2012 SCEC final report
Project #12174

Collaborative Research: Assessing slip rate variations on the Garlock fault using newly developed luminescence sediment dating

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Summary

The project has progressed in a successful manner, with significant outcomes. This research represents a major step forward in the development and application of new methods to achieve routine reliable luminescence age estimates for paleoseismic and fault slip rate contexts on timescales of 10 years to 100,000 years in Southern California. We are also able to provide a slip-rate determination for the Garlock fault for at least one late Holocene time period.

Technical science outcomes

- Successful multiple test pit excavation and sample collection at Christmas Canyon West, near Ridgecrest, CA (central Garlock fault)
- Development and assessment of novel K-feldspar single grain “post-infrared IRSL” dating protocol
- Evidence for increased slip rate for the central Garlock fault over the last 2000 years – on-going additional research determinations are in progress to reproduce and validate this finding

Training, communication and outreach outcomes

- Three UCLA and one USC graduate students closely involved in research
- Three UCLA undergraduate students participated in research including two female Hispanic students
- Two publications published in peer-reviewed journals based on results from the previous SCEC funding cycle
- Six presentations made at international and national conferences, plus three at SCEC 2012

Collaborative Research: Assessing slip rate variations on the Garlock fault using newly developed luminescence sediment dating

Technical report

The aims of this research project were:

i) to develop improved luminescence dating approaches, based primarily on K-feldspar, for application to Southern California fault slip rate and paleoseismic locations in contexts where conventional OSL methods are limited by mineral characteristics,

ii) to apply these to the central Garlock Fault at the site of Christmas Canyon West (CCW), in order to provide fault slip-rate estimates spanning the last few thousand years.

Good progress has been made towards both of these aims, detailed below.

Introduction and project rationale

The degree to which fault loading and strain release rates are constant (or non-constant) in time and space is a fundamental, unresolved issue, with basic implications for understanding fault mechanics and seismic hazard assessment. The left-lateral Garlock fault, that extends for 250 km across the northern edge of the Mojave block (Fig. 1), exhibits perhaps the world's best-documented example of transient strain accumulation, with a striking mismatch between short-term geodetic and longer-term geologic rates. Despite abundant geomorphic and paleoseismologic evidence for large-magnitude Holocene earthquakes (McGill and Sieh, 1991; McGill, 1992; McGill and Rockwell, 1998; Dawson et al., 2003), and a well-documented latest Pleistocene slip rate of ~7±2 mm/yr (Clark and Lajoie, 1974; McGill and Sieh, 1993; McGill et al., 2009), geodetic data show little or no left-lateral strain accumulation across the Garlock fault over the past several decades (Savage et al., 1981, 1990, 2001; Gan et al., 2000; Miller et al., 2001; Peltzer et al., 2001; McClusky et al., 2001; Meade and Hager, 2005). Instead, the region north and south of the Garlock fault is presently dominated by northwest-oriented right lateral shear, 9-11 mm/yr to the north of the fault (Dixon et al., 2000; Meade and Hager, 2005) and 12±2 mm/yr to the south (Sauber et al., 1994; 1999; Bennett et al., 2003; Meade and Hagar, 2005). The geodetic data suggest that the north-northwest-trending eastern California shear zone (ECSZ) extends across the Garlock fault at nearly right angles without any evidence for its presence, suggesting that the Garlock fault experiences two loading "modes"; the current "slow mode", (elastic strain accumulates along the ECSZ), and alternating "fast mode", (strain accumulates along the Garlock faster than the long-term geological average of ~7±2 mm/yr). It is currently unclear whether such periods of "fast" or "slow" slip correlate with clusters of large-magnitude earthquakes such as that documented for the Garlock fault by Dawson et al. (2003) at El Paso Peaks (EPP; Fig. 1), where well stratified playa deposits record four earthquakes in the past 2000 years, but only two for the preceding 5000 years. Geomeorphic offsets (McGill and Sieh, 1991; Dawson et al., 2003) suggest that these were large-magnitude events, implying substantial changes in short-term slip rate over a few earthquake cycles.

Problems of developing reliable chronologies

The key to examining these issues lies in documenting fault slip rates at a variety of time scales. Yet the nature of geomorphic contexts from which slip rate can be determined, such as offset terrace risers on alluvial fans, often renders them difficult to date reliably. In desert regions, where faulted landforms are best preserved, organic remains such as detrital charcoal for ^{14}C dating are generally sparse or non-existent, and are most common in fine-grained playa sediments, and less in alluvial fan environments where offset features for strike-slip rate determination are located. Several other dating techniques have been applied to offset landforms in desert regions. U-series dating of carbonate cements can provide minimum ages, but only where appropriate materials are present (e.g., Fletcher et al., 2010). Cosmogenic dating of arid zone alluvial units is often problematic (e.g. van der Woerd et al., 2006; Behr et al., 2010) and associated with large uncertainties.

Optically stimulated luminescence (OSL) dating has great promise based on its age range (1 to 200,000 years) and the presence of suitable materials (wind-blown and water-lain sands and silts) besides its significant success in other contexts (Rhodes 2011). When grains are transported through the environment, light-sensitive trapped electron populations are reduced to zero (or a low residual level) by daylight; during subsequent burial, natural environmental ionizing radiation slowly repopulates these traps. This technique has not yet yielded its full potential in Southern California, owing primarily to problematic behaviour of constituent quartz grains.

Potential of alternative luminescence dating approaches

Quartz luminescence response can suffer from a variety of problems such as low signal intensity, irregular growth and high thermal transfer signals (Rhodes and Pownall, 1994; Rhodes 2000). These problems appear more common where quartz grains are derived from recently eroded bedrock, as is often the case in mountainous environments and locations associated with fault movement in Southern California (Rhodes 2011). In this project, we have specifically designed tests to assess these problems, and to help determine the source of the observed signals in terms of minerals (primarily quartz or feldspar at this stage). Preliminary findings of these tests have been submitted for publication (Lawson et al., 2012).

Where quartz demonstrates problematic characteristics, such as sufficiently low OSL signal intensity that a proportion of the measured signal comes from mineral inclusions such as feldspar or zircon grains within the quartz, other approaches must be sought. This was found to be the case at sites sampled in this region, including El Paso Peaks (EPP) and Christmas canyon West (CCW; Fig. 1). We have targeted K-feldspar, as grains are ubiquitous in Southern Californian samples, and infra-red stimulated luminescence (IRSL) signals are often highly sensitive. Two features which make this approach less attractive than quartz OSL are the fact that K-feldspar IRSL requires more light exposure to zero the signal, and that over time, electrons escape from their traps by quantum mechanical tunnelling, a phenomenon called “anomalous fading”. The latter effect may be corrected by additional laboratory measurements, while in many sedimentary environments, grains appear to have received sufficient daylight exposure for this approach to be applicable.

In summary, where grains have received insufficient daylight exposure prior to burial, all luminescence methods may give rise to age over-estimates. This effect is conceptually similar to the presence of “inheritance” in terrestrial cosmogenic nuclide (TCN) studies, or to the reworking of charcoal fragments in radiocarbon dating. In general, K-feldspar luminescence signals are bleached by light more slowly than quartz OSL, so these effects are expected to be more pronounced for K-feldspar. The determination of single grains (either quartz or K-feldspar) may allow the isolation of a “well-bleached” population and improved age determination.

Secondly, feldspar luminescence signals have been observed to suffer from “anomalous fading” (Wintle, 1973), in which electrons “leak” out of their traps by a quantum mechanical process. Fading tests and corrections must be applied to avoid age under-estimates (Huntley and Lamothe, 2001).

Sampling strategy and data collected

At Christmas Canyon West (CCW), we collected 23 samples from 5 new test pits, including 3 modern samples to study signal zeroing. We have completed initial single grain post-IR IRSL K feldspar dating measurements from 12 samples, plus new single grain determinations from 5 samples from our 2011 test pit (Table 1). The remaining 15 samples are prepared and awaiting IRSL measurement. We are currently assessing alternative measurement protocols for the IRSL determinations, with the possibility of making these both faster and more reliable, effectively increasing sample throughput and cutting measurement costs. Preliminary results are encouraging, though not entirely clear-cut, and require further analysis and measurement. We are also exploring different approaches for making anomalous fading correctipons

Results

One of our most significant advances since 2011 is the initiation of routine single-grain (SG) K-feldspar post-IR IRSL measurements. This single-grain approach, modified from Buylaert et al. (2009), who measured conventional multiple-grain single aliquots, affords us the opportunity to observe both luminescence and geologic processes with finer resolution. Measurement comprises a two-stage IRSL determination, one at 50ºC, followed by a second IRSL exposure at 225ºC. In principle, the 50ºC determination is directly compatible with conventional IRSL, while the second, so called “post-IR” IRSL at 225ºC releases charge from more stable locations within the feldspar crystal lattice. The expectation is that the 225ºC IRSL apparent age will be greater than for the 50ºC measurement, though this can be caused both by the charge-trapping locations being more stable (a good thing), but also by incomplete signal zeroing at deposition, leading to potential age overestimation. As we started this research phase in early 2012, we did not know to what degree these different factors might be separated, and how useful this approach would prove to be. As described below, the introduction of this technique has greatly facilitated our ability to accurately and precisely date the strata exposed in our excavations.

As noted above, we have been successful at leveraging our SCEC research funding by drawing in additional external funds and completing SG K-feldspar post-IR IRSL age determinations for 20 samples from similar contexts in Southern California. Combined with the ten SG determinations completed for our 2012 SCEC project, this provides a substantial body of data allowing us to refine our approach, and from which we are able to draw several basic conclusions, summarized below:

- A high proportion of grains provide sensitive IRSL signals, making this an efficient approach.
- We observe two broad classes of behavior, one in which signal fading (a regular phenomenon observed for feldspar IRSL) appears to be dependent on signal intensity, and a second simpler pattern in which fading appears uniform for grains measured at each temperature (50 and 225ºC), with consistently greater fading for 50ºC signals than 225ºC, as expected.
- We see clear evidence of incomplete signal zeroing and post-depositional grain mixing, although both effects are rare, allowing us to identify a useful dating signal.
- Where samples form sequences or duplicates, the resulting ages exhibit a high degree of internal consistency (Table 1).

Slip Rate Determination

Because of delays in permitting resulting from changes in personnel and newly instituted review requirements at the China Lake Naval Air Weapons Station, where several of our study sites are located (our permitting application is moving forward thanks to our collaborators at the Navy's Geothermal Programs Office), we focused our 2012 efforts at the Christmas Canyon West site (CCW) and on our on-going analysis of 2012 samples collected at the El Paso Peaks site (EPP) (Fig. 1). Specifically, we focused on two slip-rate sites at CCW (Fig. 3). At site 1a, pit CCW11A was dug into a raised surface, representing a relict braid bar, with an eroded edge on its E side offset left-laterally by ~23m. The age representing the pre-offset, pre-erosion deposition for this bar is most likely 1830 ± 150 years (J0116), corresponding to a minimum slip rate of 12 ± 2 mm/yr, though we must also consider the possibility of over-bank deposition on the bar surface. The minimum slip rate using the deeper sediment age of 3360 ± 300 and 3400 ± 240 yr is 7 ± 1 mm/yr, consistent with the previous estimate of ~ 7 ± 2 mm/yr (Clark and Lajoie, 1974; McGill and Sieh, 1993; McGill et al., 2009; Ganev et al., 2012). We will explore the sediment relationships in more detail at this site by excavating several hand-dug shallow fault-parallel/bar-perpendicular trenches to resolve which is the more likely scenario. In the pit dug into the corresponding relict braid bar on the north side of the fault (Pit CCW12C) we find very stratigraphic units to those observed with pit CCW11A. The age of Unit 2 is strikingly similar in both pits, and we plan to determine the lateral relationships of these units by further excavation.

At target 1b (Fig. 3), we have preliminary SG IRSL age estimates from pits CCW12A and 12B (Table 1). Again, a very significant relict surface, incised by almost a meter, displays an eroded eastern edge. The last deposition on this surface was at 2480 ± 300 yrs, though much of the sediment was deposited by a major event at around 4300 years. Using the upper age estimate, a minimum slip rate of 9 ± 2 mm/yr is derived from the offset of 23m. Our initial interpretation is that sediment overtopped and eroded the equivalent offset unit on the north side of the fault (Pit 12B) at 1780 ±140 to 1600 ± 220 yrs, while not affecting the south side, implying slip had already occurred, modifying the local base level and flow direction, providing a maximum slip rate estimate of 14 ± 2 mm/yr. As at site 1A, we plan to explore the detail and lateral extent of these stratigraphic units by reopening and extending our trenches parallel to the fault in order to determine the depositional relationships between the dated units.

Preliminary conclusions

Our IRSL age determinations suggest that sediment deposition at CCW was concentrated into a number of discrete events. In four pits, all samples provide preliminary age estimates in the correct stratigraphic order, and with significant grouping of ages for samples in the same stratigraphic unit. The results indicate that the relict braid bars, now incised to form low terrace features, represent composite structures deposited over the course of several events. This complexity requires further investigation of the sediments by excavation to clarify the relationships between the morphology of the relict braid bars and their internal stratigraphy, but our approach is likely to provide firm maximum and minimum slip rate estimates for each offset feature targeted.

Education and Knowledge Transfer

The project has led to a significant number of educational and knowledge transfer situations. Three graduate students received support directly from the grant (Evan Wolf and Steve Okubo, UCLA and Leigh McAuliffe, USC), while one other UCLA grad student worked on material from this project and successfully completed a Masters thesis based on this research (Belinda Roder, UCLA). PhD student Mike Lawson, UCLA, continued allied research into the controls on luminescence signal characteristics and the identification of quartz OSL signal contamination. Further, three UCLA undergraduate students participated in research; Guadalupe Ochoa and Wendy Barrera, both female Hispanic students, and Tom Capaldi, all helped in luminescence sample preparation. Guadalupe Ochoa continued to participate in the MSPHDs program, and recently produced a poster based on sediment dating at a closely related paleosiesmic site, to be presented to politicians in Washington DC to, providing an extra step towards a successful future science career. Wendy Barrera is currently developing outreach activities based on understanding alluvial sediments for presentation in schools with high Latino enrolments in East Los Angeles, building on her on-going Latinas Guiding Latinas (LGL) activities; this outreach is focused at encouraging participation in science by Hispanic females and other under-represented groups. A total of around 25 UCLA and CalTech graduate and undergraduate students used the site of CCW as part of two field trips in April 2012 and January 2013, teaching them the application of a range of field geophysical techniques.

The research team has completed the publication of two research articles in peer-reviewed international journals (Lawson et al., 2012; Roder et al., 2012), based on the findings of the previous SCEC funding cycle.

Six presentations were made at international and national conferences, including three at the New World Luminescence Dating Workshop hosted by UCLA in September 2012, one at GSA 2012 and two at AGU 2012, plus an additional two presentations at SCEC 2012. The preliminary results concerning the dating techniques have been widely circulated amongst the earthquake geology community in Southern California, generating a large volume of interest from other researchers and industry.

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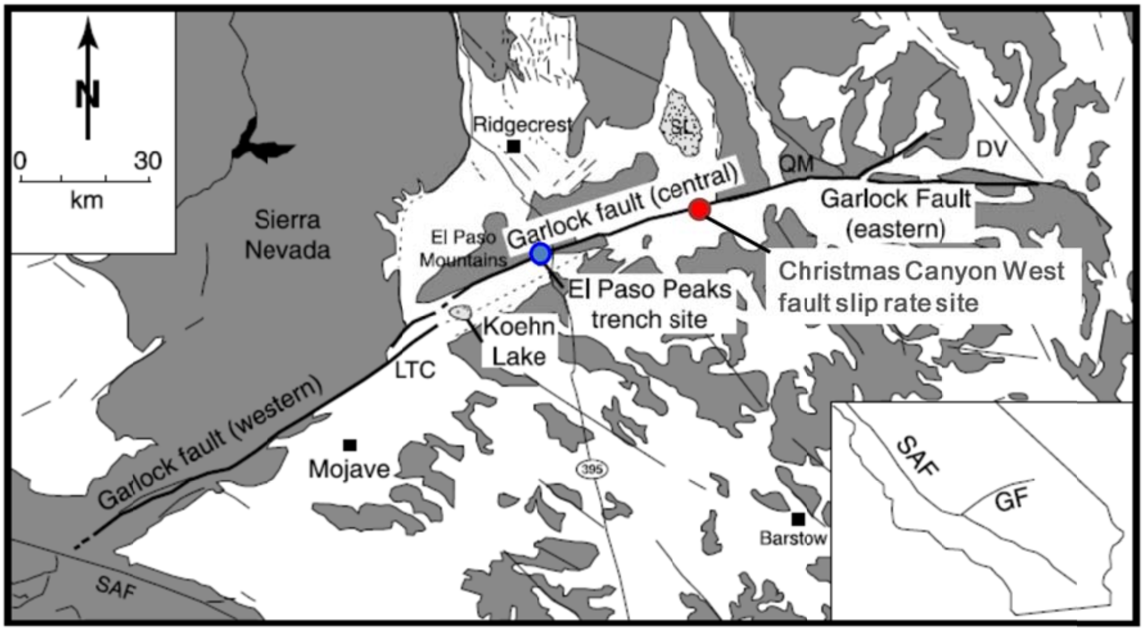

Figure 1. The central Garlock fault showing the location of El Paso Peaks (EPP) paleosismic trench site (blue symbol), from Dawson et al. (2003), and Christmas Canyon West (CCW) fault slip rate site (red symbol). Inset shows the relationship between the Garlock fault (GF) and San Andreas fault (SAF) within California.

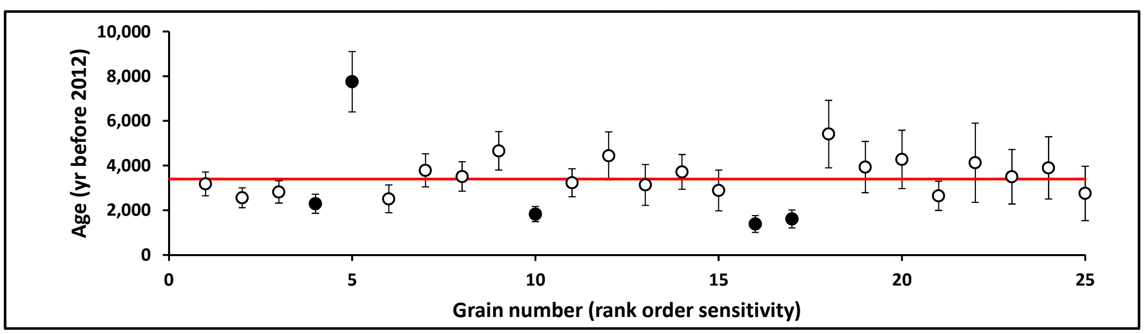

Figure 2. Single grain post-IR IRSL at 225ºC dating results for sample CCW11-A03, target 1a (see Fig. 3). Five grains shown in black have been excluded from the age calculation, as they are inconsistent with the 20 remaining grains, resulting either from incomplete zeroing (grain no. 5) or post-depositional intrusive grains (grain nos. 4, 10, 16, 17), probably translocated within the sediment by bioturbation, in particular by ant activity.

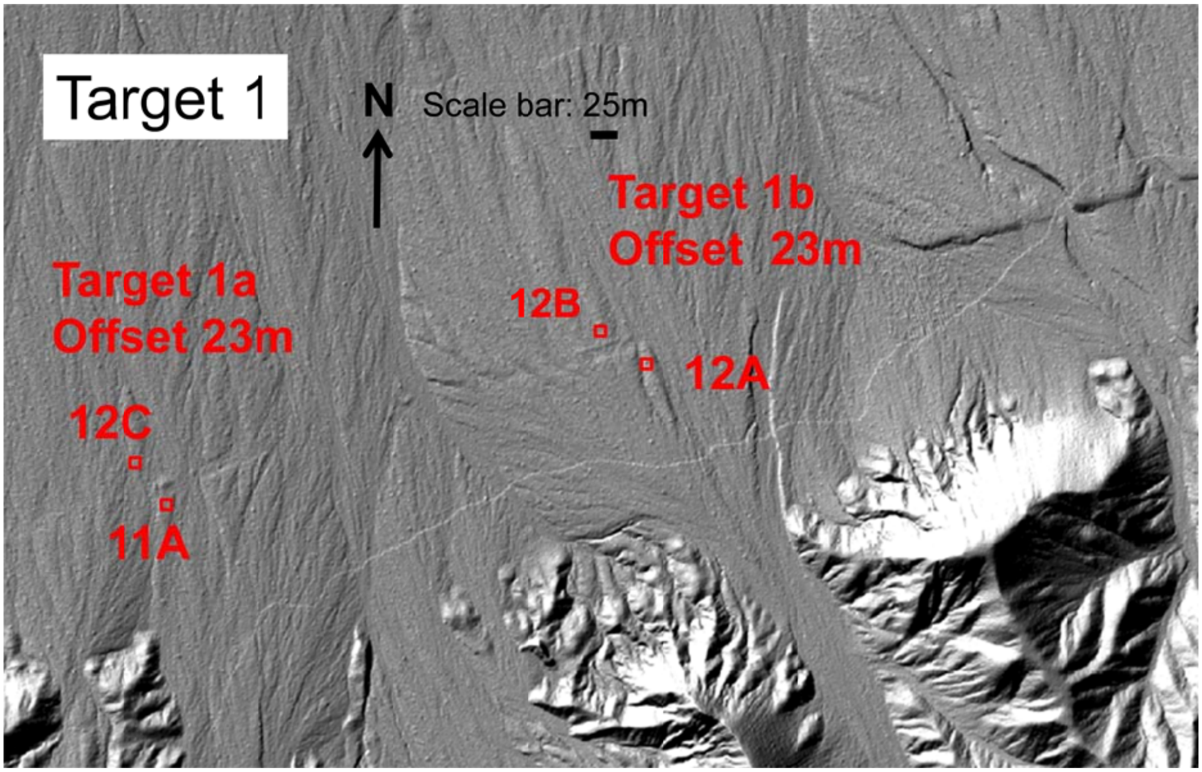

Figure 3. Lidar images from target sites 1a and 1b on east-central Garlock fault, located just outside of China Lake Naval Air Weapons Station, showing a series of closely spaced, small-scale geomorphic offsets. Red boxes show pits with multiple IRSL samples at each with IRSL dating results shown in Table 1. See text for preliminary slip rate results.

Field code	Lab code	Target	Strat unit	Depth (m)	PIR-IR-225 (years)		1 sigma error
CCW11A05	J0120	1a S side	Unit 1	0.08	30	±	20
CCW11A01	J0116	1a S side	Unit 2	0.14	1830	±	150
CCW11A02	J0117	1a S side	Unit 3	0.28	3360	±	300
CCW11A03	J0118	1a S side	Unit 3	0.49	3400	±	240
CCW11A04	J0119	1a S side	Unit 3	0.72	3350	±	200
CCW12A01	J0294	1b S side	Unit 1	0.10	2480	±	300
CCW12A02	J0295	1b S side	Unit 2	0.37	4370	±	340
CCW12A03	J0296	1b S side	Unit 2	0.61	4330	±	260
CCW12A04	J0297	1b S side	Unit 2	0.84	4230	±	340
CCW12B01	J0298	1b N side	Unit 1	0.21	1600	±	220
CCW12B02	J0299	1b N side	Unit 1	0.43	1780	±	140
CCW12B03	J0300	1b N side	Unit 2	0.58	4340	±	270
CCW12B04	J0301	1b N side	Unit 2	0.84	5290	±	330
CCW12C01	J0302	1a N side	Unit 1	0.13	480	±	50
CCW12C02	J0303	1a N side	Unit 2	0.29	2070	±	140
CCW12C03	J0304	1a N side	Unit 3	0.62	4980	±	310
CCW12C04	J0305	1a N side	Unit 3	0.84	4660	±	310

Table 1. Single grain post-IR IRSL at 225ºC dating results for ten samples from four pits at CCW, targets 1a and 1b (see Fig. 3). A very high degree of age consistency is observed between samples from the same stratigraphic unit within each pit. These results, in years before AD 2012, clearly illustrate the great performance and potential of this method. Note that stratigraphic unit names are independent for each pit, so that Unit 2 in Pit CCW12A is not interpreted to be the same depositional event as Unit 2 in Pit CCW12C, for example.

Intellectual Merit

This research contributes to the intellectual merit of SCEC in two ways. Firstly, we have developed a novel approach to dating the deposition of high-energy fluvial sediment typical of desert alluvial fans using IRSL of K-feldspar single grains. This approach represents a significant advance in comparison to existing methods based on quartz, that may be unreliable in many tectonic contexts. Secondly, by applying this method, we have produced a slip-rate estimate for the central Garlock fault over the last 2000 years that indicates a significantly higher rate than the Holocene average rate. This finding has profound implications for our understanding of fault dynamics and physical mechanisms.

Broader Impacts

The broader impacts of this research include the training in specialized laboratory and field techniques of three UCLA and one USC graduate students, plus three UCLA undergraduate students, including two female Hispanic students. Our Christmas Canyon West site was used for field training of around 20 UCLA and CalTech graduate and undergraduate geophysics students. We have published 2 papers based on previous SCEC results, and made 6 presentations at international and national conferences, besides the SCEC annual meeting. The IRSL techniques that we have developed within this project are now being applied to other sites around the world to improve our understanding of fault slip rates, paleoseismic events and past climate episodes.

Publications resulting from SCEC research

Lawson , M.J., Roder, B.J., Stang, D.M. and Rhodes, E.J. 2012 Characteristics of quartz and feldspar from southern California, USA. Radiation Measurements, 47, 830-836, doi:10.1016/j.radmeas.2012.03.025 SCEC publication 1517

Roder, B.J., Lawson, M.J., Rhodes, E.J., Dolan, J.F., McAuliffe, L. and McGill, S.F. 2012 Assessing the potential of luminescence dating for fault slip rate studies on the Garlock fault, Mojave Desert, California, USA. Quaternary Geochronology 10, 285-290, doi:10.1016/j.quageo.2012.03.013 SCEC publication 1518

Presentations made

8th New World Luminescence Dating Workshop, UCLA, September 2012

Barrera, W.A., E.J. Rhodes, M.K. Murari, L.A. Owen, M.J. Lawson, K.J. Bergen, J.F. Dolan, J.H. Shaw, Luminescence dating inter-comparison for sediments associated with the Puente Hills Blind-Thrust System recovered from cores. Oral presentation.

Lawson, M.J., E.J. Rhodes, W.A. Barrera, G.T. Ochoa, B.J. Roder, Assessing the quartz contribution to OSL signals. Oral presentation.

Rhodes, E.J., The pros and cons of single grain K-feldspar IRSL sediment dating in neotectonic and paleoclimate contexts. Oral presentation.

GSA Annual meeting, Charlotte, NC, November 2012

Wolf, E.M., E.J. Rhodes, D.M. Stang, Quaternary Deformation of Middle Pleistocene Sediments Due to Movement along Northeast Trending Faults West of Christmas Canyon, Southern California. Oral presentation.

AGU Fall meeting, San Francisco, CA, December 2012

Lawson, M.J., E.J. Rhodes, W.A. Barrera, G.T. Ochoa, Improvements to luminescence dating of Quaternary sediments deformed by earthquakes. Poster presentation.

Okubo, S., E.M. Wolf, B.J. Roder, E.J. Rhodes, S.F. McGill, J.F. Dolan, L. McAuliffe, M.J. Lawson, W.A. Barrera, Luminescence chronologies for sediments recording paleoseismic events and slip rate for the central Garlock fault, California, USA, Poster presentation.

SCEC Meeting, Palm Springs, September 2012

Barrera, W.A., E.J. Rhodes, M.K. Murari, L.A. Owen, M.J. Lawson, K.J. Bergen, J.F. Dolan, J.H. Shaw, Luminescence dating inter-comparison for sediments associated with the Puente Hills blind thrust recovered from cores. Poster presentation.

Okubo, S., E.M. Wolf, B.J. Roder, E.J. Rhodes, S.F. McGill, J.F. Dolan, L. McAuliffe, M.J. Lawson, W.A. Barrera, Progress towards developing an improved chronology for slip-rate and paleoseismic record of the central Garlock fault using luminescence dating. Poster presentation.

Lawson, M.J., E.J. Rhodes, W.A. Barrera, G.T. Ochoa, Roder, Assessing different strategies to improve the reliability and applicability of luminescence dating of high energy sediment deposition and neotectonic contexts. Poster presentation.