2012 Annual Report

Paleoseismic investigation along the inferred northernmost extent of the 1857 rupture: Do large southern San Andreas Fault (SAF) ruptures extend into the creeping section?

Southern California Earthquake Center
Award #12050

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Significant ground deformation between 780 and 1031 A.D. at the Dry Lake Valley site along the creeping section of the San Andreas Fault (SAF)

Project Abstract

This research consisted of two components. *Component A* – test the longevity of the historically-observed aseismic slip release behavior for the central creeping section of the SAF and understand the broader implications for earthquake hazard related to extreme events. *Component B* – examine size and spatial distribution of right-lateral channel offsets along this portion of the SAF to test the role of climate in the production of characteristically-sized offsets. In 2012, we completed a remote LiDAR survey of 41 right-lateral offsets with less than 30 meters of total displacement, we conducted a field review of roughly half of these offsets, and we conducted a five week paleoseismic investigation of the Dry Lake Valley (DLV) site. Remote LiDAR mapping and field analyses showed a minimum offset along this section of the fault of 2-5 meters. Beyond that minimum length, the offsets do not group into distinct size clusters. Thus, over some time periods channels may form randomly and frequently and during other periods channel incision may cease, resulting in clusters and gaps in the distribution of offset sizes. Trenching at the DLV site revealed many structures consistent with surface manifestations of aseismic slip. This site also revealed evidence for significant ground deformation between 780 and 1031 A.D. This evidence consists of a nearly vertical package of gravel and small boulders that are capped by horizontally-bedded stratigraphy. This paleoseismic result is the focus of our 2013 SCEC proposal which has been approved for funding.

Introduction

The central creeping section of the San Andreas Fault (SAF: Figure 1a) has not generated a historical earthquake greater than ~M 6.5 (e.g., Toppozada et al., 2002) and for nearly half a century it has experienced nearly continuous aseismic creep at a rate near 30 mm/yr (e.g., Titus et al., 2006). This historical slip release behavior is in stark contrast to that along the SAF segments to the south and north which are currently locked and have had historical earthquakes of nearly M 8.0. In the south the last great earthquake was the 1857 Fort Tejón Earthquake (Sieh, 1978) and in the north the great 1906 San Francisco Earthquake (Lawson, 1908) helped us realize the geomorphic and tectonic significance of the SAF. In addition to large historical earthquakes, the segments to the south and north of the central creeping section have well-documented paleoseismic records spanning multiple earthquake cycles (e.g., Weldon et al., 2004 and Kelson et al., 2006, respectively). Despite reports suggesting that the 1857 Fort Tejón rupture may have extended at least 80 km into the creeping section (Sieh, 1978 from Wood, 1955, Johnson, 1905, and Barton, 1876), there have been only a few paleoseismic studies along this part of the fault. From southeast to northwest the paleoseismic sites across this part the SAF consist of: 1 – the Water Tank site near Cholame, California (Sims, 1987), 2 – the Millers Field site at Parkfield, California (e.g., Toké et al., 2011), 3 – the Flook Ranch site near Bitterwater, California (Cashman et al., 2007), 4 – the Dry Lake Valley site (this study, Figure 1a: e.g., Toké et al., 2012), and 5 – the Melendy Ranch site located about 16 km northwest of the DLV site (Perkins et al., 1989).

Research emanating from the SAFOD drilling project (e.g., Zoback, 2010) show that fault zone materials, including talc (Moore and Rymer, 2007) and clays (Schleicher, 2010), along this part of the SAF may reduce the frictional strength of the fault zone. Low friction material within the fault zone help explain the high rate of fault creep across this section of the SAF. Additionally, none of the previous paleoseismic sites along the ~150 km creeping section of the fault have documented any unequivocal paleoseismic ruptures (Sims, 1987; Toké et al., 2011; Cashman et al., 2007; Perkins et al., 1989). The Water Tank site (Sims, 1987), the Miller's Field site (Toké et al., 2011), and the Melendy Ranch site (Perkins et al., 1989) all documented late Holocene slip rates of less than 30 mm/yr, suggesting that a slip budget for the creeping section of the SAF can be balanced by historical aseismic creep rates over the timescales captured in these slip rate measurements (< 1000 years). Thus, previous research jives with slip release models that do not include large earthquakes on the creeping section of the SAF. However, it is important to remember that strike-slip earthquakes do not necessarily leave behind strong evidence of their displacement across their entire rupture lengths (e.g., Ambraseys, 1969) and that the existing paleoseismic records only extend about 1000 years into the past. Moreover, low friction material within a fault zone does not preclude the possibility of stress accumulation and the production of large earthquakes over greater recurrence intervals or the dynamic penetration of large ruptures into a velocity-strengthening creep dominated zone.

It is an attractive hypothesis to presume that historically-observed slip release is representative of long term SAF behavior in central California. However, this hypothesis has not been tested beyond ~1000 years before present. An alternative model is that over periods longer than the past thousand years, large earthquakes may rupture the central California creeping section. This bi-modal model of slip release would balance the slip rates estimated along the creeping section of the SAF (~30 mm/yr) with those to the southeast (~35 mm/yr: Sieh and Jahns, 1984 or Meade and Hager, 2005) by contributing slip not accounted for in existing slip budgets that span only the past thousand years. This annual report presents paleoseismic observations from the Dry Lake Valley paleoseismic site. This site provides evidence for significant ground deformation between 938 and 1233 years before present. While the evidence presented herein is not unequivocal, it is challenging to explain with aseismic creep alone and will be the focus of our 2013 field work which has been approved for funding by SCEC.

The second component of our 2012 project was to analyze the size and spatial distribution of right-lateral geomorphic offsets across the creeping section of the SAF (e.g., Salisbury et al., 2012). This part of the project serves as a comparison for previous such studies along locked sections of the SAF (e.g., Zielke et al., 2010) that led to debates over whether apparently-clustered geomorphic offsets are a product of characteristic slip in past earthquakes or if offset-size clustering is due to periodic channel incisions that are modulated by climate (e.g., Grant et al., 2010). In the next section of this report we present offset statistics from LiDAR-based remote measurements and field measurements along the creeping section of the SAF. We then present the evidence for large ground deformation at the Dry Lake Valley site and an outline of our plan to further explore this problem.

LiDAR and Field Offset Measurements from the Creeping Section of the San Andreas Fault

Along the creeping section of the SAF ground-rupturing earthquakes are not expected to occur, nor have they occurred for the past ~150 years. Moreover, throughout the creeping section of the fault, no good evidence of large surface-rupturing earthquakes exists in the ~1000 year records unearthed at three previous paleoseismic sites (Toké et al., 2011; Cashman et al., 2007; and Perkins et al., 1989). Therefore, any statistical pattern in the distribution of geomorphic offsets over the past thousand years (< 30 meter offsets) would be a product of climatically-driven incisional events (Grant Ludwig et al., 2010), rather than discrete and repeating (i.e., characteristic) earthquakes. In 2012, we documented offset channels throughout this reach of the SAF from Parkfield to San Juan Bautista, California. This was done remotely using Northern California EarthScope LiDAR data and for a subset of the offsets we also documented them in the field. In total, we documented 41 geomorphic offsets between 2 and 30 meters along the creeping portion of the SAF (Figure 2). The LiDAR analysis was performed more than six months prior to fieldwork. To provide a semi-independent comparison, LiDAR-based results were not taken to the field. However, LiDAR-derived hillshades were used as base maps to document our field measurements (Figures 3-4). Due to landowner issues and time constraints, about one half of the 41 offsets were measured in the field.

Offset measurements along the creeping section indicate that the minimum displacements across this reach of the fault are 2-5 meters in length (Figure 2b). Beyond these minimum displacement lengths, it is challenging to discern clusters in the magnitudes of displacement. This appears to demonstrate that climate can modulate the production and distribution of offset lengths but it doesn't always do so. Over the last ~100 years, very few channels have incised. Thus, the minimum offsets are greater than 2 meters across the entire creeping section. However, in the preceding 900 years channel incision appears to have been locally-controlled and the temporal distribution of incision appears to have been more random, resulting in an absence of strong offset clusters.

Several of the important outcomes from this work have to do with the quantification of uncertainty in these measurements. Our field uncertainties were higher than those derived from LiDAR remotely (Figure 2a). For remotely-measured offsets the uncertainty window (the difference between the maximum and minimum acceptable offset for a given geomorphic feature) ranged from 1-3 meters, whereas field measurements had uncertainty windows of 2-9 meters. Clearly, it is challenging to confidently distinguish a 3 meter offset from a 4 meter offset, but apparently it can be done more confidently with the digital method which allows the user to manipulate the LiDAR data to create hillshade, slope, contour, aspect, and other useful maps.

Another important observation is that offset uncertainty increases with offset size. While this may seem unsurprising and the uncertainties may increase proportionally with the size of the offset, there is something important to take away from this. Using the field data (Figures 3-4) we were able to relate deformation zone widths to offset parameters. Deformation zone width increases with offset magnitude (Figure 3a) and with offset uncertainty (Figure 3b). This may be a product of the migration and varying activity of slip surfaces along the fault. Hence, the active surface trace of the fault commonly occupies a width of up to 15 meters over the 1000 year time scale. Using correlations between deformation zone widths with the age of geomorphic offsets could be useful in future refinements of Alquist-Priolo Earthquake Fault Zone regulations.

Large Ground Deformation between 780 – 1031 A.D. at the Dry Lake Valley Paleoseismic Site

In our 2012 SCEC proposal, we asked the question: Does the central creeping section of the SAF rupture with the northern or southern SAF? To address that question, we conducted paleoseismic field work along the heart of the creeping section, establishing the Dry Lake Valley paleoseismic site (DLV site; Figure 1). This site is a fault bounded sag depression within an alluvial fan complex that slopes SW across the SAF. The sag is ~40 m wide and ~250 m long. It is steep sided with a 6-9 m high scarp on the NE side and a 2-3 m high scarp on the SW side. We cut a 46 m long fault-perpendicular trench across the sag. Our excavations (Figure 5) revealed an intriguing stratigraphic relationship in which a poorly sorted gravel package, sourced from a nearby paleochannel (Figure 1c), is arranged sub-vertically (it looks suspiciously like a filled fissure) within the westernmost fault zone. The fault zone gravel is overlain by nearly horizontal stratigraphy (Figure 5). This arrangement of up to boulder-sized clasts within the fault zone is difficult to explain with only fault creep. However, despite the fact that this evidence would certainly be interpreted as a paleoearthquake at 780-1031 A.D. along a non-creeping fault, it remains challenging to discount slicing and rotation due to aseismic creep as a responsible mechanism because it overprints all paleoseismic evidence along this portion of the fault. At this point it is too early to jump to conclusions about the correlation of the ground deformation observed at the DLV site and paleoseismic sites to the northwest or southeast of the creeping section of the SAF. However, the time span between 780 and 1031 A.D. could overlap with rupture evidence observed to the northwest (e.g., Kelson et al., 2006) and southeast along the SAF (e.g., Weldon et al., 2004).

Discussion: Further assessment of the rupture potential of the central creeping SAF

Determining whether coseismic fault rupture plays a role in the slip history of the central creeping portion of the SAF remains vital for our understanding of long term statewide and southern California earthquake hazard and for constraining deformation patterns for fault slip models (e.g., SCEC science goals 2a and 1d). Currently, the Uniform California Earthquake Rupture Forecast permits large ruptures extending from the southeast or northwest to break through the central creeping section of the fault (e.g., Field et al., 2009 and UCERF3 Plan, 2012). This modeling assumption is supported by anecdotal evidence from the

Great 1857 Fort Tejón Earthquake, in which ground cracking was observed well into the creeping section of the SAF (Sieh, 1978). Also, the existence of large ruptures along the creeping section has been hypothesized to account for discrepancies in slip rates (e.g., Toké et al., 2011) between historical slip on the creeping section (30 mm/yr: Titus et al., 2006) and Holocene slip along the locked sections to the southeast (34 mm/y: Sieh and Jahns, 1984). Moreover, we know from historical records that the creeping section accumulates elastic strain that is released in earthquakes. This past October, a magnitude 5.3 earthquake occurred nearby the DLV site (USGS, 2012). While this event did not produce surface rupture, nearly 20 other historical moderate magnitude earthquakes (between M5.5 and 6.5) have been have been attributed to ruptures on the creeping section of the SAF (Toppozada et al., 2002). Additionally, provocative hypotheses such as self-driven mode switching (in which the fault may switch between conditions appropriate for fault creep and those leading fault rupture) have been proposed for the SAF at 5-10 kyr timescales (e.g., Ben-Zion, 1999). These anecdotes, hypotheses, and models remain incompletely tested over a timescale longer than 1000 years. In contrast to the hypotheses that call for large ruptures along creeping section, recent studies have shown that low friction materials are found at seismogenic depths of along the central SAF, providing a physical explanation for the observed fault creep (e.g., Schleicher et al., 2010; Moore and Rymer, 2007). Also, small slip rate discrepancies can be explained by fault-parallel distribution of slip rather than mode switching (e.g., Titus et al., 2006; Toké et al., 2011). Finally, paleoseismic trenching at the southeastern end of the creeping section did not reveal evidence for large ground rupture due to the 1857 event (Toké et al., 2011). To further test these models and hypotheses we must thoroughly assess the record of recent deformation along this part of the SAF and establish if there is convincing evidence of one or more large paleoruptures.

The DLV site warrants further study because of the observations from our 2012 work which showed some evidence for rupture over a time scale that may permit some aspects of original paleoearthquake deformation to be interpreted through significant overprinting by fault creep. To minimize the risk of equivocal results we must expand our spatial analysis, while narrowing in on this temporal window which presents potential evidence for coseismic rupture. We proposed a multicomponent approach (Figure 1c) for determining if ground rupturing earthquakes have occurred along the central creeping section of the SAF and we will carry out this work during the summer of 2013.

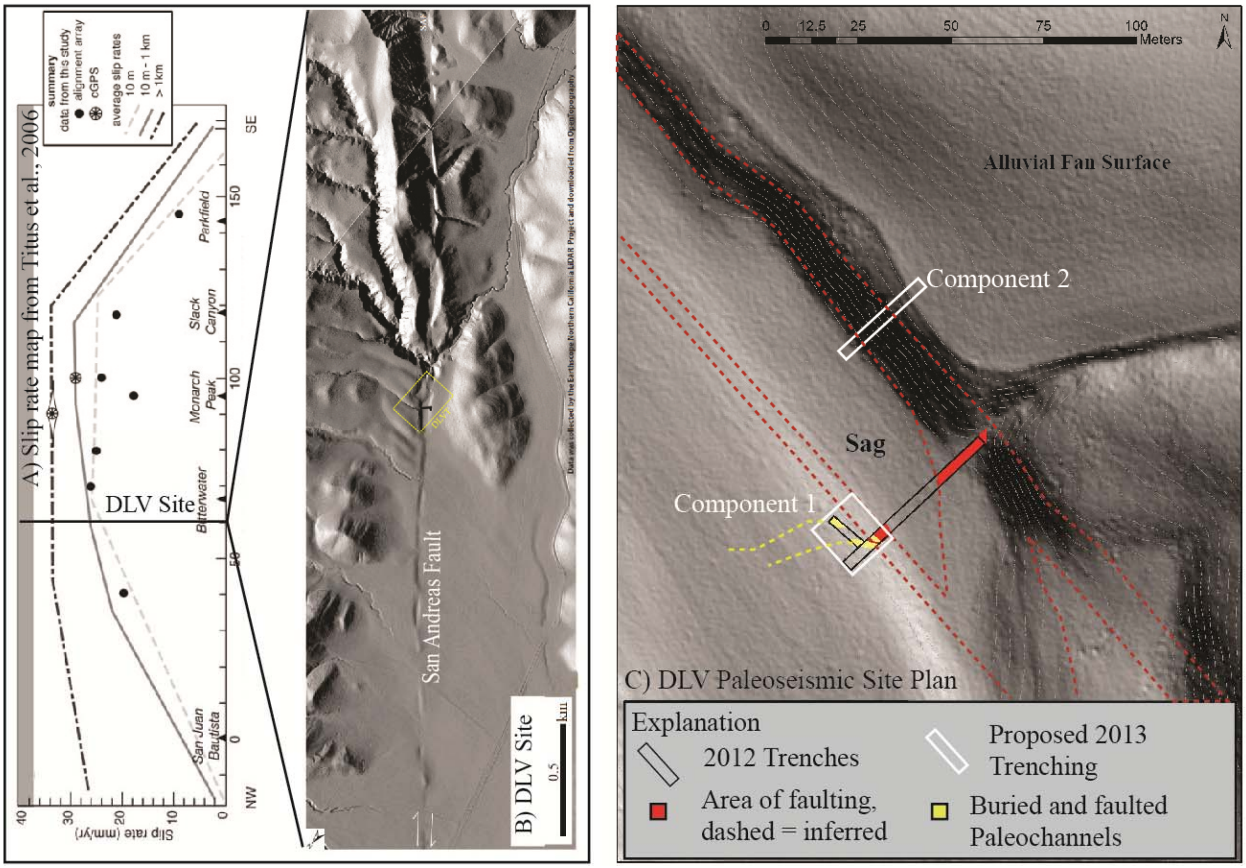

Figure 1. A) The Dry Lake Valley (DLV) paleoseismic site is located in the heart of the central creeping section of the SAF (from Titus et al., 2006). B) The site is at the SE end of the Dry Lake Valley. Here, the fault cuts through a alluvial fan complex that emanates from the hills to the NE. C) The 2012 trenching consisted of one fault-perpendicular trench across a Holocene sag depression and a fault parallel trench that was opened to locate the orientation of nearby paleochannels. The westernmost fault exposure (the portion of the 2012 trenches within the 2013 proposed trenching box; Fig. 2) revealed a fault-bounded vertical package of poorly sorted silt to boulders that may be associated with an ancient surface rupture. To improve our understanding of this stratigraphic feature we proposed Component 1: a re-excavation and extension of the western portion of the 2012 trench and Component 2: trenching investigation of the steep fault scarp to search for buried colluvial wedge deposits.

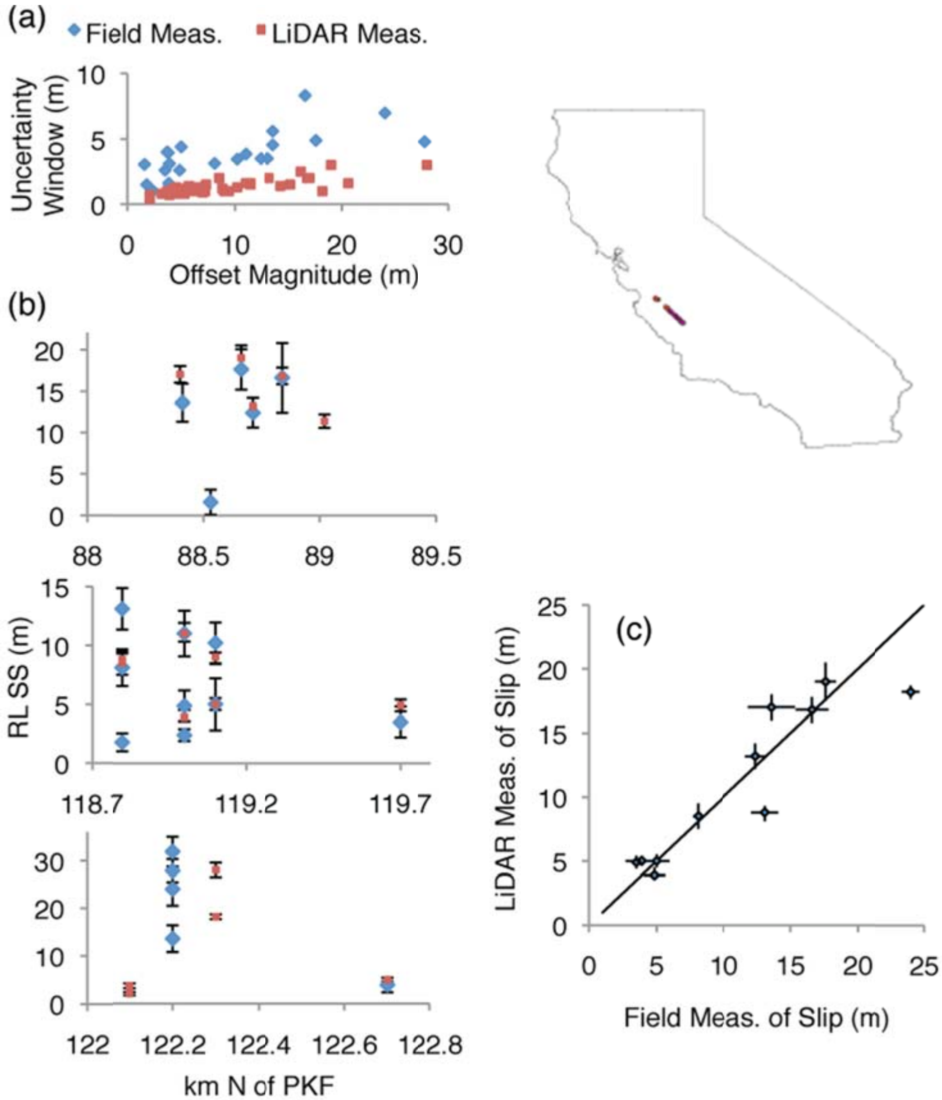

Figure 2. Comparison of field and LiDAR-based offset measurements (shown as blue diamonds and red squares, respectively) made along the creeping SAF between Parkfield and San Juan Bautista, CA for this study by J.B. Salisbury. Inset map of CA shows measurement reach. (a) Uncertainty windows (the range of possible displacements for an offset geomorphic feature) are plotted against the preferred offset of the magnitude for that feature. (b) Three subsets of the displacement measurements and their uncertainties are plotted by distance northwest of Parkfield, California along the strike of the fault. (c) One-to-one comparison of field vs. LiDAR measurements where both exist for the same geomorphic feature.

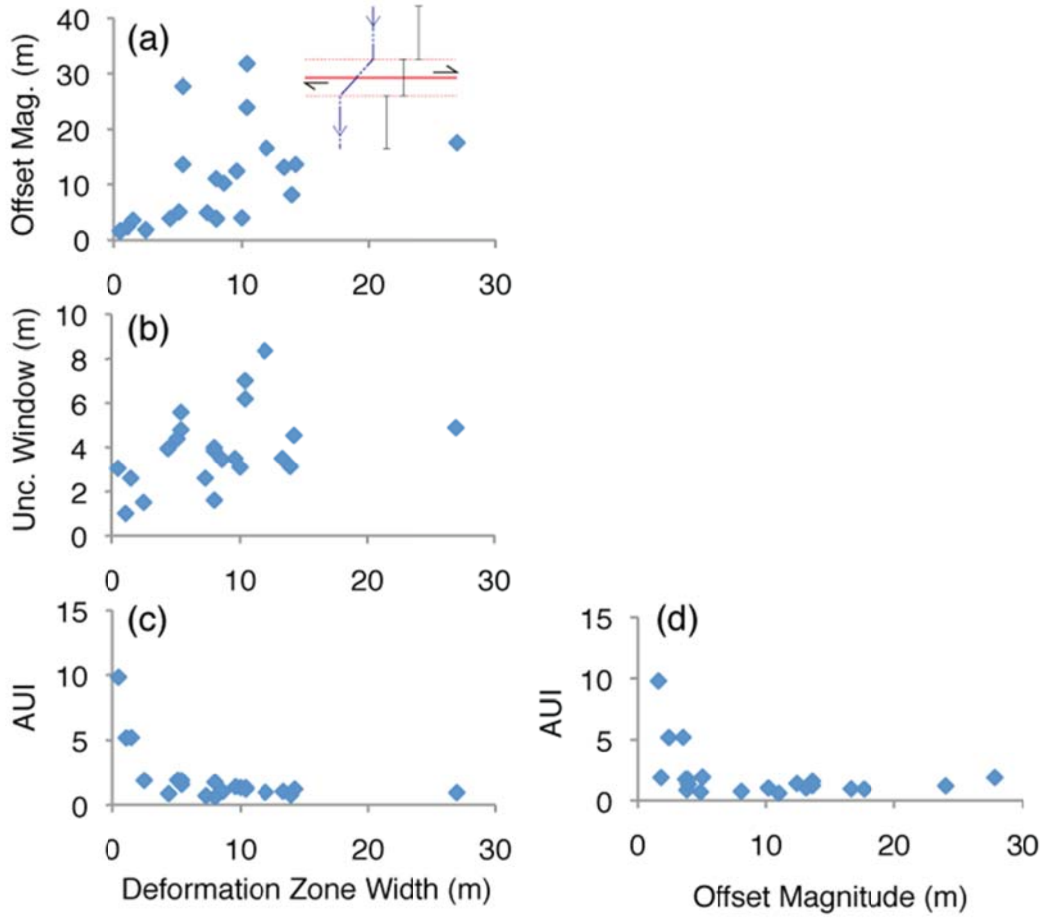

Figure 3. Summary of field-based offset measurement metrics for the creeping SAF. (a) Offset magnitude correlates positively with deformation zone width. (b) Offset uncertainty window also increases with increasing deformation zone width. For each feature visited in the field, we measure the length of the upstream and downstream channel segments, as well as the width of the perceived deformation zone – see the inset within (a). Channel segments lengths were defined using relatively straight reaches of the channel thalwegs outside of the perceived deformation zone (Figure 4) and the deformation zone was measured normal to the strike of the fault trace. We calculated an Average Uncertainty Index (AUI) as the average of the ratios between the channel segment length and deformation zone width for both the upstream and downstream channel segments. AUI is greater where the deformation zone width is smaller (c) and where the offset magnitude is smaller (d). This is probably because the length of relatively straight channel segments is limited based upon channel sinuosity, whereas deformation zone width and magnitude increase with the age of the geomorphic feature.

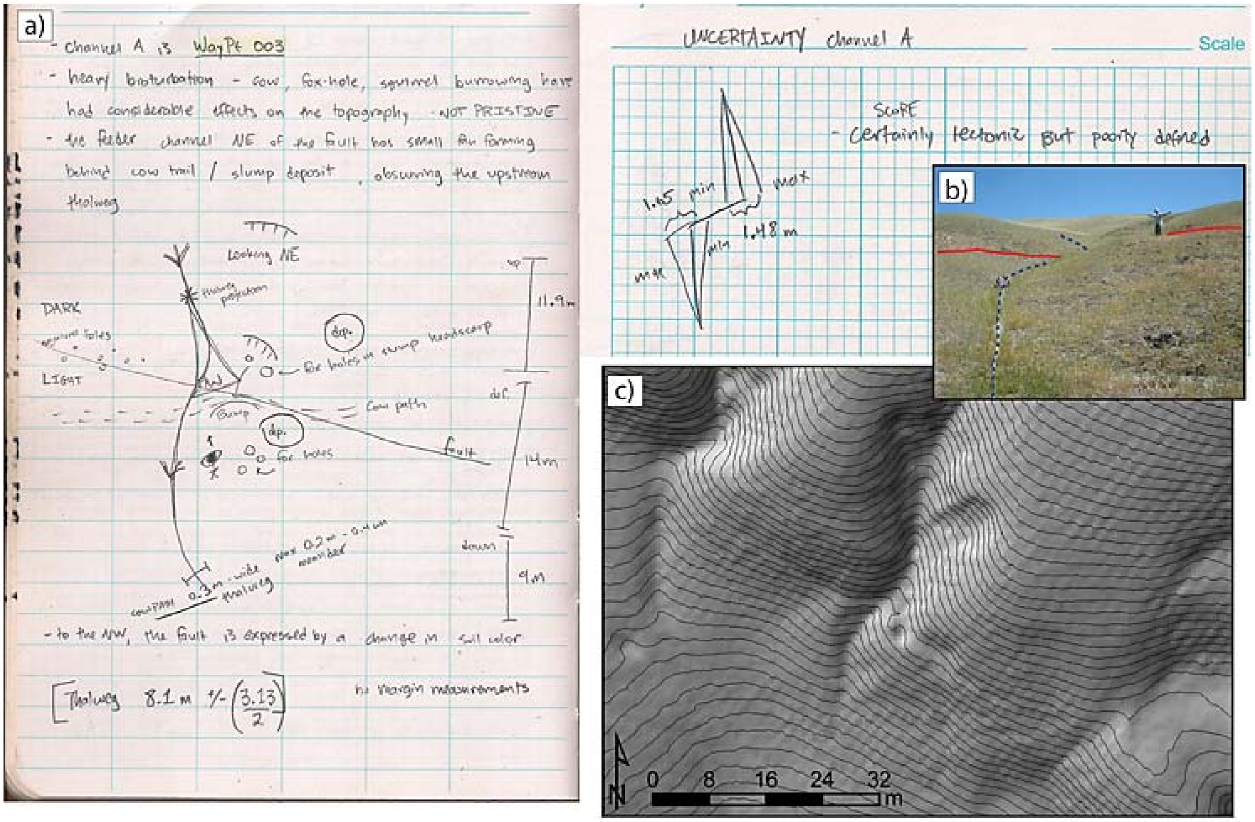

Figure 4. An example of how channel offsets were measured in the field. A) We documented channel geometry, offset length, deformation zone width, and offset uncertainty using metric tape measures. B) We performed an iterative eyeballing projection of straight channel segments into the heart of the fault zone to measure the offset piercing points and uncertainties. C) The locations of offsets were identified using LiDAR-derived hillshade maps with 0.5 meter contour lines, however measurements were not done from the maps themselves.

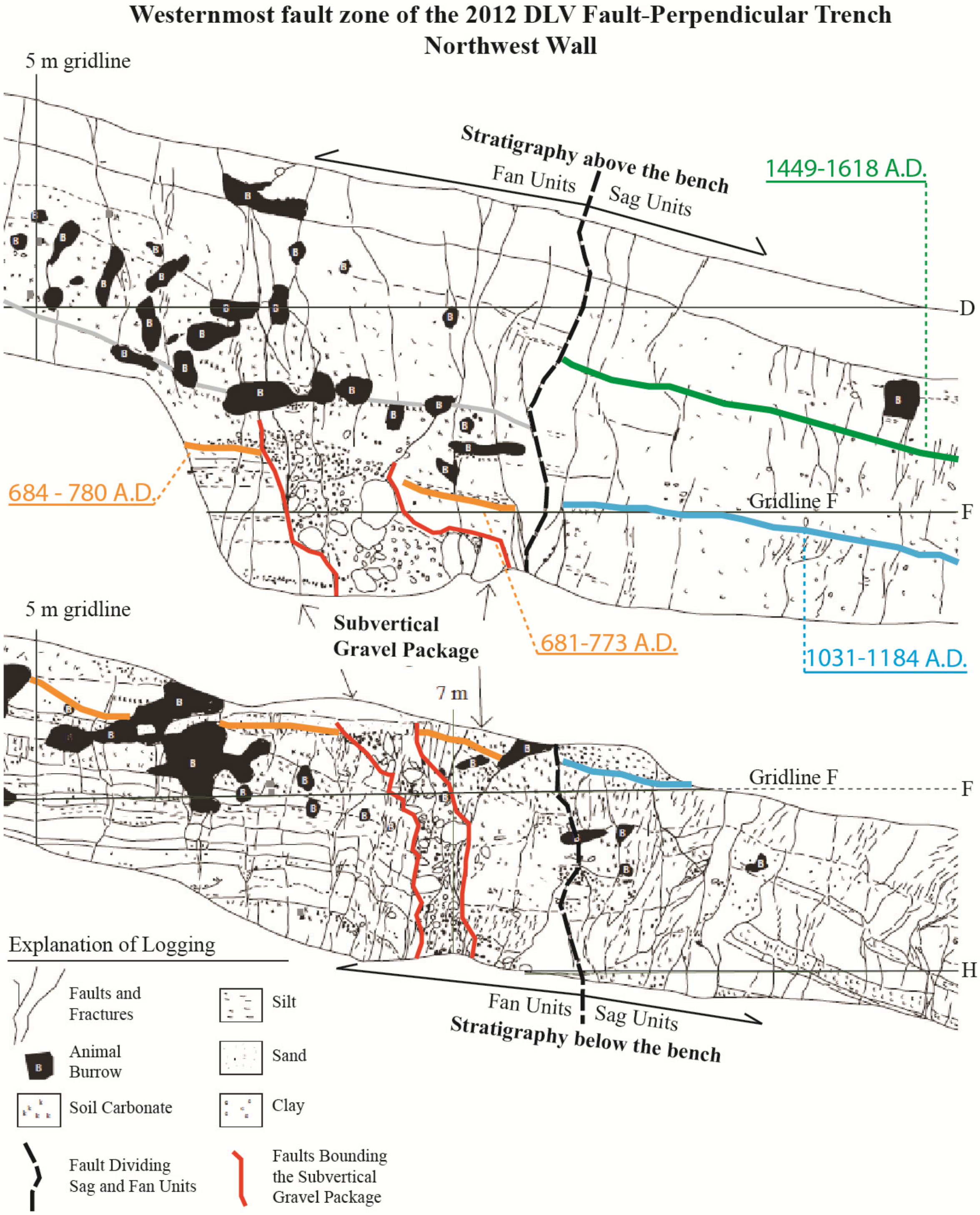

Figure 5. The northwest wall of the 2012 Dry Lake Valley trench (above and below a two meter wide bench). Calibrated radiocarbon ages (colored horizons) show that a sub-vertical gravel package, originating from a buried paleochannel (fault-parallel trench: Figure 1C), was emplaced within the fault zone between 780-1031 A.D. (~1100 years B.P). In 2013, we will slice back this trench to where the paleochannel is cut by the fault. As we do this, we will carefully document the stratigraphic and structural relationships to determine if fault zone emplacement was due to fissure infilling from coseismic rupture or shear and rotation due to aseismic creep. Minor, oblique-to-the-SAF-trend, faults and fractures were also found throughout the exposures indicating a pervasive overprinting of recent aseismic creep.

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Broader Impacts

Student Training and Mentoring:

In addition to the ongoing scientific contributions from this research, this project benefited the educational experience of two graduate students from Arizona State University and twelve undergraduates from Utah Valley University:

Arizona State University

J. Barrett Salisbury (Ph.D. Student) – *Barrett helped lead our preliminary fault strip mapping with N. Toké, paleoseismic site selection, and our effort to evaluate geomorphic offsets along the creeping section of the SAF.*

Tsurue Sato (M.S. Student) – *Tsurue led ASU's participation in the paleoseismic field season, helped rectify photomosiacs, and worked with N. Abueg to run C^{14} sample analysis at UC Irvine.*

Utah Valley University

Nicole Abueg (B.S. in Geology) – *Nicole was a paid research assistant on the project. She helped prepare field logistics, participated in the field work, and took the lead on preparing C^{14} samples for radiocarbon analyses. She took our samples to UC Irvine where she and T. Sato worked with J. Southon to obtain geochronology constraints for this work. Additionally, along with N. Toké and the other three UVU undergraduates Nicole presented in the UVU Earth Science colloquium. Nicole presented on methods the radiocarbon method and sample analysis.*

James Anderson (B.S. in Geology) – *James volunteered to participate in this project. He first participated in the project as a member of the 2012 UVU Geology field camp, but after the field camp he returned to help with paleoseismic field work. James attended the annual SCEC meeting to help present a poster on our work. Additionally, along with N. Toké and the other three UVU undergraduates James presented in the UVU Earth Science colloquium. Jim presented on methods for distinguishing between ground rupture and aseismic creep in a paleoseismic trench.*

Lawrence Kellum (B.S. in Geology) – *Larry was a paid research assistant on the project. He helped prepare field logistics, participated in field work, and attended the annual SCEC meeting to help present a poster on our work. Additionally, along with N. Toké and the other three UVU undergraduates Larry presented in the UVU Earth Science colloquium. Larry presented on methods of paleoseismic logging.*

Jeff Selck (Continuing Education in Geology) – *Jeff volunteered to participate in this project. He participated in the field work and rectifying photomosiacs following the field season. Additionally, along with N. Toké and the other three UVU students Jeff presented in the UVU Earth Science colloquium. Jeff presented on photo documentation methods.*

Utah Valley University Field Camp – *9 UVU undergraduates spent six days conducting field work at the Dry Lake Valley Paleoseismic Site. We received land owner permission for the students to do geomorphic strip mapping along a 4km stretch of the fault. They spent two days doing this mapping and 2.5 days doing industry style paleoseismic logging with a capstone trench party. The UVU Earth Science Department paid for all aspects of these students' travel expense, but this student benefit would not have been possible without the ongoing SCEC research project.*

***Scientific Presentations*:**

To date, three scientific presentations have directly resulted from this research project. They were presented at the Annual SCEC Meeting, the AGU fall meeting, and the UVU Earth Science Department Colloquium:

Toké, N. A., Abueg, N., Anderson, J., Kellum, L., Selck, J., Sato, T., Salisbury, J.B., and Arrowsmith JR., "Recognition of Paleoseismicity along Creeping Faults: Examples from the Dry Lake Valley Site on the central San Andreas" Eos Transactions, American Geophysical Union, Fall Meeting, Abstract T22C-02, San Francisco, California, December 4th, 2012.

Toké, N. A., Sato, T., Kellum, L., Abueg, N., Anderson, J., Selck, J., Salisbury, J.B., and Arrowsmith JR., "Preliminary Results from the 2012 Dry Lake Valley Paleoseismic Site on the central Creeping section of the San Andreas Fault." Annual Southern California Earthquake Center Meeting, Proceedings and Abstracts Vol. 21, Palm Springs, California, September 9-12, 2012.

UVU Earth Science Seminar Series "All Quiet on the Western Front? Tales from a trench on the creeping section of the San Andreas Fault." Presented by Nathan Toké with Larry Kellum, Nicole Abueg, Jim Anderson, and Jeff Selck on November 27th, 2012.

***Additional Logistical Support Received*:**

Utah Valley University provided significant (~$5,700) additional support to this research project:

1) The Scholarly Activities Committee Awarded all four UVU undergraduate research participants $1,000 each which helped pay for student transportation and lodging for field work.
2) In addition to the field camp expenses, the Earth Science Department paid for a month long SUV rental and gas (~$1,700) which supported travel for N. Toké, N. Abueg, and L. Kellum throughout the field season.