SCEC SoSAFE and EQ Geology Geochronology Workshop Report

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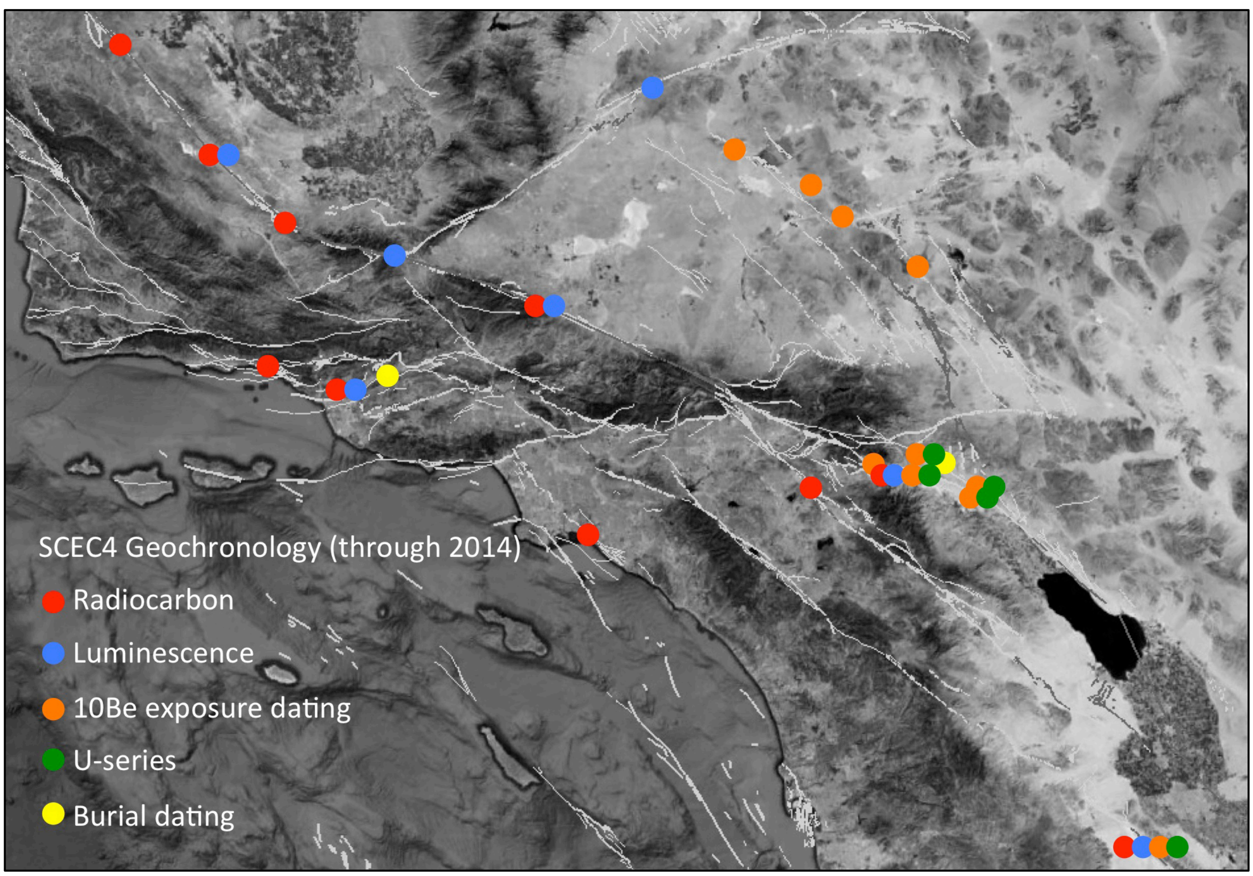
1. Introduction
The adage "no dates, no rates" remains valid: understanding earthquake processes requires that the rates of fault slip and the ages of past earthquakes are determined by dating geomorphic markers and bounding sedimentary surfaces. Over the last five years, SCEC's SoSAFE and earthquake geology research has improved the span and resolution of earthquake dating and slip rates in part through substantial use of and support for dating methods. The geochronologic work includes basic research on sample collection and laboratory analysis, application and comparison of multiple dating methods at single sites, and better understanding of the integrated history of Quaternary features whose formation is modulated by tectonic and climatic forcing. The purpose of this one-day workshop was to communicate details of these advances in order to improve field plans, sampling strategies, laboratory techniques, and date interpretation for SCEC projects, and to discuss future goals for geochronology.

The workshop focused on three techniques: exposure dating using terrestrial cosmogenic nuclides (TCN), uranium (U-) series dating of pedogenic carbonate, and luminescence dating. (Although SCEC scientists employ ^{14}C significantly, we wanted to focus on the former methods given the evolving knowledge and increasing use of these techniques.) The agenda (Appendix 1) highlighted (1) sampling and analytical strategies, (2) discussion of assumptions, and (3) interpretation and comparison of results. This report summarizes the key points from each dating technique, draws general conclusions from the SCEC geochronology efforts, and finishes with suggestions of future investigations for geochronology in SCEC5 and beyond. Workshop participants, who are listed in Appendix 1, edited and reviewed this report.



2. Summary of key points of each dating type.

Terrestrial Cosmogenic Nuclides (TCN)
SCEC dates range from very latest Holocene (a few thousand years) to Late Pleistocene (<126,000 years ago) on alluvial surfaces. Most SCEC TCN dates utilize ^{10}Be exposure dating; presentations in the workshop highlighted the following issues with this technique:

- No field sampling technique works consistently in all settings, so a spectrum of approaches is needed. These include depth profiles, individual surface pebbles or boulders, or amalgamation of clasts. Inheritance appears to be temporally and spatially variable (even within a single fan system), so careful assessment of inheritance and the resulting maximum age estimates will continue to be a focus.
- Erosion of the fan surface can confound even relatively young (~30 ka) fans, and should be addressed through multiple sampling strategies or application of other dating approaches such as U-series (see below). Examples of this can be found in Behr et al, 2010; Blisniuk et al., 2012; Fletcher et al., 2010.
- The range of precipitation and climate across southern California (and northwest Mexico) shows that the surface character and emplacement of alluvial fans varies by region, so separate studies are needed for each sub region.
- TCN studies can reveal the timing of alluvial aggradation and incision, and thus suggest how fan evolution corresponds with global and regional climate change. The potential regional synchroneity of landform response can be leveraged to better define uncertainties in the emplacement age of offset features relative to their displacement. Improved constraints on secular variation in fault slip rates could result from these studies.
- A few SCEC projects recently started to use burial dating, which should result in dates of older (200-500 thousand year old) sedimentary sections which are otherwise poorly dated yet are valuable markers for integrated deformation, especially in folded sections. These studies will be valuable for determining uplift rates in Ventura and San Gorgonio Pass, and could be used in the LA Basin to understand longer-term rates.
- Other TCN approaches, such as in situ ^{14}C or ^{3}He and ^{21}Ne dating are likely to provide useful applications in directed studies. In situ ^{14}C paired with ^{10}Be and other nuclide pairs can allow SCEC researchers to use the burial dating approach for targeted age ranges and assess surface erosion.

U Series
U-series has been effectively employed in SCEC projects focused on arid to sub arid environments where pedogenic carbonates form. Pedogenic carbonate accumulates in the subsurface of gravelly soils and provides a minimum age constraint that is particularly powerful when used in tandem with TCN. This technique has some limitations in terms of climatically induced accumulation and preservation, but can be used to improve understanding of regional paleoclimate and geomorphic responses. New laser ablation ICPMS technique allows for smaller sample size and better assessment of uranium series stability in clast coatings.

Luminescence
SCEC-funded luminescence studies have dated deposits that range from 20th century to Late Pleistocene. Much of the work is in alluvial deposits and is paired with other techniques (TCN, ^{14}C). In general, results from quartz measurements have been poor in southern California, but a new approach developed for feldspar has been shown in the last five years to work quite well.

- The advantage of the luminescence technique is that materials (fine sand to silt) are widespread and well preserved, but limitations based on need to know water content history and other factors that modulate the paleodose rate can complicate final age.
- Throughput of luminescence samples remains a challenge, as many measurements of multiple aliquots (or grains) need to be completed. This is aggravated in some projects because the amount of bleaching (resetting prior to deposition) can be low in materials largely of alluvial, or even worse, colluvial origins. Although there are three labs utilized by SCEC researchers, the

backlog of samples and processing times can result in multiple months (to years) gap between sampling and analytical results.

- Age models built from combined and stratigraphically constrained ^{14}C and luminescence dates can be very powerful for refining the timing of the last millennium of earthquakes in Southern California
- Additional work on paired techniques was recommended.

Comment on ^{14}C

Radiocarbon dating of organic material was not specifically addressed in this workshop, since it is a more established technique and the methodologies are fairly well known. Within SCEC, it has been used to verify consistency of luminescence and TCN results, and will remain a primary dating method due to the ubiquity of material, resolution at short time scales, and well-established procedures. It should continue to be paired with other techniques, as discussed below.

General Conclusions

Throughout the workshop and during discussion sessions, issues that received strong focus are summarized below.

The quality of the dates and the general science improves when projects provide opportunities for sustained collaboration and site visits between field geologists, preparation laboratories and analytical laboratories. In the last five years, dating improvements have been made by collaborations such as luminescence experts working with paleoseismologists to date alluvial packages; U-series sampling concurrent with TCN and luminescence for slip rate studies; and field geologist visits to labs to learn analytical techniques that in turn, refine sampling and pretreatment methods. We noted significant interest from geochronology experts in the topic by their strong participation in the workshop.

Locations where multiple dating methods are used have yielded improved understanding of the processes governing landform development and epistemic uncertainties in ages, as well as a more continuous record of the deformation history. Along some faults, variability in the slip rate over short timescales appears to be significant, with implications for comparison of slip rates with geodetic studies or other strain rate models. The number of sites and time periods for which such variation has been observed are small, however, and the variation is often similar to the dating resolution, so future work will need to (1) focus on high-value sites (i.e., those that have the preservation of deposits that can be dated) and (2) carefully examine uncertainties to discriminate between faults that do or do not show such variation.

It may be possible to refine and use the paleoclimate records and associated geomorphic responses to sharpen age constraints. For example, Scharer, et al., GRL, 2014 were able use the assumption of a wet and cool period manifest by clay deposition and marsh deposits at paleoseismic sites to separate earthquakes (one above and one below the synchronous response to the environmental change) which were otherwise not distinguishable within the 14C age model. This approach at the centennial and millennial time scales requires significant further testing but shows promise.

Burial dating with TCN pairs has the opportunity to date thick sedimentary packages and fill terraces that record long term activity of faulting and folding in basins in the SCEC natural laboratory. Sample preparation and analysis of ^{26}Al, ^{36}Cl (and ^{14}C for short term studies) can be difficult, so combined with the increased costs due to the requirement of two isotopic analyses, this suggests application of burial dating techniques will be limited.

Documentation and reporting standards should be met for SCEC geochronology efforts. These data are invaluable for reassessing ages when changes to systematics are made (e.g., changes in the production rate, or statistical methods for calculating uncertainties from analytical results) and for knowledge of the location and methods of dating. Each technique has different requirements; minimum information would be the location, elevation (or depth) of samples, pretreatment methods, and full analytical results.

Suggestions for TCN and radiocarbon reporting standards are shown below; similar standards should be developed for luminescence and U-series.

Frankel, K. L., R. C. Finkel, and L. A. Owen (2010), Terrestrial Cosmogenic Nuclide Geochronology Data Reporting Standards Needed, *Eos Trans*. AGU, 91(4), 31–32, doi:10.1029/2010EO040003.

McNichol, A., Jull, A., Burr, G. 2001. Converting AMS data to radiocarbon values: Considerations and conventions, *Radiocarbon*, 43, 313-320. https://journals.uair.arizona.edu/index.php/radiocarbon/article/view/3969/3394

Stuiver, M., and Polach, H., 1997. Reporting 14C data, *Radiocarbon*, 19, 355-363. https://journals.uair.arizona.edu/index.php/radiocarbon/article/download/493/498

Earthquake tempo and the pace of deformation in Southern California: Geochronology in SCEC5

The number and extent of dating efforts across southern California will provide a framework for understanding linkages between climate change and patterns of sediment accumulation, which can be used to refine patterns of earthquake histories and accumulation of slip on fans and terraces. These sedimentation and erosion patterns are likely to vary across sub regions in southern California, so both detailed studies and comparison across sub regions should yield exciting results. Elucidating these relationships will require multiple dating techniques at each location, with commensurate improvements in methodologies and dating resolutions. A greater focus on sedimentation and erosion processes is needed to begin to pair the high-resolution topographic data from lidar and SfM with the millennial records of paleoearthquakes on the San Andreas and San Jacinto faults that proliferated during SCEC4. Results will be used to test earthquake magnitude distributions and patterns of fault interaction predicted by time-independent and simulation-based seismic hazard models, respectively.

The combination of multiple dating techniques should be used to explore variations in slip rate along individual faults and fault systems in the Holocene. Existing geologic studies on the Mojave and Carrizo sections of the San Andreas Fault, the Garlock fault, and discrepancies between geologic and geodetic rates on the Eastern California Shear Zone indicate that there are resolvable centennial to multi-millennial changes in slip rates along these faults. Interactions between the faults, and switching of activity within fault networks provides a view of crustal rheology and frictional property variation that is difficult to constrain with other methods, and will inform hazard modeling of southern California faults. Given the improvement in pairing luminescence dating with feldspars and radiocarbon dating, refinement of U-series methodologies for smaller samples, and advances in the ability to use TCN on young deposits, a focus on Holocene variation in slip rates presents an intriguing focus for SCEC5.

Analytical or statistical approaches to better incorporate or assess uncertainties should be encouraged. Results of existing studies can be re-examined for age precision and the continuity of landform development (i.e. the effect of depositional hiatus or erosion on the slip or earthquake record). New statistical techniques for combining uncertainties from multiple dating methods or assessing landform development will improve the value of the geochronology efforts. Ultimately, we strive for an end-to-end treatment of deformation that utilizes spatially and temporally well-constrained earthquake and slip rate data to test models of earthquake deformation at crustal and local scales.

Appendix 1

SoSAFE Geochronology Workshop Agenda

8:30 am Introductions and overview of the workshop

8:45 - 11:00 am TCN

8:45	Intro to technique by Susan Zimmerman and Alan Hidy (LLNL)
9:15	Lewis Owen, *Developing chronostratigraphies for alluvial fans in Sn California using TCNs: examples from Mission Creek, Whitewater, Mecca Hills and Death Valley*
9:35	Dick Heermance, *TCN results from San Gorgonio Pass: terrace ages and inheritance issues in Millard Canyon*
9:50	Veronica Prush, *Statistics of cosmogenic inheritance: The long tail*
10:00	Brent Goehring, *14C and 10Be: new opportunities*
10:15	**DISCUSSION**
10:45	Warren Sharp, *Intro to U-series dating of pedogenic carbonate*
11:00	Warren Sharp, *U-series results from southern California*
11:15	Kim Blisniuk, *U-series and 10Be dating techniques on offset alluvial deposits: a case study from the San Andreas Fault System, California*
11:30	**DISCUSSION**

12:00-1:00 pm Lunch

1:00-2:15 pm Pop Ups! Presentations by students and other PIs from SoCal studies. Bring a ppt with no more than 3 slides and introduce your study, results, successes and challenges!

2:15-2:30 Break

2:30-4:00 pm Luminescence Dating

2:30	Lewis Owen, Brief introduction to luminescence dating
2:35	Shannon Mahan, Introduction to assessing measured luminescence data
2:45	Ed Rhodes, Single grain analysis for quartz, Kspar, and Bayesian approaches
2:55	Lewis Owen, Applications I
3:10	Shannon Mahan, Applications II
3:25	Ed Rhodes, Applications III
3:45	Discussion, Q and A

4:00-5:00 pm Discussion: Geochron and SCEC5

We encourage participants to come with ideas about future applications and needs for geochronology in SCEC5. What science questions can we address to understand tectonic processes with linked effects on earthquakes? What techniques do we need for these problems? Does the geochronology approach of SCEC4 need modification in the future? Think big, and think creatively.

Participants (45)

Sinan Akciz (UCLA), Ramon Arrowsmith (ASU), Kim Blisniuk (BGC), Jose Cardona (CSUN), John Conrad (UCR), Michele Cooke (UMass Amherst), Jillian Daniels (UCLA), Duane Devecchio (ASU), Brent Goehring (Purdue), Peter Gold (UT Austin), Lisa Grant Ludwig (UCI), Jessica Grenader (USC), Alex Hatem (USC), Richard Heermance (CSUN), Janis Hernandez (CGS), Alan Hidy (LLNL), Tran Huynh (USC), Kaitlyn Jones (CSUN), Katherine Kendrick (USGS), Emily Kleber (ASU), Mike Lawson (UCLA), Robert Leeper (USGS), Chris Madugo (PG&E), Shannon Mahan (USGS), Gayatri Marilyani (ASU), Sally McGill (CSUSB), Chris McGuire (UCLA), Chris Milliner (USC), Brian Olson (CGS), Nate Onderdonk (CSULB), Mike Oskin (UCDavis), Lewis Owen (UCinicnnati), Veronica Prush (UCDavis), Ani Pytlewski (CSULB), Ed Rhodes (UCLA), Tom Rockwell (SDSU), Barrett Salisbury (ASU), Kate Scharer (USGS), Warren Sharp (BGC), Ashley Strieg (Oregon), Nathan Toke (UVU), Josh West (USC), Doug Yule (CSUN), Susan Zimmerman (LLNL), and Robert Zinke (USC)