WORKSHOP REPORT: Earthquake rupture and creep in shallow earth materials Community Workshop Nov 10-11, 2025

SCEC Award #**25246**

PIs: W. Ashley Griffith (Ohio State), Alexis Ault (Utah State), Kate Scharer (USGS)

WORKSHOP DESCRIPTION:

We led a two-day, in-person workshop with scientists from across the full spectrum of Statewide California Earthquake Center (SCEC) disciplines to explore earthquake rupture and creep in shallow earth materials, and to discuss technologies and strategies for studying these processes through future observations and implementing them in modeling efforts. The workshop included a one-day field trip to visit three sites along the Southern San Andreas Fault (SSAF) at the Salt Creek paleoseismic site, Ferrum, and the Mecca Hills, CA (Fig. 1), followed by one day of presentations and moderated discussions in Palm Springs, with emphasis placed on involvement of early career researchers.

Shallow on- and off-fault earth materials are part of the geotechnical layer that can influence deformation throughout the earthquake cycle and strong ground motion. Key workshop topics were (***1***) geodetic and geomorphic observations of shallow crustal deformation associated with earthquake rupture and interseismic creep, (***2***) geological processes associated with this deformation, (***3***) the properties of the geotechnical layer that cause uncertainties in modeling seismic site response and the interpretation of surface deformation observations, and (***4***) strategies for future instrumentation and observations needed to resolve uncertainties, as well as identifying key study areas outside of southern California in the statewide center.

The field trip focused on outcrops along the SSAF system that experience seismic slip and steady and triggered creep, display damage signatures that suggest strain partitioning across the seismic cycle and demonstrate strain (de)localization in geodetic observations of steady and transient creep (e.g., Lindsey et al., 2014; Tymofyeyeva et al., 2019; Parker et al., 2021). During the field trip we explored problems of fault localization/delocalization as a function of fault geometry, lithology/sedimentology, fabric development, and depth, and the role of different fault zone components in shallow seismic rupture propagation vs. transient creep. We also discussed geologic/geomorphic, geophysical, mechanical, and geodetic observations of deformation at these sites and explore complementarities and differences between those datasets. The field trip was focused on sites in southern California that are well-studied and afford good geologic exposure, and during the second day we will focus on extending these observations to related problems statewide. (see field trip schedule at end of this report)

The second day of the workshop consisted of invited talks (2-3 per session) and discussions on four key topics (sessions):

1. Geodetic observations of rupture and creep
2. Geological processes in response (or modulating) to rupture and creep
3. Geotechnical layer properties affecting surface and near-surface deformation and ground motions
4. Observations, technologies, and approaches needed to better understand shallow deformation in space and time

KEY STATS:

- Workshop included 37 total registered participants, including the 3 workshop leaders
- Several USGS-affiliated registered participants, including 3 invited speakers, were unable to attend due to the extended government shutdown
- Workshop attendees included ~21 early career scientists (students, postdocs, and faculty)
- A post-workshop feedback survey was distributed to 34 participants (all participants except 3 PIs). 9 participants responded. Responses were uniformly and overwhelmingly positive:
    - on a scale of 5(best) to 1(worst), on the topics of content/engagement, format, and logistics, all responses were "5".
    - Positive comments were evenly divided between the field trip and formal presentation/discussion portions of the workshop
    - All respondents were interested in some sort of follow up, principally collaborations, a possible white paper/report, or a follow-up workshop

SCIENCE WORKSHOP SESSION SUMMARY:

Session 1 — Geodetic observations of rupture and creep: spatio-temporal scales of deformation and data gaps

Session 1 focused on how shallow deformation is expressed during and between earthquakes, integrating geodetic, remote sensing, and geological observations to interrogate creep, surface rupture, and off-fault deformation.

Kathryn Materna (U. Colorado) presented a new observational framework for shallow fault creep in the Salton Trough, demonstrating that creep comprises multiple behaviors (steady, triggered, and spontaneous episodic events) rather than a single process. Using GNSS, InSAR, and creep meters, she showed that creep events typically involve millimeter-scale slip, propagate along faults at km/day rates, and are not mechanically segmented, often "dancing" across fault strands. A new catalog of thousands of creep events reveals consistent propagation velocities and strain drops, suggesting that creep events act to release available shallow strain. Rate-and-state friction alone cannot reproduce these behaviors, motivating the inclusion of additional mechanisms such as dilatancy and pore-pressure diffusion. Discussion emphasized the need to better constrain creep depth, recurrence, and triggering conditions, and whether shallow creep is more widespread than currently recognized.

Solène Antoine (Caltech) used optical image correlation to quantify how deformation localizes at the surface during earthquakes and how this relates to the shallow slip deficit. Her analysis of the 2021 M7.4 Maduo earthquake showed that a large fraction of surface deformation occurs off-fault, extending hundreds of meters to over a kilometer from the main rupture. Results indicate that when slip is localized on the fault, surface deformation narrows; when shallow slip is reduced, bulk yielding accommodates strain. Importantly, plastic yielding operates over larger spatial scales (>500 m) than dynamic damage (<500 m), reframing common assumptions that greater slip necessarily produces more distributed damage. These findings have direct implications for rupture energetics, strain budgets, and how surface observations are interpreted in models.

Zachary Smith (Berkeley) examined how hydrothermal alteration influences coseismic slip localization during the Ridgecrest earthquakes. Multispectral mapping revealed that enhanced surface slip correlates with phyllic and argillic alteration zones, while propylitic alteration tends to strengthen faults and suppress slip. Laboratory and field observations suggest that mineral assemblages and anisotropic fabrics created by past hydrothermal activity exert strong control on fault rheology, localization, and damage evolution. This work highlights that inherited mineralogical structure — not just fault geometry — plays a key role in determining which fault strands activate.

Collectively, Session 1 emphasized that shallow deformation reflects a coupled system involving fault friction, bulk yielding, fluids, and inherited material structure. Key discussion points included how to define yielding thresholds in materials with long deformation histories, how to bridge field-scale strain with remote sensing observations, and how to better integrate creep, off-fault deformation, and alteration into earthquake models. Participants identified a critical need for time-series observations (including heat and fluid flow), improved constraints on shallow material properties, and closer integration between geodesy, field geology, and modeling.

Session 2 — Fault zone materials, healing, and granular processes

Session 2 explored how fault zone materials store deformation, evolve through earthquake cycles, and control healing and creep through laboratory experiments and granular mechanics.

Alex DiMonte (Utah State) presented friction experiments on clay-rich San Andreas Fault gouge, showing that water-saturated gouge is significantly weaker and heals more slowly than dry material. Slide-hold-slide tests indicate reduced frictional strengthening and diminished healing in saturated samples, consistent with geodetically inferred stress drops and recurrence intervals in the Salton Trough. Microstructural observations demonstrate that slip localizes along clay-rich layers, suggesting that mineralogy strongly governs fault behavior and may enable shallow slow slip or episodic creep. These results support a mechanistic link between clay alteration, fluid presence, and aseismic deformation.

Vashan Wright (UCSD) discussed granular jamming, yielding, and memory in fault materials, emphasizing how earthquakes drive transitions between jammed (solid-like) and unjammed (fluid-like) states. Field observations from Pallet Creek reveal greater grain damage and fabric development in coseismic zones compared to aseismic areas, with preferred grain orientations recording strain history. Granular rearrangement precedes grain breakage, and repeated earthquakes progressively modify force networks and pore structures, encoding long-term “memory” of deformation. This framework provides a physical basis for understanding rigidity loss, strain localization, and evolving fault strength.

Discussion centered on how granular processes operate during dynamic rupture versus interseismic deformation, how material memory influences subsequent earthquakes, and what observable metrics (grain fabric, porosity, mineral alignment) can be used to connect laboratory results with natural faults. Participants

highlighted the need to explicitly link small-scale material processes with geodetic and seismic observations of healing and creep.

Session 3 — Properties of the geotechnical layer and impacts on surface deformation and ground motions

Session 3 addressed how near-surface materials control surface rupture expression and seismic ground motions, bridging earthquake physics with geotechnical engineering.

Yihe Huang (Michigan) presented dynamic rupture simulations incorporating shallow sedimentary layers using continuum damage rheology. Their models show that thicker, lower-rigidity sediments promote distributed off-fault deformation and can suppress near-surface fault slip entirely, effectively decoupling surface deformation from deeper rupture. Off-fault plasticity may account for several percent of total seismic moment. Importantly, they demonstrated that both frictional and material properties (shear wave velocity, layer thickness, internal friction) jointly govern deformation patterns and high-frequency ground motion deficiency on soil sites. Smooth velocity gradients alone can reproduce observed reductions in high-frequency energy, even without invoking strong inelasticity, underscoring the importance of accurately characterizing shallow velocity structure.

Brady Cox (Utah State) focused on site effects and practical methods for measuring shear wave velocity, damping, and fundamental site frequency — parameters critical for seismic design. Using ambient noise (HVSR), surface wave methods, and distributed acoustic sensing, he illustrated how soil conditions vary dramatically over short distances and strongly control shaking intensity and resonance. Case studies from Mexico City, New Zealand, and the southern San Andreas Fault highlight how soft sediments amplify long-period motions and how fault zones themselves can attenuate and reflect seismic waves. Cox emphasized that estimating site resonance is essential for mitigating building damage and that current engineering practice often lacks sufficient near-surface characterization.

Discussion underscored a persistent gap between geoscientists and geotechnical engineers, with participants calling for stronger integration of fault-zone studies into site response analyses and infrastructure planning. Key needs identified include improved constraints on shallow shear velocities, frictional properties, and sediment thickness; better engagement of the engineering community within SCEC; and translation of fault-scale observations into parameters directly usable for ground motion modeling and building codes.

KEY DISCUSSION POINTS:

- Some research infrastructure that is key to understanding shallow earth deformation – like creep meters – are in various states of disrepair with no plan for upkeep or training of new users. This is an area of infrastructure that should expand with a sustainability plan rather than contract.
- What is the depth extent of creep, and how is it related to lithology? For example, creep in the Salton Trough is likely limited to Pleistocene sediments, whereas creep along the Calaveras fault extends the entire depth of the fault
- Shallow fault geological observations are key to understanding high resolution fault structure, but are subject to observational bias
- There is great potential for deploying new technologies (e.g., DAS) to understand shallow fault structure
- All stakeholders in shallow fault deformation come at it with a different vocabulary. For example, what means "plastic" deformation depends on one's perspective. Likewise the notion of "strength" is complex and different in different fields.
- Along a similar line, there is abundant, potentially complementary data available in adjacent fields, such as earthquake engineering and rupture simulation, that are incompatible in their typical forms. For example, 1D parameters used in geotechnical site response cannot be used in 3D rupture dynamics simulations
- Friction constitutive behavior is important (both short term behavior and longer-term evolution), but so is constitutive behavior of the bulk
- There are a lot of complementary observations that are not being fully utilized in concert. For example, high spatial resolution geological/geophysical characterization of fault zone structure and high temporal resolution observations of surface deformation (through, e.g., optical image differencing, LiDAR, etc.)

WORKSHOP OUTCOMES:

- There was general consensus that there is a need/desire to build an ecosystem for collaboration between earthquake scientists and engineers, integrating field, lab, and computational expertise in earthquake geology, paleoseismology, geodesy, geophysics, geochemistry, and numerical modeling, to study deformation and ground motions in Shallow (<3 km) Earth Materials.
- Key to this ecosystem would be dialogue between various stakeholders, training opportunities, selection of a target site for multidisciplinary data collection (e.g., southern San Andreas Fault at Salt Creek or Ferrum, Superstition Hills Fault, Calaveras Fault, and possibly the southern San Jacinto Fault), and to coordinate with the CVM/CRM on an integrated geotechnical-layer characterization.
- To this end, the PIs, along with several of the meeting participants submitted a TAG proposal with the name: ***SEM: Shallow Earth Materials***

SUMMARY OF WORKSHOP SCHEDULE:

November 10, 2025: Field Trip

Field Trip Leaders: Alexis Ault (Utah State), Tom Rockwell (SDSU), and Ashley Griffith (Ohio State)

We began with a field trip on Monday, November 10 to three key sites along the Southern San Andreas Fault: Salt Creek paleoseismic site, Ferrum, and Mecca Hills, CA. Participants will examine outcrops that exhibit seismic slip, steady and triggered creep, and damage patterns indicative of strain partitioning and (de)localization across the seismic cycle. Our discussions will explore problems of fault localization/delocalization as a function of fault geometry, lithology/sedimentology, fabric development, and depth, and the role of different fault zone components in shallow seismic rupture propagation versus transient creep. We'll also compare geologic/geomorphic, geophysical, mechanical, and geodetic datasets to explore their complementarities. These well-studied sites with excellent geologic exposure will set the stage for broader discussions on day two, extending insights to fault systems across California.

Time	Activity	Presenters
06:30 – 07:15	Breakfast	
07:15 – 07:30	Gather in Hilton Lobby, pick up lunch	
07:30 – 08:45	Depart, travel to Salt Creek, stop 1 at 33.445053, -115.842545	
08:45 – 09:00	Welcome and overview	Ashley Griffith, Kate Scharer, Alexis Ault and Tom Rockwell
09:00 – 11:00	**Stop 1: (a) Salt Creek paleoseismic site and (b) creepmeter**, *Reposition vehicles on N side of creek at 10:00 am to walk to creepmeter*	Kate Scharer and Tom Rockwell
11:00 – 11:15	Drive and walk to Ferrum site, stop 2 at 33.455325, -115.855407	
11:15 – 12:45	**Stop 2: SSAF exposed at Ferrum** *Lunch at the outcrop (~12:00)*	Ashley Griffith and Tom Rockwell
12:45 – 13:15	Drive to Painted Canyon, Mecca Hills, stop 3 at 33.605243, -116.022468	
13:15 – 16:15	**Stop 3: SSAF at Painted Canyon**	Alexis Ault, Alex DiMonte, Brady Cox
16:15	Drive back to Hilton	
17:30	Arrive back at Hilton	

November 11, 2025: Science Workshop

Organizers: Alexis Ault (Utah State), Ashley Griffith (Ohio State), and Kate Scharer (USGS)

The second day of the workshop consisted of invited talks and discussions on key topics: (1) geodetic and geomorphic observations of shallow crustal deformation associated with earthquake rupture and interseismic creep, (2) geological processes associated with this deformation, (3) the properties of the geotechnical layer that cause uncertainties in modeling seismic site response and the interpretation of surface deformation observations, and (4) strategies for future instrumentation and observations needed to resolve uncertainties, as well as identifying key study areas outside of southern California in the statewide center.

Time	Presentation	Presenters
08:00 - 08:15	Introduction	Ashley Griffith, Alexis Ault
08:15 - 10:15	**Session 1: Geodetic observations of rupture and creep – spatio-temporal scales of deformation & data gaps** Moderator: Ashley Griffith	
08:15 - 08:45	Creepy dynamics in the Salton Trough: initiation, propagation, and sequences of aseismic rupture	Kathryn Materna (Colorado)
08:45 - 09:15	Imaging earthquakes from optical remote sensing brings constraints on deformation localization and the related shallow slip deficit	Solene Antoine (Caltech)
09:15 - 09:45	Impacts of Variable Hydrothermal Alteration on Coseismic Surface Slip during the 2019 Ridgecrest Earthquakes	Zachary Smith (Berkeley)
09:45 - 10:15	Discussion	
~~10:15 - 10:30~~	~~Break~~	

10:30 - 12:00	**Session 2: Shallow geologic processes in response to rupture and creep** Moderator: Kate Scharer		
10:30 - 11:00	Geodetically observed shallow deformation, geologically explained: frictional behavior of southern San Andreas fault gouge	11:30 - 12:00	Discussion
11:00 - 11:30	Memory, jamming, and multi-step yielding in near-surface fault zone sediments	~~12:00 - 13:15~~	~~Lunch~~

Alex DiMonte (Utah State)

Vashan Wright (UCSD)

13:15 - 14:30	**Session 3: Properties of the geotechnical layer that affect surface deformation and ground motions** Moderator: Alexis Ault	
13:15 - 13:45	How geotechnical layers affect surface deformation and ground motions: Insights from dynamic earthquake simulations	Yihe Huang (Michigan)
13:45 - 14:15	Field and Data Processing Methods for Developing Shear Modulus and Damping Properties Needed to Model Near-Surface Site Effects in Design Ground Motions	Brady Cox (Utah State)

14:15 - 14:30	Discussion	
14:30 - 14:45	Break	
14:45 - 17:00	**Session 4: Observations, technologies, and target field areas in the statewide center** Moderator: Ashley Griffith	
14:45 - 15:15	Lessons from global strike-slip surface ruptures for California's next big earthquake	Alba Rodriguez Padilla (Utah State)
15:15 - 15:45	A novel Bayesian near-surface geophysics approach to characterize bedrock fracture density and their control on bedrock weathering in sedimentary ridge-valley systems in California	Mong-Han Huang (Maryland)
15:45 - 16:30	**Brainstorming Session: next steps and future observations** Facilitators: Ashley Griffith, Kate Scharer, Alexis Ault *Breakout groups (20 minutes)* *Group readouts (10 minutes)*	
16:30 - 17:00	**Group discussion, synthesis, closing remarks**	
17:00	Workshop adjourns	

Workshop Participants

Last Name	First Name	Organization	Arrive	Depart	SCEC Hilton Roomblock*
Antoine	Solene	Caltech			
Ault	Alexis	Utah State			
Contreras Alvarez	Norma	UCR			
Cox	Brady	Utah State			
Dasent	Jhardel	UCSD			
DiMonte	Alexandra	Utah State			
Dor	Ory	Independent			
Du	Nairong	UW- Madison			
Elbanna	Ahmed	USC			
Evans	Eileen	CSU Northridge			
Funning	Gareth	UCR			
Gabriel	Alice	UCSD			
Garcia	Ignacio	CICESE			
Garcia	Leslie	Utah State			

Griffith	Ashley	Ohio State
Heaton	Thomas	Caltech
Huang	Mong-Han	Maryland
Huang	Yihe	Michigan
Huynh	Tran	USC-SCEC
Idzakovich	Matthew	Ohio State
Kang	Zhenyu	Oklahoma
Kindred Weigandt	Caje	USC
Kwagalakwe	Asenath	CSU Northridge
Lin	Li-Chieh	UCR
Lozos	Julian	CSUN
Marcus	Samuel	UW- Madison
Materna	Kathryn	U Colorado
Oglesby	David	UCR
Rockwell	Thomas	SDSU
Rodriguez Padilla	Alba	Utah State
Salinas	Matthew	USC
Scharer	Kate	USGS
Smith	Zachary	UC Berkeley
Vashishtha	Mradula	Stony Brook
Waech	Maisy	Brown
Wang	Yuhan	Stanford /ETHZ
Wright	Vashan	UCSD/Scripps