Cajon Pass Earthquake Gate Area Integrated Science Plan

1. Earthquake Gate Area (EGA) General Science Questions:

One of the major questions of earthquake science is: What are the factors that can conditionally halt or pass earthquake ruptures and thus have a control on the probability of large, multi-segment or multi-fault ruptures. "Earthquake Gates" are areas along a fault, at major fault intersections, or within a fault system, where some ruptures have stopped, while others have passed through. The primary science questions regarding Earthquake Gates include:

1. How do fault intersections affect the probability of through-going earthquake ruptures?
2. How do 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?

2. Important Science Questions Specific to Cajon Pass:

SCEC has designated Cajon Pass as the initial area for focused research on the behavior of Earthquake Gates. Several major fault systems, including the San Andreas fault (SAF), northern San Jacinto fault (SJF) and major reverse faults of the Transverse Ranges, merge and interact in the Cajon Pass area. How these faults interact or modulate each other may strongly influence the propagation of earthquake ruptures through this region — a region with uniquely high seismic hazard potential to a number of critical lifelines and large urban populations. Both historic and paleoseismic records indicate that earthquakes on the SAF have both terminated in the Cajon Pass area (*e.g.,* 1857) and passed through, with through-going ruptures involving the SAF Mojave section, the SAF San Bernardino section, and/or the northern SJF (*e.g.,* 8 December 1812) [Rockwell et al., 2015; Onderdonk et al., 2015; Grant-Ludwig et al., 2015; Lozos, 2016]. Important questions related to earthquake and fault behavior in Cajon Pass thus include:

1. What is the record of earthquake rupture, and related crustal deformation during the late Holocene? What is the pattern of non-elastic deformation, slip history, and slip gradients along faults, and what can this tell us about fault geometry, fault interaction and potential future earthquake rupture behavior?
2. What is the current stress state and variation in material properties, including important material interfaces that may affect the pattern of strain accumulation, strong ground motion propagation, and future ruptures?
3. What is the 3D fault geometry in the Cajon Pass area and how may it influence variations in stress, fault strength, fault interaction and possible rupture patterns? Do the SAF and SJF directly intersect at depth in Cajon Pass, or is there instead a secondary set of linking structures or transfer zone of distributed shear? What is the significance of the actual fault configuration at depth?
4. What do crustal deformation and dynamic rupture models suggest about the pattern of strain accumulation, the geometry of active subsurface faults, and past and future earthquake ruptures? Can we understand how and why past earthquake ruptures stopped or propagated through Cajon Pass? What constraints can independent datasets like the distribution and fragility of precariously balanced rocks (PBRs) provide in terms of long-term, multi-cycle fault behavior, fault interaction, strong ground motion excitation, or possible past rupture directivity?

3. Research Priorities and Objectives to address various Cajon Pass EGA Science Questions:

A) Gather data to characterize evidence of earthquake crustal deformation and related ground shaking using methods such as LiDAR, geologic mapping, paleoseismology, InSAR/GPS, PBRs, and well data.
B) Gather geophysical, seismological, and well data to characterize subsurface conditions related to geology, fault geometry, material properties (e.g. crustal velocities and fault strength), and important material interfaces, as well as stress state, stress orientations, and style of faulting.
C) Evaluate and improve the Community Fault Model (CFM) 3D fault representations in the Cajon Pass area using improved 3D velocity models, relocated seismicity, geophysical constraints, and insights from kinematic and mechanical models. Develop more realistic 3D representations of subsurface conditions within the Cajon Pass EGA that include structural complexities, such as non-planar fault geometry, active secondary faults, and important material interfaces like older, abandoned strands of the SAF and possible mid-crustal detachments.
D) Incorporate new structural and stress representations into forward crustal deformation models, geodetic inversions, and single-event and multi-cycle rupture models that are consistent with independent datasets.

These general research priorities and objectives may be addressed by conducting possible research tasks and activities like the following:

Years 1 and 2:
a) Compile previous geologic mapping, and refine surface mapping of faults, folds, and Quaternary deposits using LiDAR and other high-resolution techniques to improve our understanding of tectonic geomorphology, crustal shortening, fault slip, and other fault-related patterns of Recent crustal or earthquake-related deformation.
b) Utilize existing detailed geology maps and available industry well data to construct cross sections and 3D structure models, and to better characterize fault geometry and the lithologic contrast across major faults at depth.
c) Look for additional slip-rate, slip gradient, and/or paleoseismic sites along the SAF and SJF within Cajon Pass. Investigate the feasibility of paleoseismic work in areas closest to the SAF-SJF junction (such as Lone Pine Canyon and along Lytle Creek), and re-evaluate and potentially extend previous high-resolution paleoseismic data sites like Pitman Canyon.
d) Update and improve CFM 3D fault representations in the Cajon Pass EGA to include faults that are currently missing or inadequately represented. Incorporate updated relocated earthquakes and detailed subsurface geology.
e) Refine variations in stress orientation, style of faulting and stress drop along major strike-slip and dip-slip faults in the Cajon Pass EGA. Evaluate available borehole data to improve estimates of fault strength and friction.
f) Investigate the feasibility of conducting and if possible, initiate passive portable seismic array(s) in the Cajon Pass EGA to more accurately record microearthquakes, refraction microtremor and ambient noise for improved crustal imaging, 3D velocity models, earthquake locations, and to provide critical insights on fault structure, how and where major faults may intersect, and the characteristics of other important interfaces at depth.
g) Improve mapping of the distribution of precariously balanced rocks (PBRs) along major faults near Cajon Pass. Better characterize and refine fragility estimates for small PBRs that may provide more accurate constraints on repeated ground motions.
h) Use high-resolution InSAR, GPS, and other geophysical datasets to help define the modern deformation field and to better resolve geodetic fault slip rates and inferred subsurface fault geometry.
i) Evaluate existing CFM 3D fault representations using various crustal deformation modeling methods for consistency with geodetic strain data (e.g., InSAR/GPS) and regional fault and fold geometry.
j) Construct single-event and multi-cycle rupture models for Cajon Pass, incorporating current observational understanding of complex 3D fault geometry, stress conditions, material properties, and surrounding rheologies. Compare these models with existing paleoseismic data to develop physics-based assessments of plausible rupture paths through Cajon Pass. Use these model results to highlight potential sites for further observational studies.

Years 3 and 4:
a) Complete detailed surface mapping and merge with subsurface data to create a high-resolution 3D fault and geologic structure model of the Cajon Pass EGA.
b) Further develop any newly identified paleoseismic, slip-rate, or slip-per-event sites on major Cajon Pass faults.
c) Create a Quaternary surface uplift map based on ages and elevations of Quaternary deposits to help constrain subsurface fault geometry and patterns of fault and fold deformation.
d) Continue to evaluate high-resolution InSAR and other datasets to help define the modern deformation field and to better resolve geodetic fault slip rates, patterns of uplift, and inferred fault geometry.
e) If feasible, continue to operate portable passive arrays in Cajon Pass to enhance microearthquake detection and location, and the recording of ambient noise, possible trapped or interface waves, and other signals. Develop other methods to help resolve the continuity of surface structure and faults to the top of seismicity at ~5 to 7 km depth.
f) Continue to update, refine, and improve the 3D CFM fault set for Cajon Pass based on geophysical, geodetic, and seismological data collected during Years 1-2. MT studies may also help to resolve fault geometry at depth.
g) Test fragilities of newly identified PBRs with improved models of expected ground motion from different Cajon Pass EGA earthquake rupture scenarios.
h) Target new observational studies for evidence that can help distinguish between viable alternative fault representations.
i) Search for observational evidence for patterns of rupture—and the physical processes behind them—that were identified as plausible by single-event and multi-cycle rupture modeling studies in Years 1 and 2.
j) Improve single-event and multi-cycle rupture models within Cajon Pass by incorporating updated 3D representations of the SAF, SJF, Cucamonga, and secondary faults. Update model fault geometry, stress conditions, and surrounding rheology based on observations collected in the first two years of the EGA program.
k) Compare model results with newly collected paleoseismic and PBR data to better constrain plausibility and resolve possible controlling physics of different earthquake rupture behavior as reflected in the updated paleoseismic record. Use these models to potentially reevaluate historic and recent paleoseismic rupture behavior.