SCEC 2026 UNREST WORKSHOP REPORT

Understanding Natural Recurrence of Earthquakes and Slip over Time: How Can Geologic Slip, Slip-Rate and Paleoseismic Data Advance Earthquake Models?

June 1-3, 2026

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I. WORKSHOP DESCRIPTION

The UNREST workshop brought together earthquake geologists with modelers to advance how earthquake geology datasets are used to test and validate earthquake-cycle, seismic hazard, and geodetic models. The goals were (1) to foster collaboration between modelers and providers of geologic records of past earthquake slip, rupture length, slip-rate as well as timing and regularity or irregularity of past earthquakes throughout California, (2) to identify and prioritize the types and locations of geologic data that are most needed to reduce uncertainties in seismic hazard models and validate earthquake simulators, and (3) to investigate the implications of differences between deformation models based on geologic data and those based on geodetic data. This report (A) summarizes the proposed Digital Twin approach to be developed by the UNREST group to enable more rapid testing of hypotheses related to earthquake recurrence through interactivity between models and curated geologic datasets, and (B) summarizes discussions of the areas in which collaboration between modelers and geologists can be fruitful and the types geologic data to be curated in the Physical Twin.

II. KEY STATISTICS:

- Workshop included 34 total registered participants, including the 4 workshop leaders
- 27 participants attended the optional field trip, including the field trip leaders
- Workshop attendees included 17 early career scientists (students, postdocs, and faculty)
- A post-workshop feedback survey was distributed to 34 participants. Twelve participants responded. Over 90% of respondents found the workshop engaging and valuable, with 58% rating it 5 out of 5 on a likert scale and 33% rating it 4 out of 5.
- Survey comments indicated that there are (a) modelers who now have a better understanding of which aspects of their modeling results are most useful to geologists in testing hypotheses, (b) geologists who now feel more confident to propose collaboration with a modeler, (c) geologists who now have a better idea how to prioritize which earthquake geology projects to pursue and which databases need to be developed, and (d) modelers who are eager to use the new geologic datasets that will be compiled as well as existing datasets that they didn't know were available.
- The workshop agenda and list of participants can be found in Appendices 1 and 2.

III. SUMMARY OF KEY WORKSHOP FINDINGS AND OUTCOMES

A. Outcomes of Discussion of the UNREST TAG proposal

Mike Oskin's presentation of the UNREST TAG proposal is available on the website for this workshop (https://www.scec.org/events/2026-scec-unrest-workshop/). Discussion of the proposal included questions, discussion and clarification of the nature of the digital twin model and its capability to provide more rapid interaction between model inputs and outputs. Thinking of the Virtual Twin as a container for seismic hazard models, deformation models, dynamic rupture models and physics-based earthquake-cycle models was accepted as a helpful concept. The Physical Twin can be thought of as a container that includes paleosesimic and other geologic data in a standardized format that can be automatically synthesized into candidate earthquake rupture scenarios (time series of events on a fault or or fault system). The data and scenarios may be queried by models contained in the Virtual Twin. What makes the Digital Twin paradigm different from the way geologists and modelers have previously interacted within SCEC is the goal of enabling greater automation of interactions between models related to earthquake recurrence and the relevant geologic data that are used as inputs to or calibrations of those models or as reality checks on the outputs of those models.

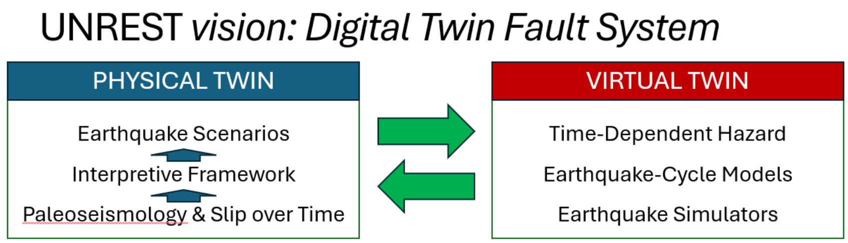

Figure 1: Overview of the Digital Twin vision for UNREST research.

The scope of the Digital Twin project was proposed to include primary plate boundary transform faults in California that have slip rates ≥ 5 mm/yr (Northern and Central San Andreas, Calaveras -Hayward-Rodgers Creek-Maacama, Southern San Andreas, Garlock, San Jacinto, Elsinore, Imperial). It was suggested that the San Gregorio fault should be included because it is very long, it merges with the San Andreas fault, and its northern section could slip > 5 mm/yr.

Abundant geologic data exist from which to build the Physical Twin for these primary plate boundary faults. One core activity of the proposed UNREST TAG is to create a database that provides the probability density function (pdf) for the age of each paleoseismic slip event (and original OxCal-formatted scripts that describe the ages and sequence of the dated samples that constrain each event) at each paleoseismic site within this fault system. The Interpretative Framework of the Physical Twin includes the Integer Linear Programming method of optimal correlation of slip events between paleoseismic trenches that Erik Perkins presented. This updated ‘stringing pearls’ approach will enable greater interactivity than was possible with previous Monte Carlo methods (Biasi and Weldon, 2009). The Interpretative Framework will also (1) make use of Kuehn et al.’s (2025) model for predicting surface displacement as a function of moment magnitude and position along the rupture length, including the asymmetry of slip distributions, (2) enable the inclusion of geologic data on slip rate, slip budget and slip over time (e.g., variable slip rate over time), and (3) allow inclusion of geologic data on rupture termination probability (Biasi and Wesnousky, 2021), so that it can interact with models of rupture termination probability (Rodriguez Padilla et al., 2024). The mutually interacting Physical and Virtual Twins of the fault system will allow for rapid development and exploration of many different earthquake rupture history scenarios that would result from different correlations of paleoseismic slip events between trenches.

B. Outcomes of Discussion of the UNREST Group Priorities

The following priorities for geologic data and modeling that will improve our Understanding of Natural Recurrence of Earthquakes and Slip over Time (UNREST) emerged from discussion of participant presentations and from break-out discussion groups each day.

Fault geometry:

Fault geometry was seen as the most fundamental type of geologic data needed as input for essentially all types of models. **Fault dip** and the **variation of dip with depth** are as important as variations in fault strike, even though the latter are more readily apparent. Changes in fault dip with depth could be characterized using categories of fault curvature with depth, which is most important to know when faults are close together. In seismic hazard models, fault dip is important both for estimating shaking at various distances from the fault and for calculating dip-slip from horizontal and vertical components of slip. Having an estimate of the **uncertainties in fault dip** is also important for many types of modeling. **Splay faults** can indicate rupture direction and can be used to constrain or differentiate between non-unique dynamic rupture models (Reitman et al., in press, BSSA). Directivity estimates from splays may be important for seismic hazard models and site-specific hazard if faults have preferred directivity. Dynamic rupture modeling that explores various fault geometries in order best fit **local uplift near fault zone complexities** can help to constrain event characteristics and fault geometry.

Slip rates:

For seismic hazard models, fault slip rates (and/or geodetic surface velocities) are the primary input for hazard, and slip rates are also very important for many other types of modeling, including the calculations of initial stresses for dynamic rupture and earthquake cycle models. Regarding prioritization of where additional geologic slip rate data are most needed to improve seismic hazard models (e.g., specific geographic regions, or more rates on fast-moving faults versus rates for faults that most likely slow but have no measured rate) no clear answer emerged. It was pointed out that “slow-moving faults are important if you live near them.” It is possible to do a sensitivity analysis of the hazard model if provided with the range of expected new results to be gathered from a specific site. In general, however, the prioritization of data gaps for both slip-rate and paleoseismic data are highly dependent on the type of modeling and the research question being addressed.

Both deformation modelers and seismic hazard modelers stressed the need for **more than one slip rate per fault** because, like slip in individual earthquakes, slip rates can vary along strike, and extrapolation to the entire fault or fault segment of a slip rate measured near the end of the fault or fault segment, can lead to poorly constrained deformation models and to errors in seismic hazard estimates (Resor et al., 2018). One modeler indicated that a database that includes both geologically estimated slip rates and **geodetically inferred slip-deficit rates** would be helpful, particularly one that flags faults for which these rates disagree.

Although slip rates averaged over relatively long time periods (Holocene and late Pleistocene) have been the bread and butter of seismic hazard models in the past, recent work has shown the value of **incremental slip rates** determined over a sequence of shorter time intervals. Such studies have revealed changes in slip rate over time for individual faults within complex fault systems (Zinke et al., 2021; Dolan et al., 2024; Fouger et al., in prep,; Gordon et al., in prep.). Progress is being made in understanding how the physics of complex fault systems could explain the temporal clustering of earthquakes that results in temporally variable slip rates (Chen et al., 2020; Gauriau and Dolan, 2021; Gauriau et al., 2023; Gauriau and Dolan, 2024; Cawood and Dolan, 2024), and earthquake cycle model modeling has shed light on the conditions that lead to alternating earthquake super-cycles in a system of two parallel faults (Rodriguez Padilla et al., 2026). In addition ideas have been proposed for how these complex fault behaviors could, in principle, be incorporated into time-dependent seismic hazard analysis. However, the number of faults for which incremental slip rates (or long paleoseismic records) are available is still small and should be expanded, while currently available geologic data on incremental slip rates and paleoseismic data on earthquake super-cycles should be integrated more fully into models of earthquake recurrence and fault system behavior.

Paleoseismology:
For seismic hazard analysis, **paleoseismic recurrence intervals** are used when they are available, but they are not available for most faults. They only make a difference in the seismic hazard model where they conflict with the recurrence intervals inferred from slip rates and slip per event (which is inferred from fault length and connectivity with other faults). Nonetheless, hazard modelers “want to know as much as we can about what actually happened on these faults for as far back as we can go.”

Average paleoseismic recurrence intervals, the **coefficient of variation** (CV) **of recurrence intervals** on a fault, and most importantly, the actual **sequence of inter-event time intervals** on a fault are highly important for comparing with the outputs of earthquake simulators and multi-cycle dynamic rupture models. Even better, when available, are **locations with both slip and time information** for past earthquakes. Paleoseismic data can also be helpful in distinguishing slip that occurs seismically versus aseismically, which is especially important for testing hazard models that include seismic rupture through the creeping section of the San Andreas fault (Philibosian, in prep.).

Other paleoseismic parameters useful for evaluating the outputs of earthquake simulators and multi-cycle earthquake models include the **average and distribution of slip** in previous ruptures and records of the **slip per earthquake in multiple previous earthquakes** and their **average, coefficient of variation and ordered time sequence**. For dynamic rupture models, the slip distribution in past earthquakes is needed in as much detail as possible. Tighter constraints on **mean slip per event** on faults will enable tighter constraints on the viscosity of the upper crust, for use in modeling shear tractions and initial stresses on faults for dynamic rupture modeling and multi-cycle rupture models. These data are most useful when they **include uncertainties**.

Information on **overlap of ruptures** (e.g., shortest time between repeating M7s on a fault) is desired for comparison to earthquake simulators and multi-cycle rupture models. This may not be distinguishable paleoseismically, but if two M7s on a fault can occur < 20 years apart, what is the probability we would have seen it by now globally? Or global compilation of faults with > 1 historic surface ruptures on the same fault. Paleoseismic evidence for multi-segment or multi-fault ruptures or a closely-spaced sequence of events are also helpful, as are examples of ruptures stopped at a geometrical or frictional complexity versus somewhere past it.

Recent compilations of paleoseismic data from multiple sites along the lengths of some of the faults in the San Andreas system (e.g., Scharer and Streig, 2019; Scharer and Yule, 2020; Rockwell et al., 2026 in review, BSSA) have provided Maximum Rupture Models, in which paleoseismic events are correlated between sites in a way that fits the paleoearthquake ages with the fewest number of ruptures. These interpretive models of compilations of paleoseismic data (which are one end member of a plethora of other possible interpretations of the data) can provide estimates of the **locations of rupture endpoints** for prehistoric earthquakes, for comparison with the outputs of earthquake simulators and multi-cycle earthquake rupture models. Modelers also indicated that a **database of large strike-slip events** would be helpful.

Of particular importance for seismic hazard analysis today are data that would help constrain the **propensity for multi-fault rupture**, which has a large impact on the overall seismic hazard model, because multi-fault ruptures produce great earthquakes that drain the seismic moment budget, leaving less moment available to be released in more frequent earthquakes earthquakes that are merely large. Such data could include compilation of **paleoseismic evidence for or against multi-fault ruptures on adjacent faults**, and compilations of **maximum slip per event** on faults, which could constrain maximum rupture lengths that would allow or rule out multi-fault ruptures for particular fault zones.

Of particular importance for viscoelastic modeling of the impact of large earthquakes on the geodetic velocity field are the **date, mean slip and rupture length of the most recent historic and pre-historic earthquakes that are M > 7.2**, in addition to the **mean recurrence interval for M > 7.2 events**.

Other useful data and modeling questions:

Other geologic data that are useful to compare with outputs of earthquake simulators and multi-cycle rupture models include **cumulative slip on faults** (and confirming that more mature faults do indeed behave differently). Other geologic data that are needed as inputs to dynamic rupture models and physics-based earthquake cycle models are information on **fault friction** and **bulk rheology**, **as a function of depth and with uncertainties**. What is especially needed is more **geological evidence for the scaling of fracture energy**. **Historic damage descriptions** enable dynamic rupture models to clarify sources for non-surface-rupturing, pre-instrumental, historic quakes. For seismic hazard analysis, we need to create better fault segmentation rules that are insensitive to poorly constrained fault geometries at depth. It is not clear how existing empirical studies (e.g., Biasi and Wesnousky, 2009) apply to the NSHM. We also need constraints on multi-mechanism ruptures. In dealing with the propensity for multi-fault ruptures, how do we avoid penalizing well-mapped (and thus complex) faults over faults with simplified representations?

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APPENDIX 1
WORKSHOP AGENDA

Monday, June 1, 2026

07:30 - 07:40	Field trip check-in
07:40 - 17:00	**Field trip to Diablo Canyon Power Plant and San Simeon fault,** led by Kim Blisniuk and Mike Oskin An all-day field trip will begin at the San Andreas Fault in the Carrizo Plain and conclude at the Diablo Canyon Nuclear Power Facility near Pismo Beach, with a focus on fault slip rates, recent earthquake slip and timing, and active faulting and seismic hazard issues in the central Coast region. Box lunches and beverages will be provided.
17:00 - 20:00	Arrival and check-in for those attending June 2-3 workshop only

Tuesday, June 2, 2026

08:00 - 08:15	Introduction: overview of the workshop goals and agenda (PDF)	Mike Oskin
	Session 1: Geologic data needed for improvement of time independent seismic hazard models	Mike Oskin
08:15 - 08:30	Utilization of Earthquake Geology Constraints in the USGS NSHM (PDF)	Ned Field
08:30 - 08:45	Development of Earthquake Geology Constraints for the USGS NSHM	Alex Hatem

08:45 - 09:00	Do earthquake ruptures propagate through the creeping section of the San Andreas Fault? Evidence from geology	Belle Philibosian
09:00 - 09:10	Missed events and over-interpretation in paleoseismic records: implications for recurrence intervals	Devin McPhillips
09:10 - 09:15	Quantifying Fault Offset Uncertainty from Displaced Landforms: Case Studies from Western North America	Veronica Prush
09:15 - 10:00	Large-group discussion	Mike Oskin
10:00 - 10:15	Break	
	Session 2: Geologic data needed for validation of earthquake catalog simulators and time-dependent seismic hazard models	Kim Blisniuk
10:15 - 10:30	Earthquake simulators and geological data constraints: current uses and opportunities for further valuable inputs	Bruce Shaw
10:30 - 10:45	Complex earthquake-cycle behavior revealed by distributions of paleoseismic inter-event times (PDF)	Mike Oskin
10:45 - 11:00	On the behavior of faults and fault systems: Geological insights into patterns and controls on earthquake occurrence in time and space	James Dolan

11:00 - 11:10	Fault-segmentation and the need for improved geologic and modeling constraints on multi-fault ruptures in seismic hazard models	Kevin Milner
11:10 - 11:15	Paleoseismic event correlation with integer linear programming (PDF)	Erik Perkins
11:15 - 11:20	Episodic deformation in Santa Maria Basin	Nate Onderdonk
11:15 - 12:00	Large group discussion	Kim Blisniuk
12:00 - 13:00	Lunch at the hotel (hosted by SCEC)	
	Session 3: Geologic data needed for comparison to geodetic and/or mechanical deformation models	Scott Marshall
13:00 - 13:15	Geodetically-derived deformation: where does all the strain rate go?	Kaj Johnson
13:15 - 13:25	Inferring geodetic slip rates with seismic-cycle models: The role of paleoseismic data (PDF)	Liz Hearn
13:25 - 13:35	Why we need a slip-rate database and more than one rate per fault (PDF)	Scott Marshall
13:35 - 13:45	Estimating evolving shear tractions on the southern San Andreas fault system based on the paleoseismic record (PDF)	Grasshopper (Emery) Anderson-Merritt

13:45 - 14:30	Large group discussion	Scott Marshall
14:30 - 14:45	Break	
	Session 4: Setting priorities for the UNREST community effort (Part 1)	
14:45 - 15:15	UNREST Proposal: Towards a Digital Twin Fault System (PDF)	Mike Oskin
15:15 - 15:45	General discussion	
15:45 - 17:00	Small-group breakout discussions (assigned groups) Each group's task is to draft priority goals for the UNREST community for the specified topic area.	
	Group A: Geologic data needed for improvement of time independent seismic hazard models	Sally McGill
	Group B: Geologic data needed for validation of earthquake catalog simulators and time-dependent seismic hazard models	Kim Blisniuk
	Group C: Geologic data needed for comparison to geodetic and mechanical models	Scott Marshall
	Group D: Geologic data needed for validation of dynamic rupture models and multi-cycle earthquake models	Mike Oskin

Wednesday, June 3, 2026

08:00 - 08:15	Introduction to Day 2	Scott Marshall
	Session 5: Geologic data needed for validation of dynamic rupture models and multi-cycle earthquake models	Scott Marshall
08:15 - 08:30	An earthquake modeler’s wish list: geologic constraints for ensemble dynamic rupture and earthquake-cycle models	Alice Gabriel
08:30 - 08:45	Earthquake sequence synchronization and alternation driven by quasistatic elastic interactions across faults (PDF)	Alba Rodriguez Padilla
08:45 - 08:55	The past 1100-1200 years of earthquake ruptures on the southern San Andreas fault system (PDF)	Tom Rockwell
08:55 - 09:05	Building Dynamic Rupture Simulations from the Geologic Data Up	Julian Lozos
09:05 - 09:15	Use of SAF-SJF paleoseismic data in multicycle earthquake models	Kate Scharer
09:15 - 09:20	Dynamic rupture modeling of the Newport Inglewood fault: explaining complex rupture paths (PDF)	David Oglesby
09:20 - 09:25	Splay faulting as a potential indicator of rupture direction	Nadine Reitman

09:25 - 09:30	3D frictional-viscous earthquake-cycle modelling of the Cascadia subduction zone	Zhang Wenqiang
09:30 - 10:15	Large Group Discussion	Scott Marshall
10:00 - 10:30	Break	
	Session 6: Setting priorities for the UNREST community effort (Part 2)	
10:30 - 11:45	Small-group break-out sessions (sign up for the group of your choice) Each group's task is to draft priority goals for the UNRESTcommunity for the specified topic area.	Kim Blisniuk
	Group A: Geologic data needed for improvement of time independent seismic hazard models	Sally McGill
	Group B: Geologic data needed for validation of earthquake catalog simulators and time-dependent seismic hazard models	Kim Blisniuk
	Group C: Geologic data needed for comparison to geodetic and mechanical models	Scott Marshall
	Group D: Geologic data needed for validation of dynamic rupture models and multi-cycle earthquake models	Mike Oskin
11:45 - 13:00	LUNCH in breakout groups at the hotel (hosted by SCEC)	

	Session 7: Building and sustaining the UNREST community	Mike Oskin
13:00 - 13:15	The Geologic Slip Rate Database (GSRD) the Community Fault Model (CFM) and Cyberinfrastructure for SCEC-hosted databases (PDF)	Scott Marshall
13:15 - 13:30	Building UNREST in a digital future	Kim Blisniuk
13:30 - 14:00	Large-group discussion	Mike Oskin
14:00 - 14:20	Summaries (up to 5 minutes each) from break-out groups A, B, C and D	
14:20 - 15:00	Large group discussion and concluding remarks	Mike Oskin

APPENDIX 2
Participants

Last Name	First Name	Organization
Anderson-Merritt	Grasshopper (Emery)	University of Massachusetts Amherst
Antoine	Solene	California Institute of Technology
Arrowsmith	Ramon	Arizona State University
Blisniuk	Kim	San Jose State University
Dolan	James	University of Southern California
Field	Edward	U.S. Geological Survey
Gabriel	Alice	University of California, San Diego
Hasuka	Syunsuke (Sunny)	California State University, Bakersfield
Hatem	Alex	U.S. Geological Survey
Hearn	Elizabeth	U.S. Geological Survey
Herman	Matthew	California State University, Bakersfield

Johnson	Kaj	Indiana University
Kindred Weigandt	Caje	University of Southern California
Lozos	Julian	California State University, Northridge
Madugo	Chris	Pacific Gas & Electric Company
Margolis	Adam	University of California, Riverside
Marshall	Scott	Appalachian State University
McGill	Sally	California State University, Bakersfield
McPhillips	Devin	U.S. Geological Survey
Milner	Kevin	U.S. Geological Survey
Oglesby	David	University of California, Riverside
Oskin	Michael	University of California, Davis
Perkins	Erik	University of California, Davis
Philibosian	Belle	U.S. Geological Survey

Pierce	Ian	U.S. Bureau of Reclamation
Prush	Veronica	New Mexico Tech
Reitman	Nadine	U.S. Geological Survey
Rockwell	Thomas	San Diego State University
Rodriguez Padilla	Alba	Utah State University
Salinas	Matthew	University of Southern California
Scharer	Kate	U.S. Geological Survey
Seitz	Gordon	California Geological Survey
Shaw	Bruce	Columbia University
Terry	Dylan	California State University, Santa Barbara
Walsh	Ashley	San Jose State University
Zhang	Wenqiang	Stanford University