jacinto (SJF) and San Gregorio (SGF) faults. The SAF-SJF step-over has experienced two large historical ruptures in 1812 (Mw 7.5) and 1857 (Mw 7.8). The SAF-SGF intersection experienced the 1906 (Mw 7.9) earthquake.

The SAF-SGF intersection is a direct connection. Paleoseismic records on the Peninsula SAF and the SGF indicate the estimated accumulated slip prior to 1906 was 3-5x greater on the SAF than on the SGF and thus it appears a SAF rupture was favored. Matching paleoseismic event series along the Peninsula and North Coast SAF with nearly identical average recurrence intervals provides strong support for continuous ruptures that like the 1906 bypassed the SG-SAF fault branch 4 times in the past 800 years. However, the merging of fault traces at the surface does suggest that SAF-SG fault ruptures occur.

The surface traces of the SAF and the SJF do not intersect; rather, the SJF terminates with a parallel reach separated by a distance of 2 km. Paleoseismology places the 1812 rupture on the Mojave and San Ber¬¬nardino (SB) SAF sections and provides an initial accumulated stress state based on the elapse times. 1812 displacements along the SB section may have played a role in the location of the 1857 rupture termination, which stopped north of the SAF-SJF step-over. A lack of seismicity along the SB SAF may indicate the 1812 rupture path. Through-going SB SAF ruptures are supported by matching paleoseismic event series at the north (Pitman Canyon; 7 events/1100 years) and south (Burro Flats; 7 events/1200 years) ends.

Although fault geometry has generally been recognized as a factor controlling rupture paths at fault branches, stress conditions are of similar importance. What may most strongly control ruptures at fault branches is stress resulting from prior earthquakes, hence we expect improvements in models informed by initial stress ¬fields.

Measuring distributed strain from past surface ruptures, with the aim to develop probabilistic hazard models of distributed ruptures

Chris Milliner, Jean Philippe Avouac, Rui Chen, Saif Aati, Brian Chiou, Andrea Donnellan, Tim Dawson, Chris Madugo, James Dolan

The propagation of rupture can be affected by a range of mechanisms, including velocity-strengthening frictional properties of the sliding surface, generation of off-fault deformation during rupture and sliding along pre-existing fractures that can dissipate rupture energy. Here we present measurements from optical image correlation of the near-field surface deformation of the 1992 Landers and 2019 Ridgecrest surface ruptures. These data provide observational constraints of the kinematics of fault linkage and interaction, and the amount of off-fault deformation within geometrical fault complexities and stepovers relevant to earthquake gates. Along the Landers rupture we find the northern termination of the Johnson Valley fault exhibits significant fault contraction possibly suggesting unfavorable stresses for rupture propagation. In addition, we find that the surface rupture across the ~5 km wide Kickapoo stepover, which links the Johnson Valley to the Homestead Valley fault, shows remarkably small amounts of extensional strain that are unexpected within a transtensional stepover. This may suggest the linking fault has evolved into a more optimal orientation than the Johnson Valley fault which favored rupture across the stepover instead. Along the 2019 Ridgecrest surface ruptures we find clear evidence of interaction between the Mw 6.4 foreshock and Mw 7.1 mainshock cross-faults. Estimates of the dilatational strain along the mainshock rupture shows significant fault contraction and extension either side of the intersection with the foreshock rupture, likely caused by stress changes imposed by foreshock rupture. Estimates of the curl also show reduced shear strain intensity and fault displacement (by ~20 cm) along the segment that underwent contraction compared to the segment that experienced extension. Although this study and others show large stress and strain changes imposed by the foreshock, they were insufficient to impede rupture of the mainshock.

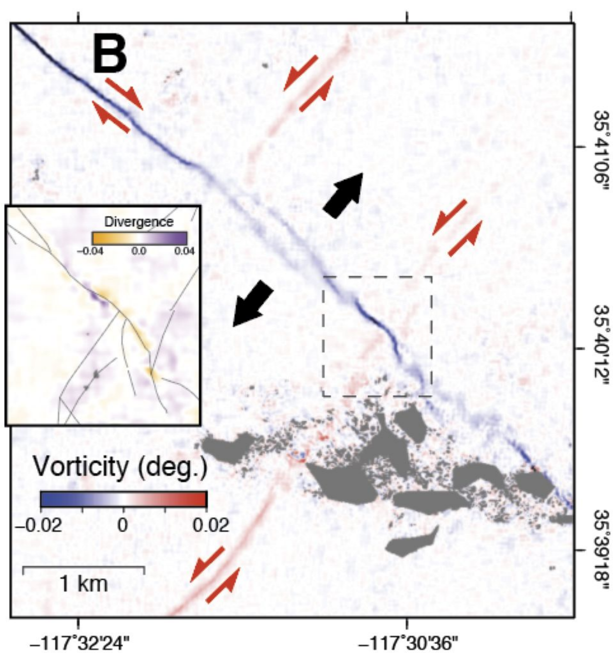


Figure: Vorticity map illustrating the different shear senses around the mainshock-foreshock intersection and how simple shear increases along the mainshock strand northwest of the intersection and decreases southeast of the intersection.

Off-fault deformation, stress field rotation, and the mechanical conditioning for rupture through an earthquake gate along the Altyn Tagh fault, northwest China

Veronica B. Prush, Michael E. Oskin, Jing Liu-Zeng, Lei Wu

Historical rupture mapping shows that fault complexities, such as bends, stepovers, and branches, are associated with the endpoints of earthquake rupture. Modeling studies show that stress heterogeneities arising from prior earthquake ruptures terminating within a complexity change the probability that a future event may break through. We term these types of complexities ‘earthquake gates’ that exhibit a probability of stopping ruptures conditioned on past recent events. We use Quaternary slip rates and mechanical analysis as tools to understand this conditionally dependent behavior for the Akatengneng Shan earthquake gate along the Altyn Tagh fault in northwest China. We find that slip rates decline from east to west along the main strand of the Altyn Tagh fault through the gate. That slip rate is lowest where the main strand exits the gate to the west suggests that the amount of distributed deformation within the bend is strongly variable along strike, possibly due to contrasting basement lithology. We explore possible causes for the observed slip rate variation by inverting for a stress field that allows for observed kinematic behavior of the Altyn Tagh fault and surrounding secondary structures. We show that there is no single stress field that can allow for the observed slip directions on all active faults within the Aketengneng Shan earthquake gate. We find that there must be rotation of the stress field near the fault to allow for left-lateral slip along its more misoriented sections. Stress rotation could be accommodated by elevated pore pressure or a weakened fault core relative to a stronger surrounding crustal volume, as has been argued along other mature continental strike-slip faults, such as the San Andreas fault. Our results suggest that future studies evaluating earthquake gate-like rupture behavior should account for the orientation and activity of secondary structures that accommodate deformation away from the main fault. Our results also show that rotation of near-fault stresses is important to consider in multi-cycle earthquake rupture models.

Complex fault rupture behaviour during the 2007 Aysen Seismic sequence along the Liquiñe-Ofqui Fault System, Chile

Gregory De Pascale, Angelo Villalobos, Gabriel Easton, Andrei Maksymowicz, Sergio Ruiz, Galderic Lastras, Manuel Hernandez, Hans Agurto-Detzel, Francisca Sandoval, and Sebastian Perroud

Although oftentimes overlooked due to the megathrust plate boundary (responsible for the Mw 9.5 Valdivia Earthquake in 1960), crustal strike slip faults in Chile play a major role in the neotectonic framework in Central-Southern Chile (including Patagonia) and associated seismic and fault rupture hazards. In particular the plate boundary sinistral Magallanes Fault System (MFS: please see SCEC 2020 poster), and the intra-arc dextral Liquiñe-Ofqui fault system (LOFS). Along the dextral-reverse strike slip LOFS a seismic sequence occurred in 2007 (up to Mw 6.2) which triggered dozens of major landslides and rock avalanches with associated casualties in the Aysen Fiord area of Chilean Patagonia. Through a combination of field mapping, bathymetric mapping, seismic profiles, seismicity analysis, and satellite mapping, we studied the LOFS in the area of the 2007 earthquake sequence to better understand the complex fault interactions and earthquake ruptures. At least three faults that are found in both marine seismic profiles (with paleo ruptures disrupting seafloor sediments in Aysen Fiord) and can be traced onshore, the Quitralco, Punta Cola, and Rio Cuervo faults (the main strand of the LOFS). In January 2007 seismicity started along the Quitralco fault, in February and March seismicity was present within the Punta Cola and Quitralco faults. In April a Mw 6.1 earthquake occurred along the Quitralco fault and then a dextral strike slip Mw 6.2 earthquake at ~7 km depth occurred along the “master” LOFS Rio Cuervo fault which was responsible for triggering the main rock avalanches. Seismic profiles within the fiord show that the Rio Cuervo fault did not rupture to the seafloor during this Mw 6.2 event because there is a thick package of non-disrupted seafloor sediments above a previous rupture. This demonstrates at least two modes of rupture behaviour along the master fault here (i.e. partial and full). Because at least 7 packages of landslides can be mapped within the fiord sediments, similar to landslides observed in 2007, we believe that at least 7 major ≥ Mw 6.2 events occurred along the LOFS since the fiord was deglaciated ca. 12 ka. Since the long and straight master LOF here slips at ~11–25 mm/yr (Quaternary, based on fieldwork further south), and because it did not rupture to the seafloor in 2007, it raises intriguing questions about why it did not rupture completely: A) Did not enough time pass since the last full rupture? B) Did the main fault rupture partially in the slow Mw 7.7 aftershock of the Mw 9.5 megathrust event in 1960? C) During previous full ruptures (i.e. to the seafloor), were the intersecting faults involved (as in 2007)? This case study provides insight into the occurrence of through-going fault ruptures from along a major strike slip fault system in a zone of complex fault interactions in Chile.

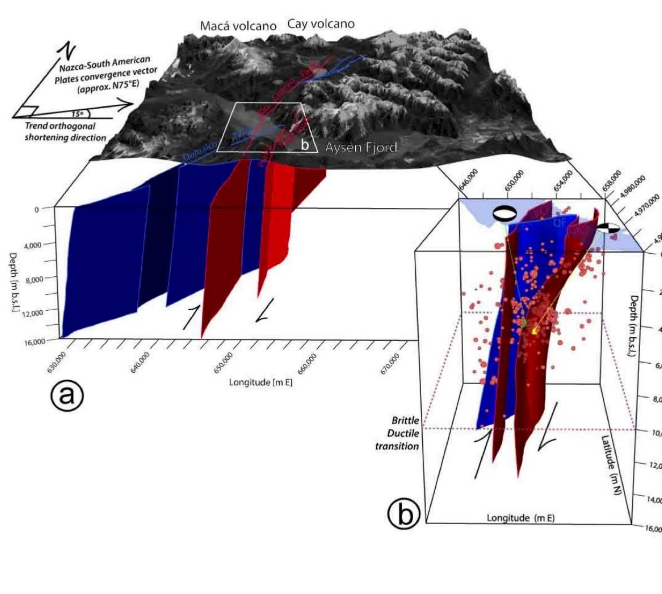


Figure: Seismotectonic model of the Aysen Fiord area showing complex fault interactions and 2007 event migration.

San Bernardino basin focal mechanisms reveal signals of interseismic loading and the 1812 Wrightwood earthquake

Michele L. Cooke, Jennifer L. Hatch and Hanna Elston

Within the San Bernardino basin, de-clustered focal mechanisms show normal slip that is inconsistent with the expected interseismic strike-slip loading of the region. The enigmatic normal slip microseismicity occurs to the northeast of the San Jacinto fault and primarily below 10-km depth (Cooke and Beyer, 2018). In the southern San Bernardino basin, Abolfathian et al (2018) also see changes in stress state with depth northeast of the San Jacinto fault. Normal slip focal mechanisms in the San Bernardino basin below 10 km depth are consistent with off-fault deformation due to spatially nonuniform ongoing creep along the San Jacinto fault below 10 km. Ongoing deep creep puts the basin in extension; however, this doesn't account for normal slip microseismicity within the northern San Bernardino Basin where the San Jacinto fault parallels the San Andreas fault. Simulations of stress state changes from the 1812 Wrightwood earthquake (Hatch et al, 2020) show that this event loads the northern San Bernardino basin in extension and the southern portion of the basin in strike-slip. These results are consistent with Rodriguez Padilla et al (2020) investigation of 1812 event impact on the Lytle creek ridge region. The pattern of microseismicity slip distribution since 1980 may owe to both the relict loading from the 1812 earthquake as well as interseismic creep along the San Jacinto below 10 km. With a long enough catalog, we might see the slip sense of off-fault microseismicity change as stresses from the 1812 earthquake are relaxed. Regional estimates of stress may not accurately reflect the spatially varying present-day stress state along the San Jacinto and San Andreas faults due to complex geometry and fault interaction, different fault behavior among nearby faults and recent earthquakes.

The effect of Asymmetric Topography on Rupture Propagation Across the Cajon Pass

Christodoulos Kyriakopoulos, Baoning Wu, David Oglesby

The Cajon Pass (CP) is a key area for the generation of large earthquakes in southern California and is thought to be an "Earthquake Gate" (EG). EG's are locations of structural complexity along major faults that, depending on a series of mechanical conditions, have the potential either to allow or stop the propagation of earthquake rupture. The mechanisms for which the CP serves as an EG are net yet understood, and for that reason are the focus of a SCEC5 interdisciplinary investigative effort. From this perspective , it is of great importance to identify first-order effects that modulate and control the generation of region-wide ruptures. Here we investigate whether the asymmetric disposition of the topographic features surrounding the CP could have an effect on this "gate-like" behavior. We organize our work to include three different types of dynamic rupture simulations. Models with a realistic (DEM based) topographic relief, models with flat free surface, and models with a synthetic topography (increasing ramp). Our experiments are further subdivided based on parameters such as nucleation location, locking depth and prestress conditions. In our preliminary results we observe a distinct pattern of normal stress change (not observed in the flat models) around the rupture front near the free surface. More specifically, in models with nucleation south of the CP (here the topography lies to the north of the fault), the rupture front is preceded by an increase in normal stress and followed by a concentration of decreasing normal stress. When rupture passes the CP (now topography lies to the south of the fault) the normal stress pattern is inverted. The same pattern of inversion is observed when rupture nucleates to the north of the CP and propagates southward. These preliminary results show that the CP marks a transition for rupture behavior and that this transition is (at least partially) related to the asymmetric disposition of the topographic relief.

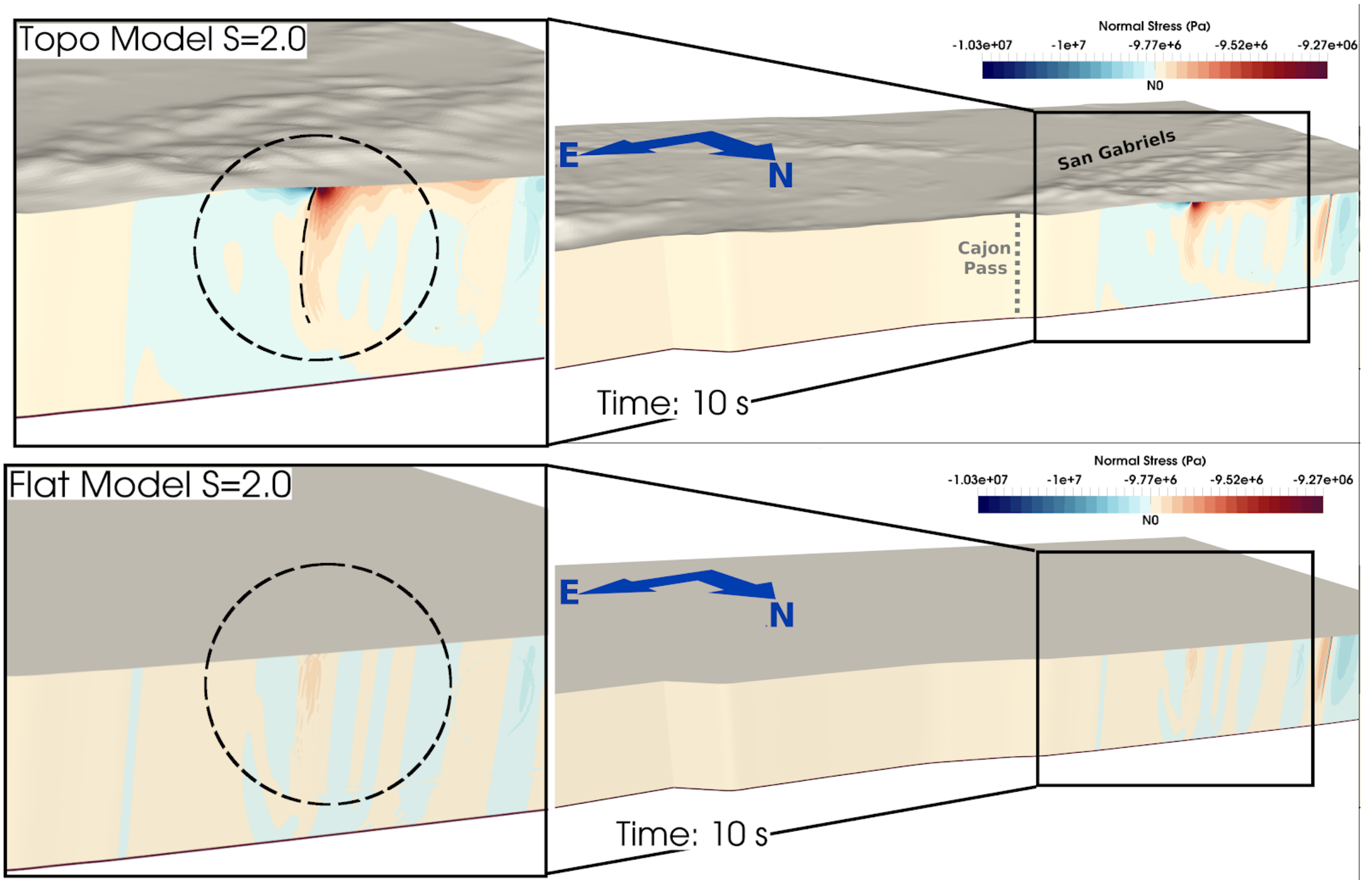
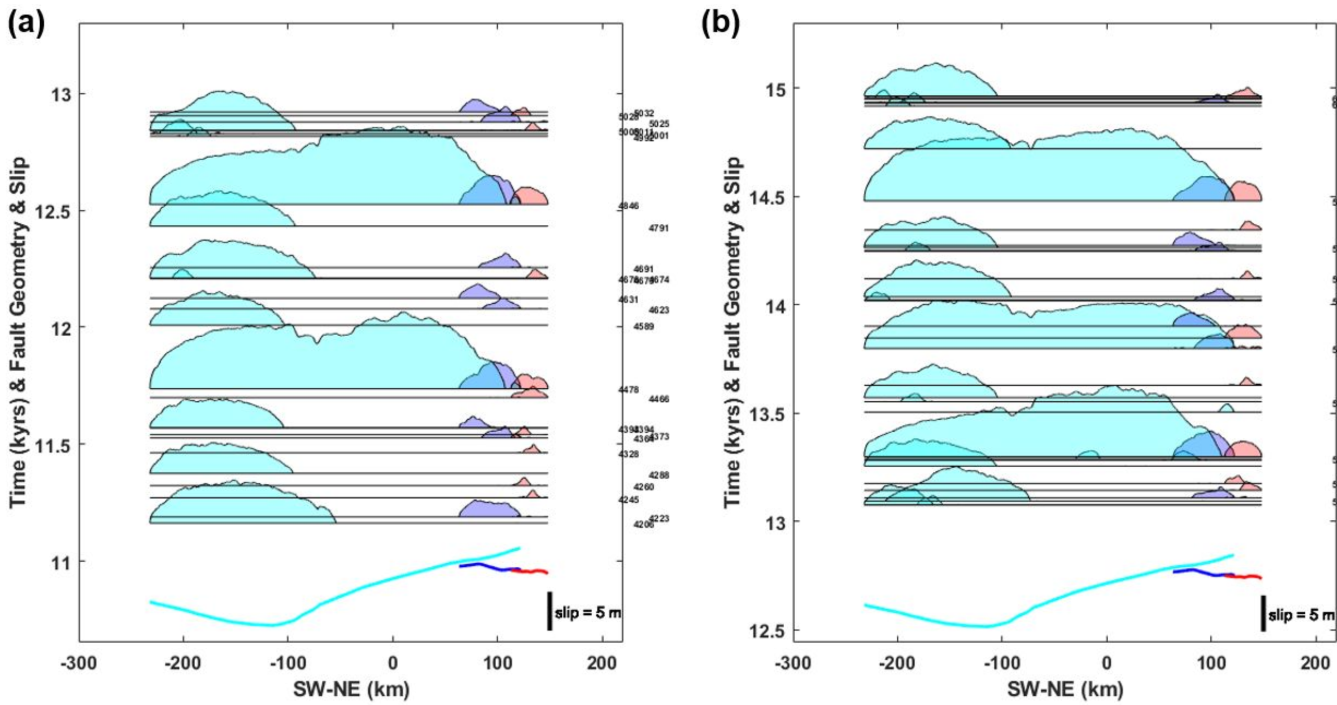


Figure: Normal stress perturbation caused by topography (experiment with nucleation north of the Cajon Pass). Normal stress perturbation at t=10 s while rupture is to the NORTH OF THE CAJON PASS for the TOPOGRAPHIC (Top Panel) and FLAT (Bottom Panel) models respectively. Blue color indicates normal stress increase (clamping) ahead of rupture front while red color shows normal stress decrease (unclamping) behind rupture front. The initial tractions in the system correspond to a seismic parameter value of S = 2.0.

Observation-constrained multicycle dynamic models of southern San Andreas fault and the San Jacinto fault: effects of the Cajon Pass and the Big Bend on rupture dynamics

Dunyu Liu and Benchun Duan

Macroscopic fault geometrical complexities such as restraining bends and stepovers, i.e., earthquake gates, show impediments to dynamically propagating ruptures. Earthquake gates occasionally pass dynamic ruptures, leading to multi-fault and multi-segment ruptures. Assessing the likelihood of multi-fault and multi-segment ruptures is in urgent need, given the recent 2016 Kaikoura and 2019 Ridgecrest earthquakes. In this study, we simulate earthquake cycles on the southern San Andreas fault (SAF) and the San Jacinto fault (SJF), with realistic fault geometries and an emphasis on physics-based dynamic ruptures. We try to understand how the Cajon Pass and the Big Bend, two major earthquake gates in the system, affect rupture extents and slip distributions. Given the extent of the 1857 Fort Tejon earthquake, the two gates should be modeled in one dynamic system to properly address seismic hazard in the region. Our 2D method consists of a finite element model for co-seismic dynamic ruptures and an analytic viscoelastic model for interseismic fault stress evolutions. With uniform shear loading, results indicate that maximum shearing at 10-15° in compression relative to the SAF south of the Big Bend yields some ruptures resembling historical events. However, the significant change in strike around the Big Bend on the San Andreas fault and GPS measurements indicates nonuniform maximum shear loading rates and directions. We then use straining rates inferred from GPS to load the fault system. In terms of maximum shearing directions, we test end-member models with maximum shearing loading parallel to local fault strikes, supported by some evidence. The system yields ruptures of the whole SAF simulated, ruptures of the whole fault system, and ruptures of individual SJF segments. In another set of models, we assign the maximum shear loading at 10° in compression relative to the SAF south of the Big Bend to reflect a slightly compressional environment. The model yields ruptures breaking Cholame and Carrizo segments but impeded by the Big Bend, ruptures of the whole simulated fault system and ruptures on individual SJF segments. Large earthquakes that break the whole system could nucleate north of the Big Bend or near the Cajon Pass on the SAF. This model indicates that ruptures tend to jump from the SAF to the SJF but less likely vice versa. The models are calibrated against long-term slip rates and slip-per-event estimations. With realistic fault geometries and dynamic ruptures, the models show potentials to reproduce past ruptures from paleoseismological records.



Slip distributions of earthquakes on the southern San Andreas fault and San Jacinto fault over four thousand years from a multicycle dynamic model. The model is calibrated against long-term slip-rate and slip-per-event estimations.

What can models of crustal stress in Cajon Pass tell us about controls on multifault rupture?

Karen Luttrell (Louisiana State University), Elliott Helgans (Louisiana State University), Bridget Smith-Konter (University of Hawaii), Liliane Burkhard (University of Hawaii)

Earthquake processes along active faults are strongly influenced by the in situ crustal stress field, which itself is comprised of multiple geophysical processes acting simultaneously at different spatial and temporal scales. We model the in situ stress field at seismogenic depth in Cajon Pass by balancing the orientation of the modern stress field inferred from earthquake focal mechanisms against the superposition of the far field tectonic driving stress, the load of topography, and the accumulation of stress on locked faults over variable loading times. We consider two main model types: one with a single driving stress for the entire region, and one with a driving stress that is heterogeneous in orientation at fault segment scale. We use these models to evaluate relative influences of each process to the contemporary stress field, describe the origin of observed heterogeneity, and assess the role each process may play in imposing control on large multifault ruptures. Our results indicate that driving stress orientation may rotate clockwise (from north-northwest to north-northeast) southward across Cajon Pass and predict in situ differential stress magnitudes between 59 and 93 MPa in this region, consistent with previous findings. We find that the modern stress field may be most strongly influenced by heterogeneity in driving stress orientation on the scale of tens of kilometers. Despite little variation in predicted rake angle for the optimal model across the Cajon Pass, predicted maximum shear stress varies along fault from ~30 – 60 MPa, with sharp variations observed between and within individual segments, suggesting that heterogeneity in driving stress orientation may inhibit multifault ruptures across the region.

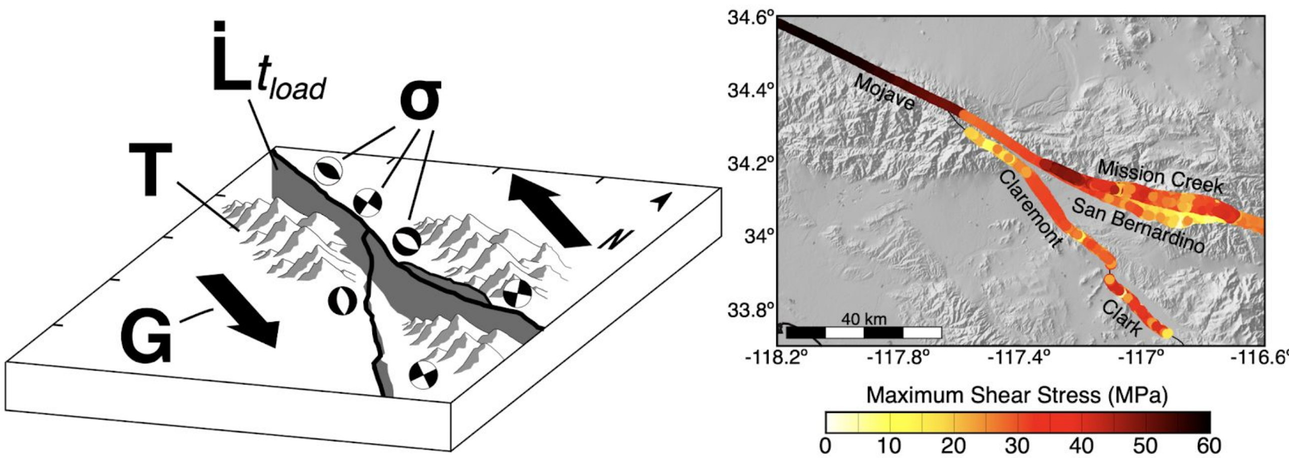


Figure: (left) schematic of components of crustal stress considered in our forward-model framework. (right) estimated resolved maximum shear stress predicted by the best-fitting model.

Variations of stress parameters in the Southern California plate boundary around the South Central Transverse Ranges

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We examine the stress field in Southern California with a focus on the region near the South Central Transverse Ranges (SCTR) including the Cajon Pass area, using a refined stress inversion methodology. The inversions are applied independently over focal mechanisms from the declustered and aftershock events from the years 1981 to 2017. Comparisons between the stress field orientations and the stress ratios from these inversions provide information on local sources of the stress field. Regionally, the SHmax trends toward NNE and the stress ratios vary from transtensional stress regime near the Eastern California Shear Zone, to strike-slip faulting near the SCTR, and toward transpression near the Western Transverse Ranges. Detailed analysis of stress parameters near the SCTR indicates deviations from the regional strike-slip faulting including the following: (1) the Cajon Pass and San Gorgonio Pass show transpressional stress regime near the bottom of the seismogenic zone likely associated with the elevated topography; (2) the stress ratio changes sharply between the NW and SE of the junction of the San Andreas Fault and the San Jacinto Fault zone and (3) in Crafton Hills, rotation of the principal stress plunges and SHmax direction and transtensional stress regime below ~10 km, along with lower estimated apparent friction coefficient, suggesting a weak fault possibly associated with deep creep. The performed multiscale analysis resolves effects of regional and local loadings. Moreover, the average stress parameters in the analyzed 37 years do not show significant temporal variations of the stress field near the SCTR region.

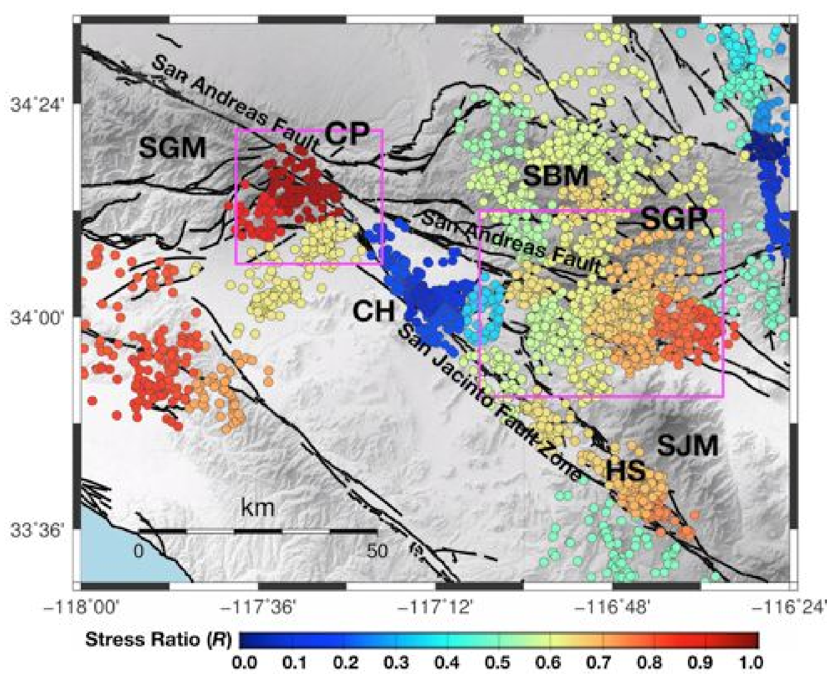
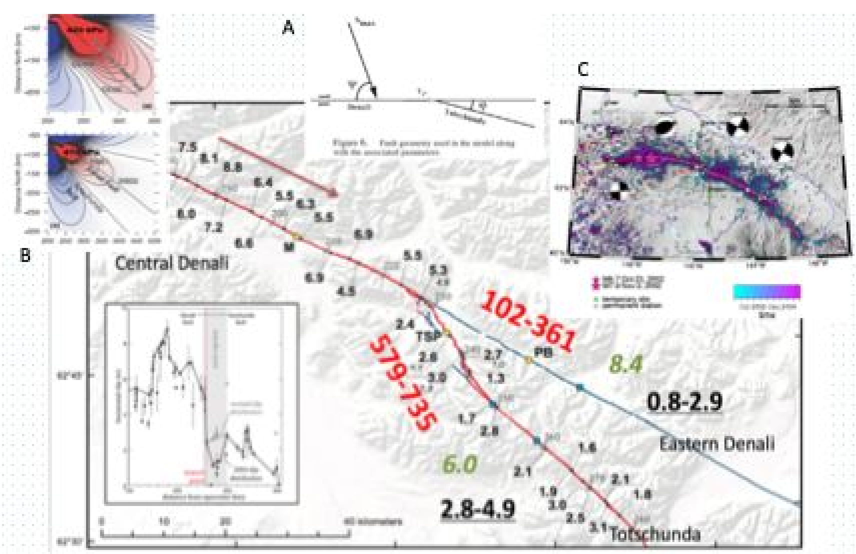


Figure: Declustered seismicity is color-coded with values of the stress ratio, R, in the selected region around SCTR. The two purple boxes indicate study areas near the Cajon pass (CP) and San Gorgonio Pass (SGP).

The 2002 Denali-Totschunda Fault Branching: Implications for Cajon Pass Ruptures?

David Schwartz

The propagation of the Mw 7.9 Denali fault earthquake rupture from the central Denali fault onto the Totschunda fault is the best modern example of fault branching. Dynamic rupture models of this branching [Bhat et al., 2004; Dreger et al., 2004; Oglesby et al., 2004] concluded that the angle of the regional or local prestress relative to the orientation of the main fault and branch played the principal role in determining which branch was taken, and that the Totschunda was more favorably oriented. GeoEarthScope LiDAR and paleoseismic data allowed us to map the structure of the Denali-Totschunda fault intersection and evaluate controls of fault branching from a geological perspective (Schwartz et al., 2012). LiDAR revealed the Denali-Totschunda fault intersection is structurally simple with the two faults directly connected. We used paleo event timing and slip rates (see figure below for all geologic data) to propose that differences in the accumulated slip on each fault segment was an important control of the branching direction. Insufficient accumulated slip, reflecting the recency of rupture, inhibited continuation along the eastern Denali fault (which had received a larger modeled coulomb stress pulse and aftershocks are absent, see figure). In contrast, the Totschunda fault was triggered because of a longer elapsed time during which slip accumulated to a failure level. We suggest that for long, high-slip-rate (a subjective value) strike-slip fault zones such as Denali (15mm/yr) that have recurrence rates of several hundred the timing of past earthquakes and ensuing stress accumulation on different structural elements is an important control of the rupture path at branching intersections or along the main fault trace. The Cajon Pass, a volumetric intersection (no surface connection), is structurally more complex than the simple Denali-Totschunda but timing of events to the north (San Andreas) and south (San Andreas, San Jacinto) may play an important role in the behavior of ruptures across this structural knot.



Rupture characteristics of the Denali-Totschunda fault intersection (modified from Schwartz et al., 2012; Schwartz 2018)). Intersection elements that are interpreted to control the propagation of the 2002 fault rupture from the central Denali to the Totschunda fault. include: (1) direct connectivity of the two faults; (2) the timing (in red in years before 2002) of the most recent pre-2002 rupture on each (rupture dates were obtained from paleoseismic sites TSP and PB); (3) fault slip rates (green italics, mm/yr, Matmon et al., 2006); and (4) the estimated accumulated slip (m, underlined) at the time of the 2002 rupture. Blue squares are slip-rate sites. Arrow is direction of rupture propagation. Numbered ticks along fault are distances (km) east of the 2002 epicenter. Values shown along fault (black bold) are measured surface offsets (m) from 2002; 2002 slip distribution profile across branch point (inset). Additional observations : A) angular relation of Smax to fault trace (Bhat et al., 2004); B) modeled static stress changes (Anderson and Ji, 2003); C) aftershocks (Ratchkovski et al., 2004].

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