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Three-Dimensional Investigation of a 5 m Deflected Swale along the San Andreas Fault in the Carrizo Plain

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Abstract Topographic maps produced from Light Detection and Ranging (LiDAR) data are useful for paleoseismic and neotectonic research because they provide submeter representation of faulting-related surface features. Offset measurements of geomorphic features, made in the field or on a remotely sensed imagery, commonly assume a straight or smooth (i.e., undeflected) pre-earthquake geometry. Here, we present results from investigation of an ~20 cm deep and >5 m wide swale with a sharp bend along the San Andreas fault (SAF) at the Bidart fan site in the Carrizo Plain, California. From analysis of LiDAR topography images and field measurements, the swale was initially interpreted as a channel tectonically offset ~4.7 m. Our observations from exposures in four backhoe excavations and 25 hand-dug trenchettes show that even though a sharp bend in the swale coincides with the trace of the A.D. 1857 fault rupture, the swale formed after the 1857 earthquake and was not tectonically offset. Subtle fractures observed within a surficial gravel unit overlying the 1857 rupture trace are similar to fractures previously documented at the Phelan fan and LY4 paleoseismic sites 3 and 35 km northwest of Bidart fan, respectively. Collectively, the fractures suggest that a post-1857 moderate-magnitude earthquake caused ground cracking in the Carrizo and Cholame stretches of the SAF. Our observations emphasize the importance of excavation at key locations to validate remote and ground-based measurements, and we advocate more geomorphic characterization for each site if excavation is not possible.

Online Material: Figures of trench logs.

Introduction

Geological investigations along active faults aim to measure total slip, slip per earthquake, rupture recurrence intervals, and slip rates (e.g., Grant, 2007). These noninstrumental data, when combined with seismic and geodetic measurements, provide insight into earthquake processes, the relationship between tectonic strain accumulation and seismic strain release, and the probability of future damaging earthquakes. Despite decades of research along major continental faults, records of prehistoric earthquake slip distributions are often insufficient to allow systematic analysis of the slip and recurrence patterns of large earthquakes along individual faults. The sparseness of offset measurements is partially due to difficulty in finding and accurately measuring offset piercing lines that were unequivocally continuous

across a fault prior to an earthquake. A further challenge involves recognizing and dating the number of paleoearthquakes that contributed to each offset (Grant Ludwig *et al.*, 2010).

High-resolution topography from Light Detection and Ranging (LiDAR) has become an increasingly important tool for measurement of fault-related geomorphic features and analysis of fault offset patterns (e.g., Bevis *et al.*, 2005; Arrowsmith and Zielke, 2009; Zielke *et al.*, 2010, 2012; Klinger *et al.*, 2011; Haddad *et al.*, 2012; Salisbury *et al.*, 2012). Digital elevation models (DEMs) produced from LiDAR topographic data enable easier identification and reproducible measurement of such piercing lines along with decimeter and finer-accuracy georeferencing (Gold *et al.*, 2013). The B4 LiDAR dataset of topography along the San Andreas fault (SAF; Bevis *et al.*, 2005) is one of several LiDAR surveys along fault zones that have made it possible to rapidly and remotely study the geomorphology of an entire fault zone at a spatial resolution comparable to that of conventional field survey methods and appropriate for

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Figure 1. Location of paleoseismic sites (white rectangles) along the southern San Andreas fault (SAF) zone (solid white line). The study area located at the Bidart fan (BF) is marked with a white star. Important locations are indicated with white boxes. Shaded topography is from Shuttle Radar Topography Mission (SRTM) data (see [Data and Resources](#)). LY4, Las Yeguas; WC, Wallace Creek; PF, Phelan fan; and VMR, Van Matre Ranch.

measuring submeter scale features (e.g., [Oskin *et al.*, 2007](#); [Zielke *et al.*, 2010](#); [Salisbury *et al.*, 2012](#)).

Our study focuses on measurement of slip from the most recently reported rupture of the south-central SAF, which occurred during the Fort Tejon earthquake on 9 January 1857 (e.g., [Wood, 1955](#); [Sieh, 1978](#)). The first systematic post-earthquake measurements of slip along the 1857 rupture were made more than a century later, using air photos and on-the-ground tape measurements ([Wallace, 1968](#); [Sieh, 1978](#)). Many of the best preserved offsets are in the Carrizo Plain ([Wallace, 1968](#); [Sieh, 1978](#)), and they have been the subject of numerous studies and textbook illustrations. A few of the initial measurements by [Sieh \(1978\)](#) were later refined by topographic mapping using a total station and 3D excavation of offset channel deposits ([Grant and Sieh, 1993](#); [Liu *et al.*, 2004](#); [Liu-Zeng *et al.*, 2006](#)).

[Zielke *et al.* \(2010, 2012\)](#) systematically examined B4 topographic data along the 1857 rupture within the Carrizo Plain (Fig. 1) and reconstructed the channel offsets revealed in the topography. Using B4 LiDAR data, the observable right-lateral offset measurements attributed to the 1857 earthquake (5.3 ± 1.4 m; [Zielke *et al.*, 2010, 2012](#)) are distinctly lower than previously reported (9.0 ± 2.0 m) ground-based geomorphic offset measurements ([Sieh, 1978](#)) and excavation-based measurements of 7–8 m offsets at Wallace Creek ([Liu *et al.*, 2004](#); [Liu-Zeng *et al.*, 2006](#)) and ~7 m offsets at Phelan fan ([Grant and Sieh, 1993](#)). Differences between offset measurements made with LiDAR data and other methods, including 3D trenching, require explanation and motivate several questions. (1) Does the present day thalweg location differ from the thalweg of the original channel at the time of the earthquake because of lateral migration within a widening channel? (2) How much deflection, if any, has contributed (either adding or subtracting from the true offset) to the measured offset amount along fault strike? Many deflected

channels are easy to identify and eliminate from consideration for slip measurements, but a subtly deflected channel is difficult to identify unless the swale is excavated and traced toward and away from the fault zone of interest (e.g., [Wesnousky *et al.*, 1991](#); [Liu *et al.*, 2004](#); [Liu-Zeng *et al.*, 2006](#); [Rockwell *et al.*, 2010](#)). In this study, we address these questions through geomorphic analysis with LiDAR data and 3D excavation of a deflected swale that was not included in any previously published dataset.

Methods

We focus on a section of the SAF at the Bidart fan site in the Carrizo Plain (Fig. 1) where the earthquake chronology is well documented ([Grant and Sieh, 1994](#); [Akçiz *et al.*, 2009, 2010](#); [Grant Ludwig *et al.*, 2010](#)). In 2008, we excavated an ~100 m long fault parallel trench, BDT-9, in the Bidart fan to identify buried channels that could be excavated for a 3D study to (1) measure offset and compare with DEM-derived offset measurements, (2) connect laterally displaced stratigraphy to the well-dated earthquake record at the site, and (3) compare with the slip-per-earthquake data of [Liu *et al.* \(2004\)](#) from the Wallace Creek site (about 5 km northwest along the SAF) and Phelan fan site (Fig. 1) of [Grant and Sieh \(1993\)](#). We identified, a subtle, previously unrecognized, ~250 cm wide, ~20 cm deep swale. Further field investigations revealed that the swale centerline and its margins take a sharp right-lateral bend (~5 m) within an ~2 m wide fault zone that was mapped based on field observations and exposures in other trenches ([Grant and Sieh, 1994](#); [Akçiz *et al.*, 2009, 2010](#)). Further analysis of the B4 LiDAR data with MATLAB GUI LaDiCaoz ([Zielke and Arrowsmith, 2012](#)) initially suggested that the swale was displaced by ~4.7 m along a simple, single fault trace (Fig. 2) and initiated the reinvestigation of the displacements along the Carrizo section of the 1857 Fort Tejon rupture using the B4 LiDAR data

Figure 2. Illustrations showing LaDiCaoz (Zielke and Arrowsmith, 2012) analysis and measurement of an apparent offset channel on a 25 cm digital elevation model computed from B4 LiDAR topography (Bevis *et al.*, 2005; see [Data and Resources](#)). (a) The white box shows the area of this investigation with respect to the two tectonically offset channels at the Bidart site (Grant Ludwig *et al.*, 2010). SAF is not labeled, but it trends northwest–southeast between the two opposite facing white arrows. White triangles point to the uphill and downhill ends of the channel being investigated (BDT19 channel). (b) A close-up view shows the sharp right bend of the swale (marked by white triangles at both the uphill and downhill ends) along the SAF (thin white line) and topographic profile locations used in the LaDiCaoz analysis (thick white lines). US and DS refer to upstream and downstream, respectively. (c) The result of LaDiCaoz back-slip suggests 4.7 m of right-lateral offset. (d) Topographic profiles across the US and DS ends of swale show that it is an uncharacteristically shallow (<25 cm) and wide (~5 m) channel.

(Zielke *et al.*, 2010). Our field investigation was complete during the latest stage of the revision of the Zielke *et al.* (2010) manuscript, thus this site was not included in that publication's offset database.

In 2009, we used an excavator to dig a 25 m × 22 m box-shaped trench (BDT19) around the swale, centered on the trace of the 1857 rupture (Fig. 3). The box trench was oriented so that exposures along the ~1 m deep and 1.2 m wide trenches would be either parallel or perpendicular to the fault. Fault perpendicular trenches (BDT19a and BDT19c) were used to locate the fault zone, and fault parallel trenches (BDT19b and BDT19d) were excavated to relocate the target channel before 3D excavations were conducted. The box-channel geometry provided continuous exposure of all stratigraphy around the target channel and allowed correlation of stratigraphic units with high confidence. Following excavation, cleaning, and installation of a string grid, and digital photography, all trench walls were mapped by hand on 1:10-scale photomosaic plots. Sedimentary units were numbered for description and correlation, increasing with relative age. [Ⓔ] Full trench logs are available in Figure S1 of the electronic supplement to this article, and excerpts with key exposures are included in Figure 3. As described by Haddad

et al. (2012), these trenches and the site were further documented with terrestrial laser scanning.

Excavation of trenches with heavy equipment in the arid/semiarid Carrizo Plain generally breaks the crusty topsoil into blocks, obscuring the original deposits and eliminating the possibility of nonunique interpretation of surficial tectonic fractures. Therefore, we used hand excavation within the interior of the box trench so that we could carefully document the relationship between structure and stratigraphy of the channel deposits. A suite of 25 trenchettes (T19-1 through T19-25) about 30 cm wide and ~30 cm deep were dug with a hand shovel in the area of the channel (Figs. 3 and 4) to document the geometry of the swale, the underlying sedimentary units, and their deformation history. Each trenchette wall was photographed, and the distance from the surface to the base of the oldest swale fill unit (unit 2) was measured at 0.5 m intervals along each trenchette. For brevity, only the trenchettes with possible deformation evidence are labeled in Figures 3 and 4, and only those are discussed in the following sections. Colleagues conducted a field review (see Acknowledgments) after we examined, mapped, and analyzed the trench and trenchette exposures.

Figure 3. (a and c) Representative subsurface and (b) surface field data from the excavation site. The shaded relief map for (b) is a terrestrial-laser-scanning-generated digital elevation model (modified after Haddad *et al.*, 2012). The study area was surrounded by four conventional trenches (BDT19a–d), excavated approximately perpendicular and parallel to the fault zone. Thick black lines within the boxed area show the locations of the trenchettes. Of the 25 trenchettes that were open during the field study, only the ones with deformation evidence are labeled (except for BDT19-1). The thick dashed black line is the trace of the swale under investigation. Black-dotted areas show the extent of the gravely sheet flow. Small black triangles show the locations of fractures that either reach to the surface or intersect unit 2. The white filled triangle is where the picture in Figure 4 is taken and is pointed in the direction of the view angle. The black star shows the location of an active burrow mound, which coincides with the deflection. (a) and (c) are excerpts of trench logs showing the deformed portions of trenches BDT19a and BDT19c. (b) The entirety of the trench logs are published in Figure S1. Blank areas are either fault or bioturbation zones. Discrete faults and boundaries of fault zones are marked with thick black lines. Fractures are marked with thin black lines.

Figure 4. Field photographs from the BDT19 box excavation at Bidart fan. (a) Oblique overview field photograph showing the majority of the trenchette locations (see Fig. 3 for all locations). (b–f) Pictures of gravel sheet flow consisting of mainly ~1 cm size pebbles as exposed in the hand-dug trenchettes in the Bidart fan (Fig. 3). The white triangles show the locations of features that disrupt the gravel layer. No displacement is observed across any of these features. (b) A lensoid-shaped channel-fill deposit observed on the southwest wall of BDT19b coincides with the thalweg of the swale. Here, the channel-fill deposit is overlain by a muddy debris-flow deposit. (c) Oblique field view of T19-1 with the northeast wall of BDT19b in the background. Within 3 m of BDT19b, gravel fill of the channel (outlined in white) surfaces and the swale is constrained by the thicker gravel lobes (unit 2) on either side. The base of unit 2 is outlined in white on T19-1. (d) A possible fissure filled with unit 2 gravels (south wall of T19-2). (e) Disruption of the otherwise continuous units 2 and 3 deposits on the north wall of T19-3. (f) The same fracture observed on the south wall of T19-3. (g) Fracture observed on the north wall of T19-4, located near BDT19c. (h) Evidence of possible faulting observed on the south wall of T19-5. The lowermost triangle marks the lower contact of the vertically displaced (?) unit 2 deposits on the southwest side of the fracture. (i) White triangles mark the locations of three fractures that cut units 3 and 2 deposits on the north wall of T19-6. (Continued)

Results

Stratigraphy and Earthquake Evidence

All trenches and trenchettes exposed alluvial fan sediments with stratigraphy and sedimentary facies that are gen-

erally similar to those reported in other studies of the Bidart fan site and are dominated by silt and gravel interbeds (Grant and Sieh, 1994; Akciz *et al.*, 2009, 2010; Grant Ludwig *et al.*, 2010). Despite the similarity, it was not possible to correlate individual units exposed in the BDT19 box with units at

Figure 4. Continued.

other trench sites (note that BDT19 is more than 50 m from the other excavations at the site). Making stratigraphic correlations in alluvial fans in arid/semiarid settings is difficult due to sporadic and discontinuous sedimentation, and the

high rate of bioturbation at the Bidart fan ([Grant and Sieh, 1994](#)) has effectively erased sections of stratigraphy sporadically throughout the site. Thus, stratigraphic layers that preserve earthquake evidence in trenches BDT19a and BDT19c

cannot be correlated definitively across trenches BDT19b and BDT19d, despite continuous exposure in the box-trench configuration.

Several deposits were distinctive and could be mapped across BDT19 (Figs. 3 and E S1). We describe key sections of stratigraphy that are relevant to analyzing the structural and sedimentary history of the site. E Additional observations, including the location of largely bioturbated sections and sections without discernible channel deposits or faulting, are shown on trench logs in Figure S1.

Unit 6, a massive silty sand, is the oldest stratigraphic layer that can be correlated between trenches BDT19a and BDT19c. Unit 6 is overlain by a clast-supported gravel deposit (unit 5, on Fig. 3) with sandy interbeds. Units 5 and 6 have been deformed to create a push-up structure in BDT19c and a small depression and push-up at BDT19a (Fig. 3). At BDT19c, local uplift exposed older stratigraphic units, which contain the best evidence for the oldest earthquake preserved at these trenches. On the south wall of BDT19c, between 12 and 13 m grid marks (Fig. 3a), older units 7, 8, and 9 are exposed beneath unit 6 due to block rotation and local uplift. Near the 12 m grid mark (Fig. 3), a fissure containing fragments of unit 8 is overlain by unit 6. No other clear earthquake indicators are observed at lower stratigraphic level due to intense bioturbation and the relatively shallow depth of these trenches.

Unit 4 is a key stratigraphic marker. Subunits 4a, b, and c (Figs. 3 and E S1) are only exposed at the northeast end (upstream side) of the site. Unit 4b, consisting of silty laminae with sandy interbeds, is the only subunit that can be correlated across the site, between trenches BDT19a and BDT19c. Unit 4b is in fault contact with unit 5 gravels in both trenches (Fig. 3a,c), is underlain by a silty-sand layer (unit 4c), and overlain by an upward-fining sand-to-silt (unit 4a), exposed in BDT19a (Fig. 3c). The thickness and distribution of units 4a–c imply that they were deposited across, or ponded against, a northeast-facing scarp that formed during a pre-1857 (possibly penultimate) earthquake. On the northwest wall of BDT19a (Fig. 3c), unit 4b is pushed up ~10 cm (between the 19 and 20 m marks); and, on the southeast wall of BDT19a, unit 4a is faulted, and the lowermost section of unit 4b appears to be blocky. These observations hint that unit 4 was faulted by an additional pre-1857 earthquake, but the field relations are not conclusive and do not allow correlation with specific events reported by others (see Grant and Sieh, 1994; Akciz *et al.*, 2009, 2010).

The most important observations pertain to the most recent surface rupture, which we infer to be the 1857 earthquake because the stratigraphic position and expression of faulting mimic observations of the 1857 rupture exposed in other Bidart fan trenches (Grant and Sieh, 1994; Akciz *et al.*, 2009, 2010). At BDT19, the 1857 earthquake occurred when units 4a (at BDT19a), 4b (at BDT19c), and 5 were at or very near the surface. This most recent great earthquake deformed an ~10 m wide zone around the main fault trace, producing fissures, upward terminations, apparent vertical

offsets, scarp formation, colluvium deposition, ponded sediments, and across-fault unit thickness changes (Figs. 3 and E S1). After the earthquake, rough surface topography was buried by a muddy debris-flow deposit, mapped as unit 3 (Figs. 3a,c, and E S1). Unit 3 appears to be bioturbated in exposures from BDT19c, but it is preserved as an intact unit within an ~0.5 m depression exposed in BDT19a (Fig. 3c). Unit 3 is discontinuously overlain by unit 2, which we informally describe as pea gravel. Unit 2 is a distinctive thin (<40 cm thick) sheet flow deposit consisting of unconsolidated, well-sorted, matrix-poor gravels (>90% of pebbles with a diameter of 2–3 cm) with a homogeneous pebble lithology (argillaceous shale, largely derived from the Tertiary Monterey shale which dominates the watershed). As shown by photographs in Figure 4, the distinctive pea gravels of unit 2 were easily mappable at the ground surface, where it appears to be a sheetflow deposit (Fig. 3), in the trenches and throughout the trenchettes. Unit 1 is a massive debris-flow deposit that covers much of the surface of the Bidart fan (Grant and Sieh, 1994; Akciz *et al.*, 2010).

Swale Geometry and Deformation Evidence

Trenches BDT19b and BDT19d expose the relationship between the swale morphology and underlying stratigraphy. Exposures in BDT19b show that the northeast head of the surficial channel coincides with a lensoid-shaped (10 cm thick, ~1 m wide) deposit of unconsolidated pea gravel from unit 2, a few centimeters below the ground surface (see Figs. 4b and E S1). Approximately 3 m southwest of BDT19b, the pea gravel of unit 2 is exposed at the ground surface, as shown in Figure 4c, and the distinctive pea gravel is exposed within the swale to the southwest toward the fault zone.

Exposures in trenchettes allowed us to map the location, thickness, and fabric of the unit 2 pea gravel. The bottom of unit 2 is nearly planar, but its thickness varies by ~15 cm locally (Fig. 4c). Trenchette T19-1 (Fig. 4a and c) provided the best exposure of the swale geometry within the box-trenched area. Figure 3 shows the thickest part of unit 2 (dot-filled enclosed area within the boxed trench), which forms gentle mounds at the ground surface. Excavation revealed depositional fabric in unit 2 and showed that the deposit contains an ~20 cm lower swale between finger-like depositional lobes. The swale and lobes are aligned in the downslope direction. We conclude that they formed during deposition of unit 2.

We excavated trenchettes T19-2 and T19-3 along the trend of the 1857 rupture trace, projected from BDT19a and BDT19c (Figs. 3 and 4) to examine tectonic deformation of unit 2. Surprisingly, we did not find measurable change in unit thickness or any discernible shear fabric. These observations preclude significant faulting of unit 2 by the underlying main trace of the SAF. However, trenchette T19-2 shows evidence for a fissure or a burrow that was later filled (Fig. 4d). This feature is not expressed on the other side of the trenchette, or in adjacent trenchettes, and there is no corroborating evidence of tectonic displacement. Minor

fracturing was observed on both sides of Trenchette T19-3 (Fig. 4e and f), but no thickness changes or pebble realignments were observed adjacent to the fracture.

Eighteen additional trenchettes were opened along the trace of the 1857 rupture zone where the swale abruptly bends. The bend is visible at the ground surface and on LiDAR images (Fig. 2). We found minimal evidence of tectonic disruption in unit 2. At T19-4, near the southeast wall of BDT19c, an ~10 cm thick gravel unit terminates at a fracture (Fig. 4g). This observation was not repeated on the opposite wall of the same trench (less than 20 cm apart) or at nearby trenchettes. The termination could be a fault contact with minor displacement or a fracture opening at the depositional terminus of the gravel deposit. Similarly, at the southeast wall of trenchette T19-5, an ~10 cm thick unit 2 deposit is vertically separated by ~4 cm near its depositional terminus (Fig. 4h). West of this structure, unit 2 thins and is overlain by a muddy debris-flow deposit (unit 1). No evidence of fracturing or vertical offset was observed on the northwest wall of trenchette T19-5. At the north wall of trenchette T19-6, three fractures were observed within a 30 cm wide zone (Fig. 4i). No unit thickness changes or pebble realignments were observed. Only one of the fractures continued to the south wall of the trenchette.

Exposures in all 4 trenches and 25 trenchettes revealed that the swale is a depositional feature that formed after the most recent major faulting event, presumed to be the 1857 Fort Tejon earthquake. The flow that carried the pea gravels of unit 2 was partially impeded by the 1857 fault scarp and deposited some gravel against the scarp, as revealed in BDT19a. The flow had sufficient energy to go around (i.e., be deflected by) the scarp, thereby creating the appearance of an offset channel. Because the swale was so wide and shallow, it could not be identified as a deflection without subsurface information on the stratigraphy and structure of the site. Minor fractures within unit 2 do not appear to be part of the major underlying fault structures.

Discussion

Our results show that the swale we investigated is not tectonically offset. This unexpected finding emphasizes the importance of confirming remotely measured offsets and interpretations, especially if such indirect measurements will be used for documenting slip distribution during prehistoric earthquakes or for characterizing seismic hazard (see also Schärer *et al.*, 2014). We excavated a swale that could potentially have provided a high-quality offset data point with 4.7 m of slip measured using LaDiCaoz MATLAB GUI (Zielke and Arrowsmith, 2012). Ground-based measurement of the channel offset yield similar results. The initial focus of our investigation was to confirm the ~4.7 m slip and/or correct for any pre-earthquake deflections by following the upstream end of the buried channel thalweg into the fault zone and out through the downstream end. This method has been successfully applied to investigation of channels

at numerous locations (e.g., Wesnousky *et al.*, 1991; Grant and Sieh, 1993; Liu *et al.*, 2004; Liu-Zeng *et al.*, 2006; Rockwell *et al.*, 2010).

Based on our findings, we recommend confirmation of remotely measured offsets where possible. Ideally, confirmation should consist of two components: (a) age determinations of features that are interpreted to be offset, and (b) subsurface documentation of displacements of actual piercing lines (e.g., buried thalweg, channel margin). Determining the relative or absolute age of piercing lines, with respect to known earthquake ages, is critical to determine if cumulative offset measurements can be uniquely interpreted. For example, our study shows that the channel we investigated formed after the most recent large surface-rupturing earthquake. If ages of confirmed-offset channels can be determined, they can be compared to known earthquake ages, and more robust slip-per-earthquake or slip-per-multiple-earthquake interpretations can be made.

Using LiDAR topographic data and LaDiCaoz MATLAB GUI (Zielke and Arrowsmith, 2012) to measure offset channels, Zielke *et al.* (2010, 2012) reported >40 displacement measurements across the Carrizo Plain and used these as the basis for a hypothesis that surface rupture along the Carrizo section of the SAF during the 1857 Fort Tejon earthquake was 5.3 ± 1.4 m. The channel described herein was specifically eliminated from Zielke *et al.* (2010) dataset because of concern that the swale was too shallow and wide to provide a representative measurement and because the field work in which this article is based was underway and our conclusion that the swale was not offset was becoming clear. In contrast, many channels measured and reported by Zielke *et al.* (2010) are moderately to deeply incised and are unlikely to be deflected. Zielke *et al.* (2010) also measured channels at Bidart fan, Phelan fan, Wallace Creek, and Van Matre Ranch (Grant and Sieh, 1994; Liu-Zeng *et al.*, 2006; Noriega *et al.*, 2006; Grant Ludwig *et al.*, 2010), which had previously been excavated and were unequivocally offset by faulting. The total number of measurements (>40), including confirmed and unconfirmed tectonic offsets, is sufficient to conclude that the Zielke *et al.* (2010) dataset is representative of tectonic slip, although we cannot rule out the possibility that one or more deflections were not recognized.

The vertical cracks observed in unit 2 might have formed tectonically. The location and orientation of the fractures is shown in Figure 3. Orientation and distribution of the fractures is consistent with the orientation and location of the underlying main trace of the SAF. The larger number of fractures observed in BDT19a and BDT19c is likely due to effects of excavation equipment, which may have overprinted or opened tectonic fractures near the surface. Similar fractures were reported at the LY4 (Young *et al.*, 2002) and Phelan fan (Grant and Sieh, 1993) sites (Fig. 1). At each site, the fractures are generally oriented parallel or en echelon along the fault zone, with less than a few centimeters of opening. The LY4 fractures were hand excavated in a horizontal exposure and their pattern was consistent with a few centimeters of

SAF parallel shearing (and not with excavation; Young *et al.*, 2002). The source of LY4 fractures, and their age, remains enigmatic. At the Phelan fan site, Grant and Sieh (1993) documented a single fracture terminating within a near-surface (top of unit within 10 cm of the surface) muddy debris-flow deposit unit (Qf2). Because of the lack of observable offset, creep, postdepositional settling, or desiccation were proposed as possible explanations. If the fractures at LY4 and Phelan fan are indeed contemporaneous with those described here from the Bidart fan site, together they would indicate at least a 34 km length of post-1857 ground cracking along the SAF. If they were generated seismically, they would be consistent with an M 5.5–6 event (based on the rupture length), with only minor surface displacements (Wells and Coppersmith, 1994). A post-1857 Parkfield earthquake, such as occurred in 1877 or 1881 (Young *et al.*, 2002), could cause centimeter-scale surface fracturing, as proposed by Topozada *et al.* (2002). Creep, possibly manifested as afterslip of one of the late nineteenth century Parkfield earthquakes, is also an intriguing possibility for the formation of the fractures. No creep has been observed along the Cholame–Carrizo section of the SAF since at least the late 1960s (Brown and Wallace, 1968; Burford and Harsh, 1980).

Conclusions

We excavated a four-sided box trench and 25 hand-dug trenchettes to determine if a wide and shallow swale with a right-bend along the SAF was tectonically offset by the 1857 Fort Tejon earthquake in the Carrizo Plain. Our data indicate that the swale near the fault zone is surficial and probably formed contemporaneous with deposition of a gravelly sheet flow. Exposures show that the sheet flow was deposited after the 1857 earthquake, and therefore the bend is probably the result of deflection along the 1857 fault scarp, rather than tectonic offset. Subtle fractures with the deflected channel, and their similarity to post-1857 fractures documented at other sites, suggests that they formed in a previously unrecognized post-1857 slip event or moderate-magnitude earthquake.

The increasing availability of remotely sensed topographic data such as DEMs derived from LiDAR, and the ease of rapidly gathering offset measurements from these datasets, make them increasingly popular for tectonic geomorphic studies and analysis of preinstrumental or prehistoric fault slip. Our findings warrant caution in interpreting these datasets. Care should be taken to eliminate possible deflections, and results at key sites should be verified by excavation. Channels and swales represent complex markers for offset given the erosional and depositional sensitivity to pre-existing topography and variably resistant-to-erosion materials along the fault zone, which can promote deflection. We recognize that high-resolution topography provides a valuable opportunity to measure many features easily, yet the epistemic certainty that they are tectonically offset is lessened without 3D excavation (see also Schärer *et al.*, 2014). We

advocate more thorough geomorphic characterization for each site, if excavation is not possible.

Data and Resources

All field data used in this article were collected during the summer of 2009. The B4 LiDAR Project (<http://www.earthsciences.osu.edu/b4>; last accessed October 2011) collected the LiDAR Point Cloud data along the southern San Andreas and San Jacinto faults. The B4 data are available for download from www.opentopography.org (last accessed October 2011). Shaded topography basemap on Figure 1 is from Shuttle Radar Topography Mission (SRTM) data (<http://srtm.csi.cgiar.org>; last accessed October 2011).

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