Refining the late Quaternary slip rate of the Sierra Madre fault with relative and absolute dating of offset fans

Report for SCEC Award #15179
Submitted March 15, 2016

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I. Project Overview

A. Abstract

In the box below, describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the abstract. (Maximum 250 words.)

The primary goal of this project is to determine the late Quaternary slip rate of the Central Sierra Madre fault (CSMF) through dating of offset alluvial fan and terrace surfaces. We used remote and field geologic and geomorphic mapping to identify offset geomorphic surfaces and identify promising locations for dating the surfaces. We tested a Schmidt hammer as a tool for relative correlation of surfaces and a calibrated dating technique. We collected a suite of nine samples for luminescence dating to complement a suite of ^{10}Be profile samples collected along the CSMF. The luminescence samples are designed to achieve three objectives: (1) directly validate cosmogenic ages from the same sediment, (2) constrain the cover sediment history of gravel deposits analyzed by ^{10}Be surface dating, and (3) determine the age of the youngest offset surface along the CSMF. All nine samples have been prepared, and are being analyzed at the Utah State University Luminescence Lab with the small aliquot IRSL technique. Preliminary IRSL ages from five samples are consistent with the preliminary age estimates we have made with ^{10}Be surface dating. The preliminary IRSL ages tentatively suggest that fine grained sediment covering the gravel sampled for ^{10}Be dating was deposited soon after terrace abandonment and that the younger portions of the current ^{10}Be uncertainty distributions are more likely than the older age ranges. As the IRSL results become complete, we will use this information to better characterize sources of uncertainty in the ^{10}Be dating and develop landform age models consistent with both types of geochronologic data.

B. SCEC Annual Science Highlights

Each year, the Science Planning Committee reviews and summarizes SCEC research accomplishments, and presents the results to the SCEC community and funding agencies. Rank (in order of preference) the sections in which you would like your project results to appear. Choose up to 3 working groups from below and re-order them according to your preference ranking.

Earthquake Geology
Southern San Andreas Fault Evaluation (SoSAFE)
Working Group on California Earthquake Probabilities (WGCEP)

C. Exemplary Figure

Select one figure from your project report that best exemplifies the significance of the results. The figure may be used in the SCEC Annual Science Highlights and chosen for the cover of the Annual Meeting Proceedings Volume. In the box below, enter the figure number from the project report, figure caption and figure credits.

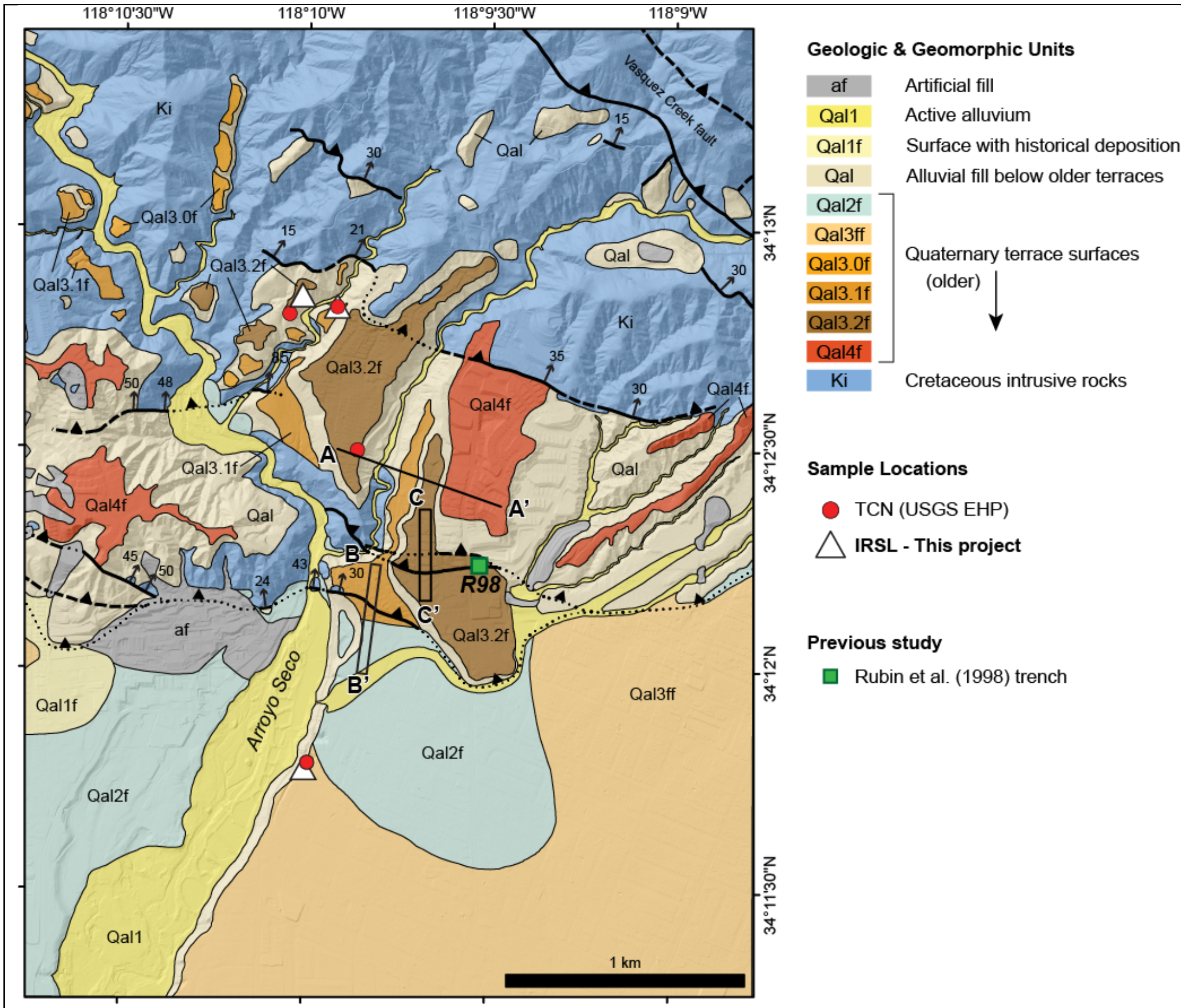

Figure 2. Geologic and geomorphic map of the Arroyo Seco area showing locations of samples collected for dating. Mapping is modified from Crook et al. (1987), and basemap is shaded relief derived from a USGS 0.5 m resolution lidar digital elevation model. Boxes B-B' and C-C' show locations where we have made preliminary swath profile estimates of vertical separations of terrace surfaces (Hanson et al., 2015).

Credit: Burgette and Scharer, 2016, Refining the late Quaternary slip rate of the Sierra Madre fault with relative and absolute dating of offset fans, Report for SCEC Award #15179.

D. SCEC Science Priorities

In the box below, please list (in rank order) the SCEC priorities this project has achieved. See *https://www.scec.org/research/priorities* for list of SCEC research priorities. *For example: 6a, 6b, 6c*

1a, 4b, 4c

E. Intellectual Merit

How does the project contribute to the overall intellectual merit of SCEC? *For example: How does the research contribute to advancing knowledge and understanding in the field and, more specifically, SCEC research objectives? To what extent has the activity developed creative and original concepts?*

At a broad scale, this project contributes to understanding how plate boundary zone deformation is partitioned spatially in the western Transverse Ranges. The broader Sierra Madre fault zone is one of the longest continuous structures in the western Transverse Ranges. This reverse fault system cross-cuts major lines of infrastructure leading into the LA area and heavily populated basins lie up-dip of its earthquake source areas. These tectonic and societal factors motivate our study to resolve the spatial distribution of slip rate on this major fault system. Additionally, recent work has suggested that very large prehistoric earthquakes have occurred on faults in the Ventura area, which has motivated the SCEC Special Fault Study Area. Possible scenarios for large slip in Ventura include ruptures that link through the Sierra Madre fault zone, and our work will help evaluate such behavior.

This project is designed to determine slip rates over a latest Quaternary time period that is recorded by a suite of prominent alluvial fan surfaces. This time scale is longer than that recorded by existing trench-based investigations on this fault, but short enough that the slip rates we derive may still be influenced by irregular earthquake recurrence. The rates we estimate here will contribute to understanding the temporal variations in fault slip, when integrated with paleoseismic records and our work in progress on a longer-term Quaternary slip rate for this fault zone.

This SCEC funding has supported collection of luminescence dating to complement terrestrial cosmogenic nuclide and radiocarbon dating of alluvial fan surfaces along the San Gabriel Mountains rangefront. The combination of techniques is giving us an especially strong dataset to resolve the Quaternary history of landforms which have been offset by the Central Sierra Madre fault zone. This will help us resolve epistemic uncertainties inherent in the interpretation of the geochronologic data types, which will contribute to studies elsewhere in southern California, as well as the broader Quaternary neotectonics community.

F. Broader Impacts

How does the project contribute to the broader impacts of SCEC as a whole? *For example: How well has the activity promoted or supported teaching, training, and learning at your institution or across SCEC? If your project included a SCEC intern, what was his/her contribution? How has your project broadened the participation of underrepresented groups? To what extent has the project enhanced the infrastructure for research and education (e.g., facilities, instrumentation, networks, and partnerships)? What are some possible benefits of the activity to society?*

This project has directly contributed to the education of one graduate student and one undergraduate intern. The USGS undergraduate intern assisted with the majority of our fieldwork, and gained significant experience in interpreting tectonic geomorphology and sampling for Quaternary dating methods, and assisted with the presentation of results at SCEC and AGU. NMSU graduate student Hanson has had a primary role in the field, lab, and interpretation portions of the project. This SCEC funding enabled him to travel to the USU Luminescence Lab to prepare samples for IRSL dating. This project has also allowed a pre-tenure PI to develop new collaborations with a USGS colleague and other SCEC community members. The ultimate product from this project will be more accurate slip rates for a major fault bounding the LA metropolitan area. Our results will complement the work of other members of the SCEC community investigating the late Quaternary temporal and spatial distribution of deformation and those modeling fault slip rates from geodetic data. Our results will contribute to hazard mitigation when incorporated into future seismic hazard analyses.

G. Project Publications

All publications and presentations of the work funded must be entered in the SCEC Publications database. Log in at *http://www.scec.org/user/login* and select the Publications button to enter the SCEC Publications System. Please either (a) update a publication record you previously submitted or (b) add new publication record(s) as needed. If you have any problems, please email *web@scec.org* for assistance.

Hanson, A.M., Burgette, R.J., Scharer K.M., and Midttun, N., 2015, Late Quaternary Offset of Alluvial Fan Surfaces along the Central Sierra Madre Fault, Southern California, Abstract T41A-2857, presented at 2015 Fall Meeting, AGU, San Francisco, Calif., 14-18 Dec.

Hanson, A.M., Burgette, R.J., Scharer K.M., and Midttun, N., 2015, Late Quaternary Offset of Alluvial Fan Surfaces along the Central Sierra Madre Fault, Southern California, SCEC Annual Meeting, Palm Springs, CA Sept. 9-11, 2015.

II. Technical Report

A. Objectives

The Sierra Madre fault (SMF) system juxtaposes the San Gabriel Mountains against a series of basins north of the broader Los Angeles basin (Fig. 1) (Crook et al., 1987; Dolan et al., 1995; Rubin et al., 1998). The SMF system is part of the complex network of faults in the western Transverse Ranges, and undoubtedly interacts directly or indirectly with the adjacent San Jacinto and San Andreas faults to the east and the reverse faults of the Ventura basin at its western end. Along strike, this 135 km long reverse fault system has been divided into four main segments, from east to west: the Cucamonga, Central Sierra Madre, San Fernando, and Santa Susana faults. Estimated potential earthquake magnitudes are as high as Mw = 7.6 for single ruptures on SMF segments, and up to ~ Mw = 8 in multi-fault earthquakes (Rubin et al., 1998; Field et al., 2013).

This study focuses on the Central Sierra Madre fault (CSMF), the longest of the four SMF segments, and one of the least studied with modern Quaternary geochonologic techniques (Fig. 1). Our understanding of the Quaternary history of the CSMF rangefront has built on a previous investigation by Crook et al. (1987). They mapped Quaternary deposits along the rangefront, recognizing four ages of fan surfaces: Qal4 (oldest) to Qal1 (modern). Conventional radiocarbon dating yielded a 2 ka age for Qal2 along the Central SMF (Crook et al., 1987). Based on correlations to dated soil chronosequences, ages of the Qal3 and Qal4 surfaces were interpreted to be roughly 10 and 300 ka, respectively. We have targeted the western portion of the CSMF, where these fan surfaces have been offset and provide geomorphic markers on both sides of the fault. Our dating strategy has been focused on obtaining accurate ages for fan surfaces mapped as Qal3 by Crook et al. (1987).

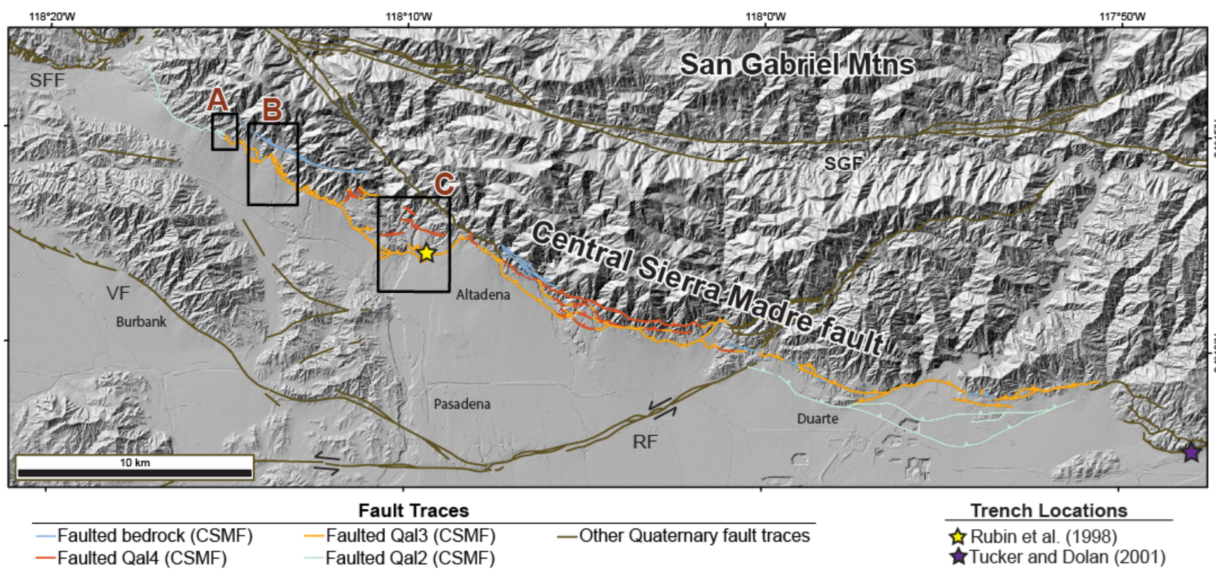

Figure 1. Central Sierra Madre fault map. Fault traces are from the USGS Fault and Fold Database (USGS and CGS, 2006). Faulted CSMF units are based on mapping and nomenclature of Crook et al. (1987), with Qal4 being the oldest alluvial unit. Labeled faults include: San Fernando fault (SFF), Verdugo fault (VF), Raymond fault (RF), and the San Gabriel fault (SGF). Labeled boxes show our areas of focus: A, Dunsmore Canyon; B, Pickens Canyon; and C, Arroyo Seco (Fig. 2).

Most of the existing slip rates for the CSMF used in seismic hazard assessments are based upon trench studies that crossed only one fault strand, and are limited by averaging over only one to two seismic cycles (Field et al., 2013; Dawson and Weldon, 2013). Our primary goal is estimating a slip rate across the entire fault system by targeting late Quaternary fan surfaces [primarily the Qal3 fans of Crook et al. (1987)], offset across all of the fault strands. A complementary project funded by the USGS Earthquake Hazards Program (USGS EHP; PI: Burgette) has yielded age estimates for offset fans along the CSMF with cosmogenic nuclide dating (Hanson et al., 2015). This SCEC project focused on improving relative and numerical ages for offset surfaces through quantitative measurement of clast weathering and luminescence geochronology.

B. Methodology

We employed three primary strategies to identify, correlate, and date offset fan surfaces. First, field mapping aided by GIS analysis of high resolution topographic data generated a sequence of relative ages of landforms along the CSMF rangefront. Second, we trialed measurement of clast hardness with a Schmidt hammer to test a calibrated relative dating technique. Third, this SCEC project enabled collection and analysis of samples for luminescence dating of fan sediment deposits to complement our terrestrial cosmogenic nuclide dating.

1. Surface correlation and offset estimation

We conducted field reconnaissance of the potential field sites identified in our proposal. Based on the quality of geomorphic and geologic evidence we focused our investigation on fans at the mouths of three catchments along the western portion of the CSMF (Fig. 1). Fans along the eastern part of the fault zone do not have significant late Quaternary fault or fold scarps, suggesting the deformation may be concentrated along faults bounding the crystalline basement thus limiting our ability to estimate surface offsets.

We validated and updated interpretations of previous mapping with field observations aided by 3 m to 0.5 m resolution lidar-derived digital elevation models (e.g., Fig. 2). Extraction and analysis of topographic profiles both down terraces and across drainages provides an effective way of testing hypotheses regarding classification of surfaces. This technique was useful for correlating discontinuous remnants of geomorphic surfaces and determining relative ages of surfaces based on inset relationships. We subdivided the Quaternary units defined by Crook et al. (1987) to reflect the full range of distinct geomorphic surfaces present in these catchments. We found up to four distinct terrace levels within the Qal3 map unit in some catchments.

We validated our geomorphic analysis with additional targeted mapping in the field. Observations of sediment and soils developed on the terrace surfaces aided in recognizing relative age relationships. We surveyed surfaces and unit contacts that were not well-represented in the digital topography data with a differential GPS unit. Much of our field effort was used to find effective sites for obtaining meaningful terrace ages from luminescence, terrestrial cosmogenic nuclide, or radiocarbon techniques.

Based on this work, we determined the Arroyo Seco area in north-central Pasadena, CA provided the best place for determining the ages and stratigraphy of several fan terraces (Fig. 2). This site has the most complete geomorphic record that we found along the rangefront, due to the presence of a large upstream catchment, frontal faults that have stepped well out from the main rangefront, and preservation of the land surface in a City of Pasadena park.

2. Relative dating from Schmidt hammer analysis of clast weathering

We investigated the potential of the Schmidt hammer as a tool for providing a calibrated dating tool for alluvial sediment along the San Gabriel Mountains rangefront. Crook (1986) developed an early quantitative study of the degree of clast weathering and relative age in alluvial deposits using clasts of the Lowe Granodiorite, a distinctive lithology that occurs in the upstream portions of most of the drainage basins along the CSMF rangefront, using clast seismic velocity. In contrast to clast seismic velocity measurements, Schmidt hammer measurements are much less time consuming, and a methodological study suggests ~30 measurements of rocks from a single deposit are sufficient to accurately characterize the representative clast strength of a surface (Niedzielski et al., 2009). Schmidt hammer rebound data, calibrated with Quaternary geochronology data, have recently been shown to quantitatively distinguish alluvial terrace surfaces of different ages in New Zealand (Stahl et al., 2013).

We used a Silver Schmidt hammer to measure clast strength in several fan deposits in the study area. We attempted to find clasts > 30 cm in minimum dimension on stable surfaces. We delivered 10 impacts per clast, normal to the local clast surface to minimize the effects of local variability in rebound/ degree of weathering. We made an effort to identify consistent lithologies for this test, using three varieties of granodiorites, including the distinctive Lowe Granodiorite used in the earlier clast seismic velocity study (Crook, 1986; Crook et al., 1987). In the Arroyo Seco area, most terraces had distinctive clasts of the Lowe Granodiorite, but this rock is absent in catchments to the west, limiting its utility for correlating along the part of the fault zone where we worked most extensively.

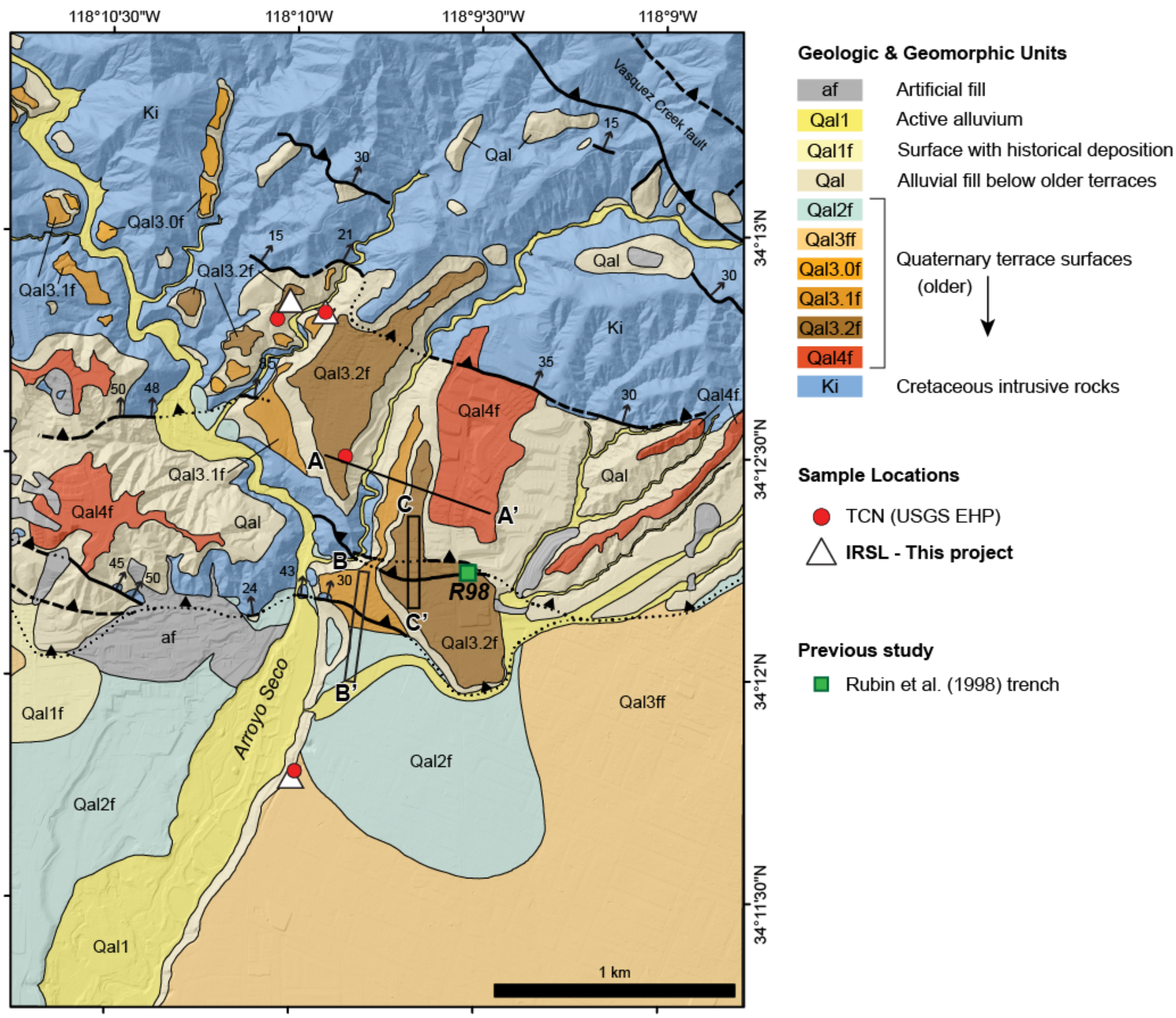

Figure 2. Geologic and geomorphic map of the Arroyo Seco area showing locations of samples collected for dating. Mapping is modified from Crook et al. (1987), and basemap is shaded relief derived from a USGS 0.5 m resolution lidar digital elevation model. Boxes B-B' and C-C' show locations where we have made preliminary swath profile estimates of vertical separations of terrace surfaces (Hanson et al., 2015).

3. Luminescence dating of terrace deposits

We used luminescence geochronology to determine the absolute ages of deformed fan surfaces along the CSMF. Ages determined from the luminescence technique complement existing trench-based radiocarbon estimates of deformed deposits (Crook et al., 1987; Rubin et al., 1998; Tucker and Dolan, 2001), as well as the cosmogenic ^{10}Be profile dating funded by the USGS EHP. Each of the Quaternary dating techniques has unique pitfalls and systematic error sources that can be difficult to accurately identify and mitigate when a single technique is used. For example, previous ^{14}C dating in this area indicates detrital charcoal can be older than the age of the deposit by at least a factor of two (Rubin et al., 1998). Inheritance in cosmogenic isotope studies can be addressed by sampling along depth profiles, but this technique can be biased young by surface erosion or cover with more recent sediment, which can be difficult to recognize without independent constraints (e.g. Gosse and Phillips, 2001; Behr et al., 2010). Likewise, luminescence dating of southern California sediment can be complicated by the characteristics of local quartz and feldspar grains (Lawson et al., 2012).

We collected a suite of nine samples for luminescence analysis (Table 1), focused on three objectives: (1) validating the age of gravel from terraces also sampled for ^{10}Be profile surface exposure dating, (2) the age of capping sediment above gravels sampled for TCN dating, and (3) the age of younger Qal2f surfaces, which we did not sample for TCN dating. Where the sediment permitted daytime sampling using a sharpened metal pipe, we followed protocols outlined by the Utah State Luminescence Laboratory. We did not find fine-grained stratigraphic intervals interbedded with the gravel sampled for all of the ^{10}Be profiles, and fine-grained capping sediment was too indurated in other locations to be sampled with a pipe. In these instances we sampled matrix material or blocks of indurated sediment collected at night, following protocols described by Kenworthy et al. (2014). Additional sample material was collected at each location for quantifying radiation dose rates and moisture content.

Light-shielded samples were transported by ground to the Utah State University Luminescence Laboratory to be dated with support from the SCEC geochronology infrastructure. Graduate student Austin Hanson conducted sample preparation, yielding separates of both quartz and feldspar in the target grain size range (125-250 μm). Based on initial trials, Dr. Tammy Rittenour is using the small aliquot approach to date the feldspar fraction using infrared-stimulated luminescence. Ages are being determined for the first 5 of our samples currently. We have initial results for these samples, and more refined ages as well as ages for the other samples will follow later this spring.

C. Results

1. Surface offset estimates

The best locations we have identified for estimating fault displacements are the Arroyo Seco area and the Pickens Canyon fan (Fig. 1). At Arroyo Seco, two fault strands offset Qal3f age surfaces that we have mapped as Qal3.1f and Qal3.2f in our more detailed terrace sequence (Fig. 2). Our analysis to date estimates the vertical separation of these surfaces across the two strands as 5.5 ± 0.2 m, and 4.9 ± 0.2 m, respectively (Hanson et al., 2015). A scarp across the Pickens fan displaces a terrace surface that we have mapped as Qal3.2f based upon geomorphic and geologic criteria. The vertical separation of this surface is 16.6 ± 0.5 m (Hanson et al, 2015).

Additional offsets of ~3 m and 2 m were reported at scarps across a Qal2f surface at the Dunsmore Canyon fan (Fig 1; Crook et al., 1987). Although this exposure has been destroyed by human modification, we plan to analyze historic aerial photography to better characterize the fan and scarp geometries in addition to using the previously published trench and surface observations (Crook et al., 1987).

2. Progressive clast weathering

Our trial of the Schmidt hammer showed that there was a large variation in hardness among clasts on surfaces of the same age. Our preliminary results show evidence for the expected decrease in clast strength from fresh to more weathered conditions (Fig. 3). However, we found significant effects of lithology and depth within the deposit superposed upon the broader age relationship. The best records of late Quaternary fault offset are from the Arroyo Seco area and west to Dunsmore Canyon (Fig. 1). As the distinctive Lowe Granodiorite used in previous studies (Crook, 1986; Crook et al., 1987) is not present in deposits west of Arroyo Seco, we also experimented with more ubiquitous white granodiorite lithologies, and found differences in rebound values that correlated with grain size (Fig. 3).

Our initial results suggest that there is some potential for developing a calibrated Schmidt hammer dating tool for the San Gabriel rangefront. However, a large effort would be required to develop a dataset with sufficient statistical power to overcome the scatter in Schmidt Q-values we observed from our pilot study. Challenges would also include finding clasts of a consistent target lithology and texture that are widespread over the study area, controlling for clast depth within deposits, as many surfaces are developed and/or do not have extensive populations of large clasts at the surface. In light of these challenges, we focused our effort on collecting a strong suite of samples for luminescence chronology.

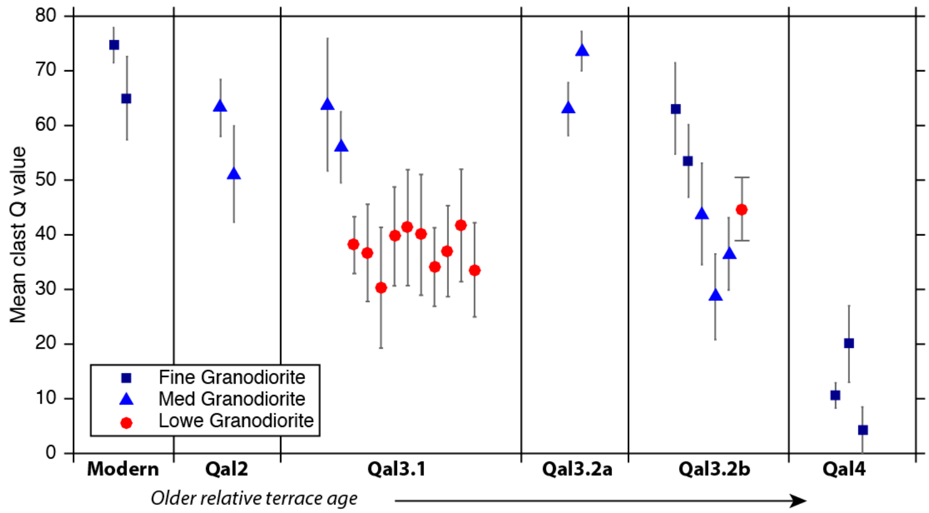

Figure 3. Results of preliminary Schmidt hammer analysis of clast weathering. Overall, the data show a decline in clast strength with age, but there is significant variation in Q-values for clasts of different lithology/grain size on the same surface. The medium-grained granodiorite exhibits a notable change between Qal3.2a and 3.2b.

3. Numerical terrace ages

We have focused our dating strategy on attempting to resolve the ages of terrace surfaces where we have the best vertical separation estimates, as noted in section C.1. Our luminescence samples were chosen to complement and validate results from ^{10}Be profile dating.

Arroyo Seco

We collected luminescence samples from three locations to support our cosmogenic dating of three surfaces: Qal3.2f, Qal3.1f, and the Qal3ff surface in the footwall (Fig. 2). Our 10Be profile dating site for Qal3.2f, the oldest dated surface, is located at the toe of a wedge of cover sediment shed from the hillside above. We collected two samples in a profile, vertically spaced 1.5 m apart from a thick part of the cover wedge upslope (north) of the ^{10}Be sample site. Preliminary IRSL ages from these samples overlap within uncertainties, with ages of 19.8 ± 1.1 ka (2-SE) and 20.1 ± 5.4 ka. Preliminary analysis of 10Be surface exposure dating results indicates an age of $27.5^{+8.1/-5.3}$ ka (updated from Hanson et al., 2015), which we estimated with the Hidy et al. (2010) calculator allowing for wide ranges of deposition and erosion parameters. The preliminary IRSL ages suggest that the wedge of colluvial cover may have grown rapidly following abandonment of the Qal3.2f terrace surface, and when better resolved, will aid in appropriately modeling the TCN history of the dated sediment.

We sampled fine-grained cover sediment 15 cm above the top of gravel sampled for 10Be surface exposure dating on Qal3.1f. The forthcoming IRSL age will provide a limiting young age for the abandonment of the Qal3.1f surface, and the age of the higher Qal3.2 surface will provide a limiting older age.

We collected two samples for luminescence analysis from a prominent Qal3 surface on the fault footwall immediately east of Arroyo Seco. At this location the IRSL samples were taken in a vertical profile spaced by 4.0 m from within the coarse gravel deposit in the same location as the 10Be profile. These samples will be analyzed in the second round of analysis at the USU Luminescence Laboratory. The results of the 10Be profile have suggested a potential unconformity or other complication in the dated section, and the IRSL ages will aid in making a consistent interpretation of these data as well.

Pickens Canyon

Two luminescence samples at locations along the heavily modified Pickens fan (Fig. 1) were taken from coarse sediment below the Qal3.2f and Qal3.1f surfaces. One IRSL sample was collected from the pit of our ^{10}Be sample on Qal3.2f. The preliminary age estimate for the Qal3.2f sediment is 20.6 ka (only one analyzed aliquot- no uncertainty reported). This sediment yields a preliminary 10Be surface age of 25.0 $^{+13.8/-5.6}$ ka (updated from Hanson et al., 2015). As the IRSL results for this site become better resolved, we will be able to refine the uncertainty range allowed by the cosmogenic dating, and better address the epistemic uncertainties which are driving the current large uncertainties for this site.

A second sample comes from a Qal3.1f terrace, which does not have measurable offset across the CSMF at the Pickens fan. The IRSL age from this terrace will provide a limiting young age on the Qal3.2f surface, which is our primary deformation marker, and provide some evidence for the paleoseismic history of the fault. A preliminary age base on two aliquots is 12.5 ± 9.2 ka (2-SE) for this sample.

Dunsmore Canyon

We collected two samples from the Qal2f terrace surface reported as offset by a cumulative ~5 m at Dunsmore Canyon (Fig 1; Crook et al., 1987). The IRSL samples come from sand layers interbedded with cobble-boulder gravel. The samples come from deposits underlying both a higher surface and an inset surface, which were not differentiated in earlier mapping (Crook et al., 1987). Forthcoming IRSL ages will help us understand the ages of these deposits and surfaces, and allow an additional slip rate estimate when combined from information from historical air photos. A preliminary IRSL age for the higher surface is 13.8 ± 11.1 ka.

Table 1. Locations, depth below local gravel surface, and preliminary ages for IRSL samples.

Sample	Longitude (°)	Latitude (°)	Depth (m)	Preliminary IRSL age (ka)		
Dunsmore Canyon						
SM-DCL-1	-118.2480	34.2521	1.85	13.8	±	11.1
SM-DCL-2	-118.2490	34.2515	4			
Pickens Canyon						
SM-BTL-1	-118.2248	34.2403	1.72	20.6	±	
SM-BTL-2	-118.2250	34.2461	1.37	12.5	±	9.2
Arroyo Seco						
SM-FWL-1	-118.1664	34.1970	4.25			
SM-FWL-2	-118.1663	34.1970	1.25			
SM-3.1L-1	-118.1653	34.2137	-0.15			
SM-3.2L-1	-118.1669	34.2142	-2.44	19.8	±	1.1
SM-3.2L-2	-118.1669	34.2141	-0.95	20.1	±	5.4

D. Next Steps

Major outcomes of this project to date are: (1) the luminescence samples have been collected (2) Hanson completed the sample preparation for all samples (3) USU is completing the lab work (small-aliquot IRSL) based on the initial success. Final results of this project depend upon the finalized IRSL ages that are on track to be completed later this spring.

Once we have the full IRSL results, we will develop a final age model for the late Quaternary terraces along the CSMF, and calculate slip rates with uncertainties following the method of Thompson et al. (2002). We will present the results of our multi-method dating strategy and slip rates at the SCEC 2016

Annual Meeting. The compatibility of the preliminary TCN and IRSL ages is promising, and the multiple dating methods should allow us to refine ages with a strategy that emphasizes the complementary strengths of each technique.

E. References

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