2013 SCEC Report

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. We have developed minimum slip-rates for five offset features along the the Garlock fault spanning the past 2600 years, demonstrating a significantly higher rate than the average Holocene rate. We have also assessed the luminescence chronological methods used in comparison to independent dating controls. We have made new technical developments in sample preparation, and achieve good agreement between techniques, raising confidence in this approach.

Technical science outcomes

- Successful test pit and trenching excavation at Christmas Canyon West, near Ridgecrest, CA (central Garlock fault)
- Development and assessment of novel K-feldspar single grain “post-infrared IRSL” dating protocol using novel “super-K” preparation
- Evidence for increased slip rate for the central Garlock fault over the last 2600 years at five locations in comparison to the Holocene average rate. Minimum slip rate values range from 8.1 ± 1.9 to 12.4 ±1.5 mm per year.

Training, communication and outreach outcomes

- Three UCLA students and one USC graduate student closely involved in research
- Two publications submitted to a peer-reviewed journal including results from this study
- Six presentations made at international and national conferences, plus three at SCEC 2013

Project objectives

The objectives of this project were to assess the degree to which the Garlock fault, California, exhibits transient strain accumulation with periods of increased slip and frequent earthquakes, separated by periods of little or no slip and few accompanying seismic events. The methodology involved determining minimum slip rates over the past 2600 years at a number of offset alluvial fan features. Age control was provided by newly developed post-IR IRSL (infra-red stimulated luminescence) using sand-sized single grains of K-feldspar. The project has been successful, with age control now developed for five locations, plus several modern sample locations to assess performance of the technique. Additionally, eight further samples from locations with slightly more ambiguous geomorphic offsets were dated, contributing to the paleoclimate record for this part of the Mojave desert. The results are significant, demonstrating slip rates higher than the Holocene average rate, with uncertainty margins that clearly demonstrate an increase in slip rate over this period.

Executive Summary

In our highly productive 2013 SCEC project, we used lidar-based geomorphic offsets dated with the innovative and robust post-IR-IRSL$_{225}$ luminescence dating protocol developed and refined at UCLA to document extremely large, millennial-scale variations in rate. Specifically, although the Holocene (8-12 ka) average rate of the fault is ~5.0 – 7.5 mm/yr, our 2013 SCEC studies revealed a 2 ka slip rate of the Garlock fault of ≥12.5 mm/yr, with a likely rate during a paleoseismologically documented cluster of four earthquakes at 0.5–2.0 ka of ~15-20 mm/yr. This interval of very rapid slip followed a period of no earthquake activity and presumably a 0 mm/yr "slip rate" between ~2 ka and 5 ka. As pointed out in the Advisory Council report at the 2013 Annual Meeting, such records of incremental slip-rate variations along major faults are of critical importance for understanding earthquake occurrence in southern California and elsewhere. They are of obvious importance for establishing more realistic input parameters for next-generation Probabilistic Seismic Hazard Analysis (PSHA) as well as for studies of regional fault interactions and the physics that underlies such interactions, and thus form a key target for SCEC research.

Introduction and Rationale

The degree to which fault loading and strain release rates are constant (or non-constant) in time and space is one of the most fundamental, unresolved issues in modern earthquake science, with basic implications for our understanding of fault mechanics, regional fault interactions, storage and release of elastic strain energy, and seismic hazard assessment. For example, current PSHA models assume steady fault slip and do not account for the possibility of large temporal variations in slip that span multiple earthquake cycles (N. Field, Pers. Comm., 2013). But we do not know whether this assumption of steady slip rate is correct, and if it is not, we do not yet know the degree to which slip rates vary through time and space.

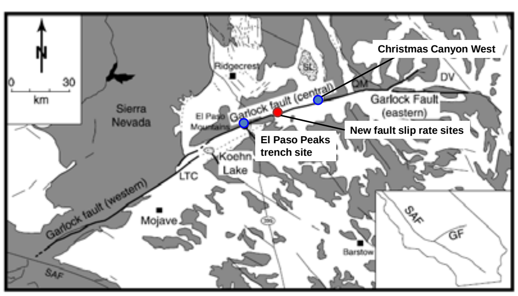

Figure 1. Location map of Garlock fault showing our 2013 Christmas Canyon West site (eastern blue dot), and Dawson et al. (2003) El Paso Peaks trench site (western blue dot), re-dated with luminescence techniques in 2011. The red dot shows proposed future study sites,

Despite the importance of understanding the temporal and spatial variability in slip rate, detailed data sets of incremental fault slip rates are extremely rare, hampering our understanding of this basic feature of seismic slip along faults. Moreover, the few detailed data sets that are available suggest that major faults may exhibit a wide range of behaviors that we do not yet fully understand. For example, data from some parts of some faults (e.g., San Andreas [SAF], Kunlun fault) suggest that slip is relatively constant over a wide

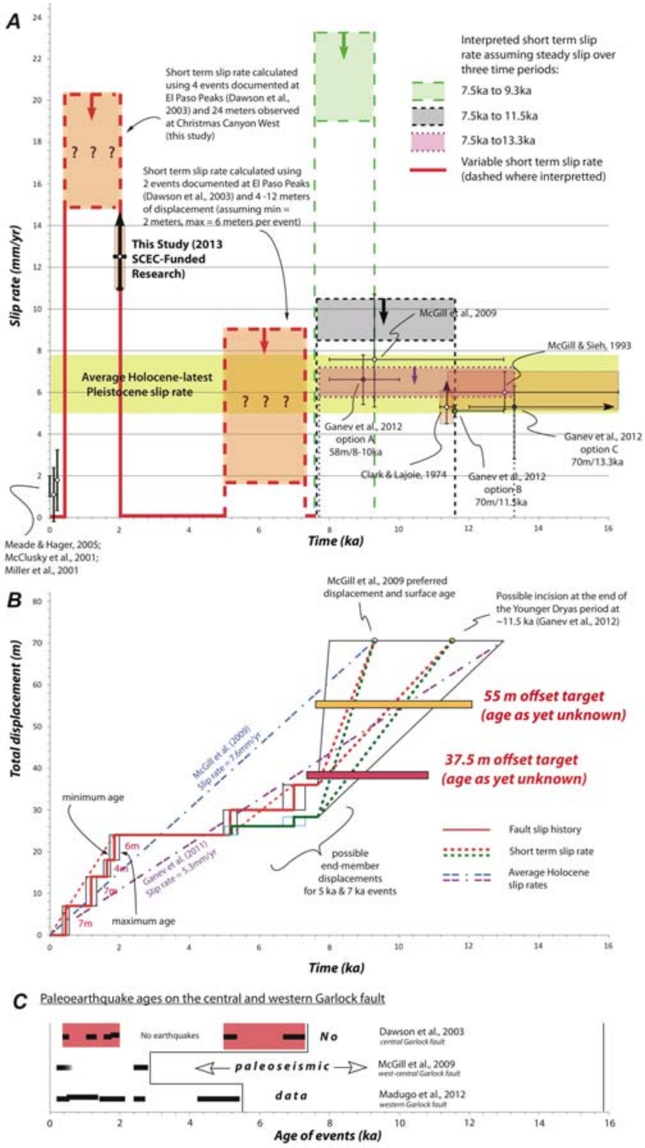

Figure 2. *Available slip rate and paleo-earthquake age data from the central Garlock fault. (A) Incremental fault slip rate plotted vs. time. Yellow horizontal band encompasses range of preferred average latest Pleistocene-Holocene rates measured by Clark & Lajoie (1974); McGill & Sieh (1993); McGill et al. (2009); and Ganev et al. (2012). Solid red line shows known rates. Note correspondence of rapid latest Holocene rate measured during our 2013 SCEC studies with cluster of four earthquakes observed by Dawson et al. (2003) at their El Paso Peaks site 25 km west of our slip rate study site. Dawson et al. (2003) documented an absence of earthquakes between 2ka and ~5ka, yielding a 0 mm/yr rate for this interval. For the two earthquakes they documented at ~5ka and ~7ka we assume a range of possible displacements for each event of 2 m (the smallest geomorphic displacement measured along the central Garlock fault by McGill & Sieh, 1991) to 6 m (ave. slip in four earthquakes totalling 24 m as measured at our Christmas Canyon West study site), yielding 4-12 m of slip within this ~2kyr period. Combined with the 24 m of fault slip measured by us over past 2kyr, this yields a total of 28 to 36 m of slip on the Garlock fault since 7ka. Green, gray, and pink boxes show possible incremental rates prior to 7ka that are consistent with the 70 m of total displacement measured by McGill et al. (2009) and Ganev et al. (2012) that has accrued since latest Pleistocene-early Holocene time. Three possibilities are shown, given the uncertainty in the exact time at which the 70 m of displacement began to accumulate: (1) a 19-24 mm/yr incremental rate from 7.5 ka to 9.3ka (preferred age of incision for 70 m offset at McGill et al., 2009, study site); or (2) a 9-11 mm/yr incremental rate from 7.5ka to 11.5ka (following Ganev et al.'s suggestion that incision began during return to wetter conditions at end of Younger Dryas climatic regime); or (3) 5-7 mm/yr incremental rate from 7.5 ka to 13.3 ka (age of incised surface at Ganev et al., 2012, 70 m offset). Note that these three speculative "rates" assume constant steady slip during these time periods, a behavior we consider unlikely, especially for the 4-6 kyr-long periods represented by the latter two possibilities. This method of presentation thus artificially reduces the average rates shown during these intervals. (B) Same data plotted as cumulative displacement through time. Triangular region between 7.5ka and 13.3ka denotes range of possible cumulative displacements. Note the pink and yellow horizontal bands. These show the key positions of our 37.5 m (pink) and 55 m (yellow) offset targets. Dating of these two offsets with our robust post-IR-IRSL$_{225}$ luminescence dating technique will allow us to complete our characterization of the incremental slip rate of the Garlock fault for the entire Holocene. The addition of our proposed study of the rate based on the 175 m offset should tell us if the longer-term rate on the fault is also comparable to the average latest Pleistocene-Holocene rate. (C) Available paleoseismologic data for the central and western Garlock fault. The well-constrained site of Dawson et al. (2003) lies closest to our study sites.*

range of time intervals (e.g., Sieh & Janhs, 1984; Weldon & Sieh, 1985; Gold & Cowgill, 2011). In contrast, other studies show that some faults experience large variations in slip rate over a range of time scales (e.g., SAF [Weldon et al., 2004]; Awatere fault, New Zealand [Mason et al., 2006; Gold & Cowgill, 2011]; Garlock fault [McAuliffe et al., in prep., this study]).

Although it is clear from even these rare glimpses that different faults slip in different ways, and that sometimes even the same fault can behave very differently in different locations and over different time scales, there are far too few data to even begin to understand the range of these behaviors, nor the causes of such variability (or lack of variability). In this regard, the central Garlock fault offers perhaps the richest stretch of readily datable incremental fault slip rate sites anywhere in California, and we seek to continue our research by using the newly refined pIR-$IRSL_{225}$ technique (described below) to target a number of geomorphic offsets at key displacements that will allow us to more fully constrain the incremental slip rate of the Garlock fault throughout the Holocene and back into late Pleistocene time.

Our 2013 SCEC research focused on constraining the incremental rate of the central Garlock fault at the Christmas Canyon West (CCW) study site (Figure 1). These studies reveal extremely large temporal variations is slip rate during mid- to late Holocene time (Figure 2). Key to the success of this ongoing effort has been the continued rapid development of an innovative new luminescence dating protocol that incorporates repeated cycles of two infrared stimulated luminescence (IRSL) measurements, one at 50ºC followed by one at 225ºC, referred to as p-IR-$IRSL_{225}$. Using this technique, our most significant 2013 result is the determination of multiple minimum slip rates from a number of incised drainages on two alluvial fans that have been consistently offset by 23–24 m at the CCW site. Our concentrated efforts at this site have resulted in a dating approach that allows us to collect samples at almost any location in the sandy gravels that typify this stretch of the Garlock fault, and determine age estimates for deposition with good precision and a high degree of internal consistency, leading to a highly robust age model for sediment accumulation and erosion.

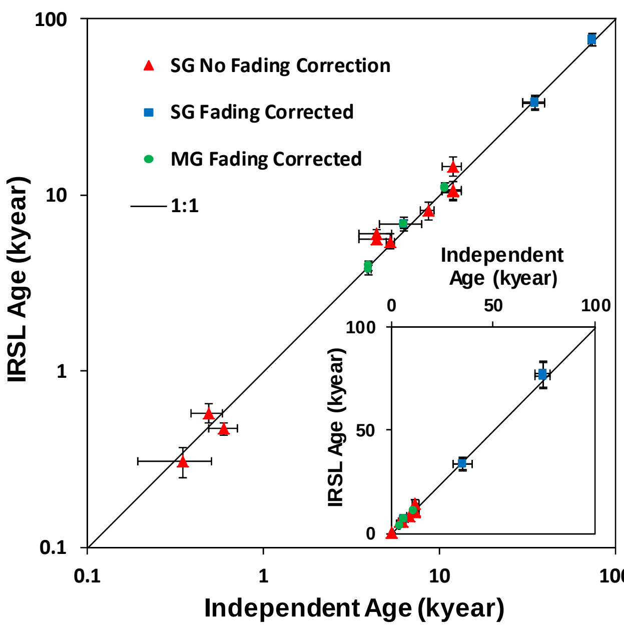

Figure 3. Comparison of UCLA K-feldspar P-IR-IRSL at 225ºC sediment age estimates with independent chronological control from fluvial, alluvial and lake shoreline deposits in active tectonic settings in California, Mexico, Tibet and Mongolia, spanning 400 to 80,000 years. SG = single grain, MG = multiple grain; all data are considered preliminary at this stage.

We have tested our new luminescence dating approach at a wide range of different sites in the western U. S. and elsewhere in the world in areas with active tectonics where independent chronological control was available (cosmogenic ^{10}Be profiles, ^{14}C of organic carbon). As summarized in Figure 3, the excellent agreement between IRSL age estimates using the p-IR-$IRSL_{225}$ protocol demonstrates that this is a highly robust new tool for dating previously problematic depositional environments. The second IRSL measurement provides access to electron traps that have greater thermal stability in comparison to the first, but are sufficiently sensitive to light to be useful in high-energy alluvial fan contexts. This approach was originally developed by Buylaert et al. (2009) for conventional multiple grain aliquots but has been extended by Rhodes at UCLA to encompass a wider range of suitable depositional environments using single grains of K-feldspar. Incompletely zeroed or intrusive grains can be identified readily, and omitted from age calculations. This approach is of particular importance for fault slip rate and paleoseismic applications, as in these locations our previous SCEC research demonstrates that quartz often has low OSL signal sensitivity and is not well suited for age estimation (Roder et al., 2012; Lawson et al., 2012).

In a further 2013 development, we have introduced a new preparation approach, selecting only the most potassic alkali feldspar grains. Conventional feldspar preparation procedures select a K-feldspar-rich fraction by floating off grains with a density below 2.58 g.cm^{-3}. We have discovered that we can achieve a greater proportion of measured grains giving p-IR-IRSL$_{225}$ signals if we tighten this constraint and select grains with a density below 2.565 g.cm^{-3}; we refer to this procedure as "super-K". It yields a smaller, but significantly more sensitive population of grains; in one case, the total IRSL light sum from 300 grains was increased by a factor of almost 100, representing a dramatic improvement in measurement efficiency. We have determined that different sample suites are characterized by single grains displaying IRSL sensitivity distributions comprising the sum of just two or three log-normal components. These vary with bedrock lithology, so we plan to use this information to build up a database of optimal field locations for IRSL application, where experiments or assessments of enhanced quality can be made. These prime target areas include parts of the central Garlock fault (Fig. 1), the San Gabriel Valley, and the Carrizo Plain, amongst others. We are also building a database of the timing of high-magnitude fluvial events (our target material in slip rate studies), allowing us to better interpret the likely geomorphic history of other sites in the region.

Application of this robust new dating technique at CCW has allowed us to determine a well-constrained minimum slip rate for the past 2,000 years along the central Garlock fault. Our principal target last year was determining the Garlock rate during a cluster of four surface ruptures identified at El Paso Peaks by Dawson et al. (2003). This earthquake cluster, which occurred between ~500 and 2,000 years ago, was preceded by a ~3,000-year-long lull and two more surface ruptures at ~ 5 ka and 7 ka. As part of our previous SCEC research, we searched the GeoEarthScope lidar along the Garlock fault and identified a series of 23–24 m offset drainages incised into several alluvial fans at the CCW site. Dating of the fan surfaces into which the offset drainages were incised revealed a range of depositional ages from ~ 1.9 ka to 6 ka in our 1.5-m-deep hand-dug sample pits, with several sites having a ~1.9-2.5 ka deposit overlying 3.5-5.9 ka strata. To rule out the possibility that the young capping deposit was somehow deposited after initial incision, we hand-excavated a trench that confirms that all deposits are flay-lying sheets that predate incision of the drainages used to define the 23-24 m offsets.

As shown in figure 2, combining the paleo-earthquake ages of Dawson et al. (2003) from the nearby El Paso Peaks trench with our dated 24 m offsets at CCW yields a minimum slip rate over the past 1,860 years (age of the youngest incised strata) of >12.4 mm/yr (Table 1). During the 0.5-2.0 ka cluster the fault therefore must have been slipping at an average rate of 15-20 mm/yr (Note: although traditional fault slip rates are expressed as an average rate over some time interval ending at the present, in order to show the true variation in rate through time we think it is important to show when and how fast the fault was slipping as well as when and for how long it was *not* slipping [i.e., a 0 mm/yr "slip rate"]). In this regard, the absence of earthquakes at the EPP trench site between 2 ka and 5 ka indicates that the slip rate of the fault during that interval was likely zero (we propose a test of this inference below). Assuming a range of potential displacements in the ~5 ka and ~ 7 ka earthquakes at EPP of 2 m (minimum geomorphic offset from McGill & Sieh, 1991) to 6 m (average slip in past four earthquakes at EPP (24 m offset/4 eqs = 6 m) and using the full paleoseismic age uncertainties suggests that the average rate during the 5-7 ka period was between ~ 2 and 9 mm/yr. For comparison, longer–term (8-13 ka to present) preferred rates are 5.3 to 7.6 mm/yr (Clark & Lajoie, 1974; McGill & Sieh, 1993; McGill et al., 2009; Ganev et al. 2012). But the McGill et al. (2009) and Ganev et al. (2012) rates are based on 70 m offsets, and even with the combined 4–12 m of displacement in the 5 ka & 7 ka earthquakes, the total slip at ~ 7 ka on the central Garlock fault would be only 28–36 m. Thus, ~34–42 m of slip must have occurred between ~7.5 ka (the oldest dated strata at the EPP trench) and the time of incision of the 70 m offset drainages. Determining the timing and variability of this early Holocene phase of fault slip forms the main focus of this proposal.

Finally, we note that during 2013 we continued our efforts to gain access to our previously proposed slip rate sites within the China Lake Naval Air Weapons Station. Unfortunately, there was yet another personnel turnover in our Navy contact last year, plus the government shutdown, both of which delayed this process even further.

Intellectual Merit

The project contributes to the intellectual merit of SCEC by providing clear evidence for irregular fault slip rates for the Garlock fault. This result is significant in requiring modification to simple earthquake cycle models with uniform strain accumulation, with the prospect of developing improved models for strain release and seismic events for this fault, and possibly in other contexts. The new luminescence chronological developments are also providing a means to date sediments on timescales of 10 to 100,000 years, allowing fault slip rates and paleoseismic records to be measured in contexts where no organic material for radiocarbon exists, or where the events are too old (>40,000 years) or too young (post AD 1750) for that technique.

Broader Impact

This project has provided opportunities for training and teaching; In 2013, two UCLA masters projects have been based around the target sites, and one USC PhD student project. UCLA and Caltech undergraduate and graduate students took advantage of the site to be trained in field geophysical methods. The advantages to society include a cohort of aware students, some with specific skills, taking up positions in academic or industrial settings, and improvements in our understanding of earthquake timing.

Table 1. Minimum slip rates for five locations at Christmas Canyon West on the central Garlock fault, California, determined by IRSL dating of sediments deposited before erosion of offset terrace risers. Note age estimates are in years before 2014, rounded. Each pit contains multiple dated sediment samples; in most cases, the age of the uppermost sample provides an estimate of the last deposition before erosion began.

Pit	Sample		Slip rate	±	1 sigma			Age (yrs)
11A	J0116	>=	11.4	±	1.6	mm/yr	since	2010
12C	J0303	>=	10.1	±	1.1	mm/yr	since	2280
12A	J0294	>=	8.8	±	1.0	mm/yr	since	2620
12B	J0298	>=	12.4	±	1.5	mm/yr	since	1860
12D	J0306	>=	8.1	±	1.9	mm/yr	since	1230

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