The Age and Origin of Small Offsets at Van Matre Ranch along the San Andreas Fault in the Carrizo Plain, California

by J. Barrett Salisbury,* J Ramón Arrowsmith, Nathan Brown, Thomas Rockwell, Sinan Akciz, and Lisa Grant Ludwig

Abstract To better understand the relationship between geomorphology and fault slip, we investigated the origins of topographic depressions previously interpreted as beheaded channels representing small offsets at Van Matre Ranch (VMR) along the San Andreas fault, Carrizo Plain, California. We excavated four fault-parallel trenches (T1–T4) across depressions and sampled for single-grain postinfrared infrared-stimulated luminescence (p-IR IRSL) age estimates of channel fill. Only T2 sediments are young enough (0.38 ± 0.06 ka) to be associated with a nearby drainage (sourced ∼12 m southeast [SE]), providing a short-term slip rate of 31.6 ± 9/−6.6 mm/yr. The age of the T2 channel fill falls within the uncertainty ranges of the penultimate through fourth event back as dated at Bidart Fan ∼12 km northwest (NW). Hand-excavated exposures at nearby T1 indicate that the T2 channel sediments have experienced at least two earthquake events and that the T1 beheaded gully is a fosse between two small offset alluvial fans (∼10 m radius). Reconstructing the alluvial fan apex shows that offset at this location in the 1857 $M_w$ 7.8 Fort Tejon earthquake was ∼4 m. Therefore, offset in the penultimate earthquake is < ∼8 m at the VMR site because we cannot discount that T2 channel sediments experienced four earthquakes. Interestingly, buried channel ages are older at other trenches (4.26–8.12 ka), indicating distant, larger drainage basin sources SE of the study area. Our results indicate that for the Carrizo Plain, (a) there may be appreciable high-frequency variation in paleoearthquake offset along strike and in successive earthquakes at a point; (b) beheaded topographic depressions on the downstream side of the fault have the potential to, but do not necessarily, capture drainage basins on the upstream side of the fault with continued slip; and (c) small catchments may not produce channel landforms or deposits as frequently as has been suggested.

Introduction

It is crucial to investigate geomorphic processes and landform evolution along active fault zones at the 100-yr timescale to refine estimates of slip in successive earthquakes at a point. Remote studies of active fault zones around the world are accelerating thanks to new and affordable high-resolution topographic data. Photogrammetric approaches have quickly found appropriate niches alongside light detection and ranging (lidar) and other remote-sensing-based techniques for generating submeter elevation models (Gao et al., 2017; Gruetzner et al., 2017). However, as remote fault studies expand into a greater range of climates and biomes, it is increasingly important that ground-based studies advance parallel to remote assessments. Subsurface sedimentary investigations and absolute age control are necessary for detailed understanding of geomorphic processes—an understanding that directly affects the interpretation of fault-related geomorphic features represented in high-resolution topographic maps.

To this end, we explore young depositional ages for channel sediments using a relatively new technique—single-grain postinfrared infrared-stimulated luminescence (p-IR IRSL) dating—to refine our understanding of the interplay between tectonic and fluvial processes in a semiarid landscape. We apply our results to a relatively well-understood section of the San Andreas fault (SAF) to refine the short-term slip history at Van Matre Ranch (VMR), in the Carrizo Plain, California.

Small-scale (less than tens of meters) fault-offset fluvial landforms are commonly cited in slip-per-event studies as
indicators of slip magnitude for earthquakes (e.g., Zielke et al., 2010, 2012, 2015). Although it has long been assumed that even small-scale drainages in semiarid settings generate fluvial markers more frequently than the earthquakes that offset them (e.g., Wallace, 1968; Sieh, 1978; Sieh and Jahns, 1984; Lindvall et al., 1989; McGill and Sieh, 1991; Zielke et al., 2010, 2012; Klinger et al., 2011; Salisbury et al., 2012; Madden et al., 2013), these offsets (<10s of m) are rarely dated, potentially making attribution of slip to dated earthquakes tenuous (Grant and Sieh, 1993; Grant Ludwig et al., 2010; Akciz et al., 2014). Improved understanding of the relative frequency of geomorphic marker (e.g., rill, gully, or levee) formation versus marker displacement is key for understanding the fault-offset accumulation patterns used to inform models of earthquake recurrence (e.g., Field et al., 2014).

In this project, we excavated and dated four subtle topographic depressions previously interpreted as ~10 m offset (beheaded) gullies (Sieh, 1978) at VMR along the SAF to understand the creation and preservation of topographic channel forms and resulting cut/fill sequences in the southeastern Carrizo Plain, California (Figs. 1 and 2). We test the hypotheses that (1) depressions seemingly offset from nearby feeders are not only sourced from the nearby feeders but also contain channel sediments that are progressively and predictably older with greater offset from their inferred nearby sources; and (2) dating their incision ages should reveal the number of earthquakes that the beheaded gullies have experienced (provided we have the earthquake chronology for the same time period). We refine the short-term slip rate, evaluate slip in the most recent event, combine these results with recent earthquake timing (from an existing nearby paleoseismic site at Bidart Fan) to speculate about slip in older events, and synthesize a better understanding of the geomorphic controls of subtle, small-scale fault-zone topography in the southeastern Carrizo Plain.

Background

The Carrizo Plain section of the SAF, located between Parkfield and Big Bend, has a relatively simple geometry, the highest slip rate in California (3.39 ± 0.29 to 3.58 ± 0.54/−0.41 cm/yr, Sieh and Jahns, 1984; 3.59 ± 0.05 cm/yr, Meade and Hager, 2005; 2.93–3.56 cm/yr, Noriega et al., 2006; 3.6 ± 0.2/−0.15 cm/yr, Schmalzle et al., 2006), and ruptured historically in the Mw 7.8 Fort Tejon earthquake of

Figure 1. (a) Inset map of California showing major faults of the San Andreas system with the ∼350 km 1857 rupture. The reach of the Carrizo Plain shown in (a) is denoted by the small rectangle superposed on the 1857 rupture trace. Main image is B4 light detection and ranging (lidar) hillshade with semitransparent digital elevation model (DEM) overlay for Van Matre Ranch. The arrow northwest (NW) of the study area (pointing northeast [NE]) highlights the 28 m offset channel that was the focus of Noriega et al. (2006). PKF, Parkfield reach; BB, The Big Bend reach. (b) B4 lidar hillshade showing locations of main excavations and associated drainage basins as well as neighboring basins to the southeast (SE; shaded by catchment-average gradient). Drainage basin areas and gradients are shown at top right. The color version of this figure is available only in the electronic edition.
1857 (Fig. 1). Early models of earthquake recurrence for this stretch of the SAF were simple, which suggests that repeated, large events at longer time intervals dominated the earthquake record (Schwartz and Coppersmith, 1984; Sieh and Jahns, 1984; Grant and Sieh, 1994; Liu et al., 2004; Liu-Zeng et al., 2006; Zielke et al., 2010), although some evidence suggests that smaller slip events occurred (Grant and Sieh, 1993). For example, excavations of stream offsets and beheaded channels by Liu-Zeng et al. (2006) near Wallace Creek revealed that as many as four of the last six events ruptured with >5 m of slip, implying not strictly uniform rupture behavior. Excavation of buried channels at Phelan Fan suggested that larger surficial offsets were generated by multiple slip events (Grant and Sieh, 1993). Similarly, Zielke et al. (2010, 2012) use high-resolution topographic data to suggest that average slip in 1857 was ~5 m, and that some other older large earthquakes may have similar magnitudes of slip.

We can accurately measure the surface expression of small-scale offset landforms (Salisbury et al., 2015; Zielke et al., 2015) but it is important to note that the surficial geomorphic record will be dominated by the largest event offsets. It is possible that discrete evidence of the smallest events (e.g., <1 m, from smaller earthquakes or the tail ends of ruptures) will be lost at the surface (and lost in cumulative offset probability stacks; e.g., Zielke et al., 2015) and only preserved in the paleoseismic record (e.g., Akciz et al., 2010; Zielke et al., 2010, 2012, 2015). In a paleoseismic and paleoflood correlation study, Grant Ludwig et al. (2010) suggested variable slip (0.5–5.9 m) for the last five ruptures at the nearby Bidart Fan (Fig. 1).

Continued investigations in the Carrizo Plain with improved geochronologic techniques have refined the paleoseismic earthquake catalog and shown evidence that the average recurrence of earthquakes along the SAF could be as frequent as 99 ± 46 yrs (includes current open interval; Akciz et al., 2010) instead of the >200-yr recurrence proposed by Sieh and Jahns (1984). The Uniform California Earthquake Rupture Forecast, version 3 (UCERF3) calculates a maximum-likelihood recurrence for the Carrizo Plain segment of the SAF (at Bidart Fan) at 115 yrs (86–154 yrs, 16%–84% bounds; Field et al., 2014). If we assume a perfect correspondence between successive paleoseismic events and discrete offsets identified at the surface or in the shallow subsurface, then coupling the conservative recurrence rate proposed by Akciz et al. (2010) with cumulative offsets from Liu-Zeng et al. (2006) or Zielke et al. (2010) implies slip rates as high as ~60 and ~50 mm/yr, respectively, both of which greatly exceed the ~33 mm/yr rate measured from millennial-scale offset landforms (Sieh and Jahns, 1984) and geodesy (Meade and Hager, 2005; Schmalzle et al., 2006).

This mismatch between inferred slip rates, recurrence intervals, and slip per event suggests that recurrence timing and moment distribution are significantly more variable than originally thought (Weldon et al., 2004; Dawson, 2013; Madden et al., 2013; Field et al., 2014; Rockwell et al., 2014; Scharer, Weldon, et al., 2014). In the Carrizo Plain, therefore, it is incorrect to assume a perfect correspondence between the earthquakes preserved in subsurface sediments and the earthquakes preserved in the geomorphic record (as suggested by Akciz et al., 2010, 2014; Grant Ludwig et al., 2010). Reconciliation of these discrepancies between measurable fault parameters is crucial for proper hazard characterization based on analysis of geomorphic offset measurements. We must explore the possibility that slip in individual earthquakes may be overall smaller or significantly more variable than previously estimated. We combine investigation of the geomorphic evolution of small-scale fault-offset features and single-grain p-IR IRSL dating of K-feldspar grains to test the linkage of geomorphic offsets to dated paleoearthquakes.

We focused on the VMR reach of the Carrizo Plain where the SAF is well expressed and preserves several closely spaced topographic depressions, previously interpreted as beheaded gullies (Figs. 1–3) (Sieh, 1978). At VMR, several catchments (~1500–3000 m²) northeast (NE) of the SAF drain to the southwest (SW) and are truncated by the well-expressed SAF. There, groups of displaced offset features, noted by Wallace (1968) and investigated by Sieh (1978), have been attributed to displacement in successive earthquakes (Figs. 1–3). These earthquakes are radiocarbon dated at the nearby Bidart Fan, ~12 km to the northwest.
Prior to the 1857 Fort Tejon (MW 7.8) earthquake, the most recent ground-rupturing events, expressed as 2σ ranges, occurred in A.D. 1631–1823, 1580–1640, 1510–1612, 1450–1475, and 1360–1452 (Akciz et al., 2010). The last four events (including the historic 1857 rupture) from Bidart Fan are shown in Figure 4.

At VMR, Sieh (1978) identified and measured several topographic depressions to estimate slip magnitudes for the 1857 Fort Tejon earthquake (Fig. 3). Some of these features were remeasured by Zielke et al. (2010, 2012) with the B4 light detection and ranging (lidar) data (Bevis et al., 2005). The topographic depressions, interpreted to represent fluvial channels, are offset ∼8 to ∼12 m (Fig. 3). Noriega et al. (2006) investigated a 28-m offset channel nearby and dated the timing of initial incision (using detrital charcoal samples from within the channel fill) at A.D. 1160, inferring a 29.3–35.6 mm/yr slip rate for the site (Fig. 1a). Considering the foundation of work conducted there (and the nearby paleoseismic record at Bidard Fan), VMR is an excellent natural laboratory to directly test whether we can use chronometric approaches to date short-lived ephemeral fluvial features.

Methods

We targeted four subtle topographic depressions previously interpreted as beheaded channels offset ∼10 m from feeder channels. Prior to excavation, we used low-altitude balloon aerial photographs to construct a 3 cm digital elevation model for the 1857 Fort Tejon earthquake (Fig. 3). Some of these features were remeasured by Zielke et al. (2010, 2012) with the B4 light detection and ranging (lidar) data (Bevis et al., 2005). The topographic depressions, interpreted to represent fluvial channels, are offset ∼8 to ∼12 m (Fig. 3). Noriega et al. (2006) investigated a 28-m offset channel nearby and dated the timing of initial incision (using detrital charcoal samples from within the channel fill) at A.D. 1160, inferring a 29.3–35.6 mm/yr slip rate for the site (Fig. 1a). Considering the foundation of work conducted there (and the nearby paleoseismic record at Bidard Fan), VMR is an excellent natural laboratory to directly test whether we can use chronometric approaches to date short-lived ephemeral fluvial features.
control points used in our structure from motion models. We collected 19 sediment samples from within channel fill deposits for p-IR IRSL analysis of single-grain potassium-feldspar crystals at the Department of Earth, Planetary, and Space Sciences at the University of California, Los Angeles. We analyzed 15 of these samples, the results of which are tabulated in Table 1. We were unable to find any radiocarbon contents of this sediment from each sample tube.

Post-IR IRSL Dating Methods

Sample Preparation, Instrumentation, and Environmental Dose-Rate Determination. In southern California, quartz crystals generally have notoriously low optically stimulated luminescence (OSL) sensitivity (Lawson et al., 2012). For all samples, we instead isolated K-feldspar grains under dim amber lighting conditions. We wet-sieved samples to isolate the 175–200 μm size fraction and treated with 3% HCl to dissolve carbonates and iron oxides. We separated grains by density within lithium metatungstate (measured density 2.565 g/cm³) to isolate the most potassium-rich portion of feldspar grains (Rhodes, 2015). We washed grains in hydrofluoric acid for 10 min to remove the grain surface and increase brightness, and lastly we dry-sieved to remove grains etched below a diameter of 175 μm. We mounted samples on aluminum single-grain discs for analysis in a TL-DA-20 Risø automated reader equipped with a single-grain IR laser, and detected emissions with a Schott BG3-BG39 filter combination.

We used a portable NaI gamma spectrometer to determine the in situ gamma dose-rate contribution for all samples except J1055, which was within 22 cm of J1054; we applied the J1054 gamma dose-rate measurement to both samples (Table 1). For the beta dose-rate, we employed inductively coupled plasma mass spectrometry to estimate the U and Th contents, and inductively coupled optical emission spectrometry to determine the K content. We converted compositional values to annual dose-rates using the conversion factors of Adamiec and Aitken (1998). We derived the internal dose-rate contribution from an assumed feldspar potassium content of 12.5 ± 0.12 wt% (Huntley and Baril, 1997) and measured the water content by oven drying a portion of sediment from each sample tube.

Equivalent Dose Determination. We measured the luminescence responses of samples with a p-IR IRSL protocol (Table 2). Until recently, luminescence dating of sedimentary

<table>
<thead>
<tr>
<th>Lab Code</th>
<th>Field Code</th>
<th>Depth (m)</th>
<th>K (%)</th>
<th>Th (ppm)</th>
<th>U (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1054 CP15-01</td>
<td>2.00</td>
<td>2.4</td>
<td>7.0</td>
<td>2.69</td>
<td>1.2300 ± 0.0040</td>
</tr>
<tr>
<td>J1055 CP15-02</td>
<td>2.10</td>
<td>5.1</td>
<td>2.12</td>
<td>Same as J1054</td>
<td>4.50 ± 0.31</td>
</tr>
<tr>
<td>J1056 CP15-03</td>
<td>2.20</td>
<td>3.9</td>
<td>5.4</td>
<td>2.41</td>
<td>1.8486 ± 0.0058</td>
</tr>
<tr>
<td>J1058 CP15-05</td>
<td>2.20</td>
<td>3.4</td>
<td>5.5</td>
<td>2.41</td>
<td>1.3429 ± 0.0044</td>
</tr>
<tr>
<td>J1061 CP15-08</td>
<td>2.57</td>
<td>7.3</td>
<td>3.11</td>
<td>1.3584 ± 0.0043</td>
<td>4.32 ± 0.24</td>
</tr>
<tr>
<td>J1062 CP15-09</td>
<td>2.10</td>
<td>5.8</td>
<td>3.8</td>
<td>1.4072 ± 0.0045</td>
<td>4.37 ± 0.24</td>
</tr>
<tr>
<td>J1063 CP15-10</td>
<td>2.00</td>
<td>2.9</td>
<td>6.5</td>
<td>1.4978 ± 0.0047</td>
<td>4.66 ± 0.29</td>
</tr>
<tr>
<td>J1064 CP15-11</td>
<td>2.00</td>
<td>5.4</td>
<td>2.11</td>
<td>1.4153 ± 0.0045</td>
<td>4.49 ± 0.28</td>
</tr>
<tr>
<td>J1065 CP15-12</td>
<td>2.00</td>
<td>2.7</td>
<td>5.2</td>
<td>1.5860 ± 0.0048</td>
<td>5.18 ± 0.35</td>
</tr>
<tr>
<td>J1066 CP15-13</td>
<td>2.00</td>
<td>6.6</td>
<td>2.20</td>
<td>1.5301 ± 0.0048</td>
<td>4.68 ± 0.28</td>
</tr>
<tr>
<td>J1067 CP15-14</td>
<td>2.00</td>
<td>6.0</td>
<td>1.80</td>
<td>1.5338 ± 0.0046</td>
<td>4.83 ± 0.31</td>
</tr>
<tr>
<td>J1068 CP15-15</td>
<td>2.00</td>
<td>5.2</td>
<td>2.31</td>
<td>1.4026 ± 0.0046</td>
<td>4.70 ± 0.29</td>
</tr>
<tr>
<td>J1069 CP15-16</td>
<td>2.00</td>
<td>7.7</td>
<td>3.06</td>
<td>1.4887 ± 0.0045</td>
<td>4.50 ± 0.25</td>
</tr>
<tr>
<td>J1070 CP15-17</td>
<td>2.00</td>
<td>4.6</td>
<td>5.2</td>
<td>1.4978 ± 0.0047</td>
<td>4.66 ± 0.29</td>
</tr>
<tr>
<td>J1071 CP15-18</td>
<td>2.00</td>
<td>4.6</td>
<td>5.2</td>
<td>1.4978 ± 0.0047</td>
<td>4.66 ± 0.29</td>
</tr>
<tr>
<td>J1072 CP15-19</td>
<td>2.00</td>
<td>4.6</td>
<td>5.2</td>
<td>1.4978 ± 0.0047</td>
<td>4.66 ± 0.29</td>
</tr>
</tbody>
</table>

Luminescence uncertainties are reported at 1σ.

*Measured g-value of 1.33 ± 0.02% loss per decade (tC = 1173 s).
K-feldspars suffered due to signal fading (Huntley and Lamothe, 2001). To circumvent this limitation, workers noticed that, although the initial IR stimulation fades at room temperature, a subsequent IR stimulation at elevated temperature (i.e., p-IR IRSL) is less affected by fading (Buylaert et al., 2009). Our protocol (Table 2) employs a second stimulation at 225°C (lower than the conventional 290°C to balance signal stability with solar sensitivity; e.g., Smedley et al., 2015).

Most samples yield single-grain equivalent dose ($D_e$) distributions that are internally consistent. The variability of $D_e$ values between grains is characterized by the overdispersion parameter, which quantifies the unaccounted for between-grain variance with defined sources of error. Well-bleached sediments typically have overdispersion values within the ~10%–30% range (Arnold and Roberts, 2009), and of our well-bleached samples (all except J1054, J1061, and J1063), overdispersion ranged from 12% to 29% (with an average value of 20% ± 5%) (e.g., Fig. 5a). For these samples, we used the central age model to determine $D_e$ values (Galbraith et al., 1999).

Of the three poorly bleached samples (J1054, J1061, and J1063), J1054 and J1061 exhibit dose distribution groupings (e.g., Brown et al., 2015). We selected the youngest group from each sample, and in both cases, overdispersion values are consistent with a well-bleached population. For sample J1063, the dose distribution is continuous. We used the minimum age model (MAM, assuming four parameters; Galbraith et al., 1999) for this sample, imposing an overdispersion of 15%. Figure 5 illustrates the two end members of $D_e$ distributions, plotted as a function of precision, increasing radially from the left, and $D_e$ value, increasing counterclockwise (i.e., the “Radial Plot” of Galbraith et al., 1999). The poorly bleached J1063 exhibits a range of single-grain $D_e$ values, the lowest edge of which likely represents the true burial dose (Fig. 5b). By contrast, J1065 is well bleached, with nearly all grains consistent within ±2σ (the shaded region; Fig. 5a).

The $D_e$ values (and ultimately, the fading-corrected ages) display notable internal consistency for distinct cut-and-fill sequences found within individual buried channels. Nearly all the ages we obtained are in agreement (at 1σ) with the lithostratigraphic order determined by our trench logging. The one sample that presents an age inversion at 1σ is in accordance with the stratigraphic ordering of three neighboring fill strata at 2σ (Table 1 and Fig. 6). Such consistency between samples with well-defined depositional order is taken as further support for our methodology.

Fading Correction. We tested eight of the samples for signal fading at room temperature (Huntley and Lamothe, 2001). We gave samples a known beta dose, preheated them for 10 s at 250°C, and then left them in the dark for a range of pause times, from ~20 min to 2 months. After each pause, we measured the luminescence response to determine how much the signal faded. Although the responses between samples varied, we observed a mean $g$-value of 1.33% ± 0.02% loss per decade (time constant of 1173 s) for the tested samples. We corrected all samples for fading loss using the Luminescence package within the R programming environment (Kreutzer et al., 2012).

Results

We use the p-IR IRSL age estimates of channel fills to estimate how long the fluvially transported sediments have been buried. Figure 3 shows locations of the exposed channel fills (bold trench outlines) with respect to the subtle
topographic depressions. Three of the four subtle depressions (T2, T3, and T4; Figs. 7–9) have channel fill deposits that are aligned directly beneath the modern topographic depression (previously interpreted as beheaded channels). One trench (T1) contains two distinct channel fills that are not associated with any modern topographic depression (Figs. 3 and 6).
Based on the existing short-term slip-rate study conducted at this site (2.93–3.56 cm/yr, Noriega et al., 2006), fading-corrected p-IR IRSL age estimates of channel fill indicate that only one channel fill (T2) was buried recently enough to be associated with flow from a nearby feeder drainage. The package of sandy silts from within a coarse pebble channel deposit at T2 are buried ∼57 cm below the surface and are capped by unconsolidated sediments that showed very little evidence of soil formation and support the contention that they were deposited recently (sample J1063, Figs. 5b and 7). These sediments have a 1σ minimum age estimate of 0.38 ± 0.06 ka (J1063).

In the field, we used the subsurface exposures of T2 channel elements (the thalweg and margins) to measure the trend of the channel from one trench wall to another (∼2 m across the trench). We projected these measured piercing lines into the precisely located fault trace exposed in T8. We then measured the along-fault distance to the D2 feeder thalweg and margins for a slip measurement of 12 ± 1 m (Fig. 3). Our measurement uncertainty primarily stems from the collective variability in trend measurements of the subsurface channel margins and thalweg and from visually projecting this trend ∼5 m NE to the fault trace (e.g., Salisbury et al., 2015). Our subsurface slip measurement is similar to that made by Zielke et al. (2010; 11.8 + 0.7/−1.3 m) from surface geomorphology represented in the B4 lidar data. Combined with our minimum age estimate (and associated uncertainties) we calculate a short-term slip rate of 31.6 + 9/−6.6 mm/yr based on the 12 ± 1 m offset measurement. This slip rate is consistent with decadal geodesy and other slip-rate studies in the area (Sieh and Jahns, 1984; Meade and Hager, 2005; Noriega et al., 2006, Schmalzle et al., 2006) (Fig. 10), but it is impossible to be sure of the channel configuration at the time T2 sediments were deposited. Also, only a small portion of the measured grains are young. The poorly bleached T2 sample (J1063) exhibits a range of single-grain $D_e$ values, the lowest edge of which (MAM) likely represents the true (or minimum) burial dose (Fig. 5b).

At T1, although we exposed two distinct sets of buried channel fills, neither of the two are associated with the subtle topographic depression interpreted as a beheaded channel by Sieh (1978) (Figs. 3 and 6). Within our hand-dug trenches beneath this topographic depression, we observed highly bioturbated, lightly indurated fan material and no definite evidence of fluvial sediments beneath the top 2 cm of discontinuous laminated surficial silts. However, our excavations reveal two very young (unconsolidated) alluvial fan deposits (∼10 m radius) (Fig. 11). Between these two alluvial fans is the fosse, or depression that was previously...
interpreted as a once-active channel. We precisely locate the fault trace in trenches T9 and T5, confirm fan stratigraphy in T7, and excavate the paleofeeder channel location in T6 to confirm the young source of the offset alluvial fan and reconstruct the tectonic offset of the young alluvial fan apex (Fig. 11). Measured with high confidence, slip in 1857 (the most recent earthquake, A) was $3.8 \pm 0.000650 \text{ cm}$ at this site (Fig. 11).

Interestingly, at trenches T4, T3, and T1, buried channel ages are much older (Figs. 9, 8, and 6, respectively). From the southeast (SE) to NW, buried channel ages are T4, 4.28 ka; T3, 5.62 ka; T1 SE, 7.32 ka; and T1 NW, 7.04 ka (Table 1, ages summarized on Fig. 3). Coupling these results with an assumed long-term slip rate of $33 \text{ mm/yr}$ suggests distant sources that have significantly larger drainage basins ($\sim 7000-6000 \text{ m}^2$) beyond the SE end of our study area (Fig. 1; Table 3). Although it is not possible to pinpoint the exact sources because of p-IR IRSL uncertainties and ambiguous paleochannel configurations, we speculate about how far the buried channels have traveled. Table 3 shows the distances channel deposits have traveled (and potential correlative drainage basins) based on their depositional ages and a constant slip rate throughout the Holocene.

At T4, we have two distinct sets of sediments at different stratigraphic positions ($\sim 70 \text{ cm}$ of stratigraphic separation) beneath the modern topographic depression, albeit on laterally opposite trench walls located $\sim 2 \text{ m}$ apart (Fig. 9). There is a 1-m-deep coarse sand and pebble channel fill from which we have two p-IR IRSL age estimates: $4.26 \pm 0.36 \text{ ka}$ (J1069) and $4.30 \pm 0.44 \text{ ka}$ (J1070). There is no corresponding channel deposit directly across the trench, but there is an equivalent channel shape cut into the older, indurated fan material (Fig. 9, shown with dashed outline). At the top of the NE exposure, there is a $\sim 2 \text{ m}$-wide, 20-cm-thick surficial package of laminated channel silts (Fig. 9). There is no equivalent channel deposit on the opposite side of the trench. This latter deposit was not sampled for p-IR IRSL age control.

**Discussion**

**Channel Processes Used as Offset Markers in the Carrizo Plain**

A significant result of this study is the discovery that the channel sediments buried $< 2 \text{ m}$ beneath the subtle topographic depressions (interpreted as beheaded, locally sourced gullies) are significantly older in origin than expected. The major incisional and depositional episodes (i.e., the cutting and subsequent backfilling of paleochannels) that occurred at the outlets to the drainage basins to the SE are significantly larger than drainages 1–4 (Fig. 1; Table 3). Furthermore, this incision and deposition occurred several thousands of years ago and each one of the downstream channel segments we see buried in the subsurface was beheaded from its original feeder. We emphasize that the topographic form at VMR may not necessarily be the same as the subsurface form. At T1, these buried sediments are not associated with a modern topographic expression of a

### Table 3

Speculated Sources for Old Channel Deposits Based on a Constant Slip Rate of $33 \text{ mm/yr}$

<table>
<thead>
<tr>
<th>Site</th>
<th>Oldest Sample (ka)</th>
<th>Youngest Sample (ka)</th>
<th>Maximum–Minimum Distance (m)</th>
<th>Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1 NW</td>
<td>$7.45 \pm 0.58$</td>
<td>$6.62 \pm 0.51$</td>
<td>$246–218$</td>
<td>78–7</td>
</tr>
<tr>
<td>T1 SE</td>
<td>$8.12 \pm 0.77$</td>
<td>$6.33 \pm 0.48$</td>
<td>$268–209$</td>
<td>89–7</td>
</tr>
<tr>
<td>T3</td>
<td>$6.17 \pm 0.54$</td>
<td>$5.18 \pm 0.41$</td>
<td>$204–171$</td>
<td>98–9</td>
</tr>
<tr>
<td>T4</td>
<td>$4.30 \pm 0.44$</td>
<td>$4.26 \pm 0.24$</td>
<td>$142–141$</td>
<td>89</td>
</tr>
</tbody>
</table>

NW, northwest; SE, southeast.
channel (Figs. 3 and 6). At T2, T3, and T4 (Figs. 7–9), however, the buried sediments and modern topographic expressions of channels reveal a more complex story of incision and backfilling of channels, abandonment, and only recent fluvial rejuvenation with faulting throughout the Holocene. This complexity is a significant limitation to measuring slip markers in only surficial geomorphology and shows that (aleatoric) measurement uncertainties may be dwarfed or negated by epistemic uncertainties pertaining to the offset feature (e.g., Gold et al., 2012; Scharer, Salisbury, et al., 2014; Salisbury et al., 2015; Zielke et al., 2015). We emphasize the importance of dating offset channel sediments used for single- and multiple-event slip markers, as pedology in very young deposits can also be ambiguous.

There are several important implications. First, we are only able to reach the conclusion that the buried sediments in our trenches have distant sources after excavating and establishing age control for multiple buried deposits. When possible, field mapping should be combined with analysis of high-resolution topographic data or aerial photographs (e.g., Scharer, Salisbury, et al., 2014), but to positively remove most epistemic uncertainties associated with offset reconstructions, subsurface observations are necessary (Akciz et al., 2014). This is problematic, as excavations and high-precision dating are time consuming and expensive. Therefore, as we continue active fault studies using high-resolution topography and field mapping, it is crucial that we strategically employ subsurface studies like this one as a linchpin around which to base more abundant, more loosely constrained data (e.g., surface slip measurement catalogs).

Figure 10. Summary of slip-rate studies in the Carrizo Plain for landforms up to 4500 yrs old. The box dimensions represent age and offset measurement uncertainties for the landforms. The background rate of 33.9 ± 2.9 mm/yr (solid lines show uncertainty) is from Sieh and Jahns (1984), and closely matches slip rates inferred from geodetic measurements (dashed line; 3.6 cm/yr, Meade and Hager, 2005; Schmalzle et al., 2006). The color version of this figure is available only in the electronic edition.

Figure 11. (a) Map view of T1 and additional hand excavations on 0.03 m hillshade shown with 10 cm contours. Shaded polygons define small alluvial fans that surround the T1 fosse. Stars are piercing points for lateral offset measurement. (b) Oblique 3D view of ground photo-based Agisoft PhotoScan Pro model of the T5-6-7 complex. View is almost directly north showing young alluvial fan stratigraphy (shaded, confirmed in T7) faulted and offset from the excavated paleofeeder (located in T6). The lateral separation of the fan apex from its across-fault equivalent (piercing points shown as stars) is 3.8 m. (c) Fault-perpendicular trench log and photomosaic from T5NW showing young alluvial fan deposited directly on older fan material, faulted in 1857, and capped by colluvium. The color version of this figure is available only in the electronic edition.
An initial channel was cut and filled of its present location. Since then, it has been covered by colluvium. (c) T4 channels. The topographic depression did not capture a drainage capture and incision (a partial bleaching event) that occurred (∼210 m SE of its present location), drainage capture triggered another cut and fill episode. The surface expression of the channel diffused after fluvial abandonment and colluvial aggradation. The original topographic depression (if any) is obscured today by deposition of young alluvial fans (dashed). (b) T2 channels. An initial channel was cut and filled in a manner similar to T1, also likely associated with drainages D7–D9 (see Fig. 5b for complex age distribution of grains). Over time, the topographic depression did not capture drainage basins and channel deposits were mantled by colluvium until it reached D2. The young T2 sediments preserve evidence for the most recent drainage capture and incision (a partial bleaching event) that occurred ∼0.38 ka (∼12 m SE of its present location). Since then, it has been covered by colluvium. (c) T4 channels. An initial channel was cut and filled ∼4.30 ka (∼140 m SE of its present location) and subsequently covered by colluvium. The topographic depression did not capture a drainage basin until it reached D4, where it is currently experiencing minor incision and moderate sediment aggradation at the modern surface. The color version of this figure is available only in the electronic edition.

Even small-scale topographic depressions in semiarid, active strike-slip environments have the potential to be long-lived and reoccupied after their initial beheading or abandonment. However, when and how these long-lived topographic stream channels and their subsurface deposits and boundaries are totally or partially rejuvenated in an episode of stream piracy is complex and site specific. Although drainage capture and stream abandonment may happen multiple times during continued faulting, we first consider the simple scenario—the possibility that at some point drainage capture and sediment rejuvenation ceases even as a topographic depression is passed in front of new catchments. In these cases, like we observe at T1, buried channel deposits can potentially outlast their surficial expressions, particularly if the buried channel fill is covered by additional colluvial sediments or alluvial fans (Fig. 12a). This suggests that if the beheaded depression passes in front of a potential feeder catchment during an overall aggradation phase, there may be no fluvial incision.

In the Carrizo Plain, geomorphic diffusion is controlled primarily by vigorous bioturbation (e.g., burrowing by kangaroo rats) in addition to other geomorphic processes (e.g., rainsplash and soil creep). The diffusive transport rates are ∼10× higher in the Carrizo Plain than in the Basin and Range (see e.g., Arrowsmith et al., 1998). Topographic signatures of channels of this size (∼4 m wide and < ∼2 m deep) have disappeared after about 6 ka, as the channel deposits in T1 that are ∼8.12–6.33 ka (SE channels in T1; samples J1054, J1055, J1056, and J1058) and ∼7.45–6.62 ka (NW channels in T1; samples J1061 and J1062) no longer have any surface expression (Figs. 3, 6, and 12a; Table 1).

In more complex cases where downstream (beheaded) channel segments capture existing upstream feeders, there is a chance for renewed fluvial modification in the downstream channel segments. Whether or not and to what extent incision (and subsequent deposition) occurs is dependent on many site-specific conditions including the relative sizes and slopes of channel elements and the sizes of storms driving geomorphic change. This study shows that each offset marker—as straightforward as it may seem at the surface—can potentially warrant its own set of subsurface 3D excavations to fully understand the recent history of tectonic offset versus geomorphic response. These unavoidable epistemic uncertainties must be explored to confidently use such geomorphic markers as earthquake slip indicators.

We see preserved sedimentological evidence for two different styles of renewed fluvial modification in long-lasting, beheaded channel segments: one at T2 (Fig. 12b), where capture triggered significant incision; one at T4 (Fig. 12c), where capture produced very little incision. The first scenario, at T2, occurred as the surface expression (SW of the SAF) of an existing beheaded channel (sourced from far SE,
D7–D9) captured basin D2 and triggered significant reincision into the subsurface sediments sourced from D7 to D9 (Fig. 12b). Trench T2 contains buried channel sediments with a complex age distribution indicating significant reincision resulting from drainage capture (sample J1063, Fig. 5b and Table 1). We use the MAM for an age estimate of 0.38 ± 0.06 ka. Although only a portion of the grains reflect this minimum age, we can reasonably assume that the youngest grains were subaerially exposed and most-thoroughly bleached during an active transport event prior to burial in a partial bleaching event. If sediment transport occurs without sufficient sun exposure (e.g., during a heavy storm event, in an opaque slurry of sediments) then existing OSL signals are not properly reset, resulting in an age overestimation (Rittenour, 2008). We interpret the distribution of grain ages to indicate that ~380 yrs ago, an existing topographic depression with a buried channel deposit was incised and backfilled, causing a partial bleaching of sediments at the surface (Fig. 12b). We take the youngest age estimates, therefore, to represent the small portion of grains that were completely reset in the last exposure, or the maximum age for the recently refreshed deposit.

In the second scenario, at T4, the surface expression of an existing beheaded channel (sourced from D7 to D9) captured a drainage basin farther NW after beheading but did not trigger significant incision. In this case, the original, subsurface sediments sourced from D7 to D9 are largely intact (Fig. 12c). Trench T4 contains two distinct sedimentary packages that indicate the topographic depression under investigation is from a distant source and that there has been a recent, local drainage capture, albeit without significant incision (Fig. 12c). In addition to the deep sediments buried beneath the modern topographic depression in the SW wall of our trench (~4.28 ka; J1069 and J1070), the NE exposure contains fine-grained silty channel sediments at the surface (Figs. 10 and 12c). We do not sample these surficial sediments because the uncertainties associated with the long-term geologic dose-rate (and thereby the luminescence age) become large within about ~30 cm of the modern surface (due to the overwhelming influence of cosmic ray bombardment and the incomplete geometry of gamma rays from surrounding sediments). However, the fact that these delicate sediments are preserved at the surface in an area of such vigorous bioturbation indicates that they are very young and are likely sourced from the most proximal drainage (D4). We use these two packages of channel sediments to argue that the original topographic depression was sourced from the larger basins to the SE and captured the D4 drainage basin without triggering significant incision because D4 is such a small catchment at only ~1500 m² (Figs. 1 and 12c).

Channels incise when they have sufficient specific stream power per unit bed area—a function of discharge (i.e., drainage area) and local stream gradient (e.g., Whipple and Tucker, 1999). We hypothesize that in the semiarid Carrizo Plain, drainage area is more important than channel gradient to generating the power required to incise new channel forms. Figure 1b shows catchment-averaged gradients (as a general proxy for local stream gradient) and lists drainage areas. Although drainage D2, at ~3000 m², apparently does have the power to erode and refresh sediments at ~60 cm depth, it appears that in general there may be a critical threshold in this setting with typical channel slopes for drainage area at ~7000 m² required to cut significant channels that persist in the landscape. If the bulk of our channel deposits are indeed sourced from the larger basins to the SE of our trench area, then the implication is that small-catchment systems (< 7000 m²) in the Carrizo Plain produce fewer channel deposits than has been assumed and tend to produce unchanneled, subtle alluvial fans instead. We discovered that the beheaded channel depressions have very little to do with the smaller, steeper catchments nearby, making it more important to date small-scale offset markers by accessing their related subsurface deposits when possible.

Recent Slip along the SAF

We have a high-quality, single-event 3D excavated slip measurement of 3.8 m ± 50 cm for the 1857 event at VMR (Fig. 11). The 12 m offset channel at T2 (sample J1603) is dated at 380 ± 60 yrs B.P. and therefore represents slip in at least two earthquakes. We compare the depositional age range of the T2 channel sediments (sample J1603: A.D. 1596–1716; Table 1) to the palaeoseismic record at nearby Bidart Fan, ~12 km to the NW (Fig. 4). The ages of events B–D, prior to event A (1857), expressed as 2σ uncertainty ranges are A.D. 1631–1864, 1580–1640, and 1510–1612, respectively (Fig. 4). This confirms that the T2 channel has experienced at least two earthquakes but could have experienced as many as four. Therefore, penultimate earthquake slip could have been as much as 8 m, but we cannot discount that there may have been 8 m total slip in events B–D, similar to slip at Bidart Fan (Grant Ludwig et al., 2010). There is ambiguity regarding the exact channel configuration at the time young T2 sediments were deposited.

For this ~150 m reach of the SAF, existing surface slip measurements are 7.8–8.2 (four measurements, Sieh, 1978) and 11.8 m (single measurement, Zielke et al., 2012) (Fig. 3). Although the former measurements were interpreted as single-event offsets, the 11.8 m measurement is attributed to slip in two events (because Zielke identified several ~5 m offsets nearby in the B4 lidar data). Elsewhere in the Carrizo Plain, only a few subsurface estimates of 1857 slip exist: 7.9 m at Wallace Creek (18 km NW, Liu-Zeng et al., 2006), and 6.7 m at Phelan Fan (16 km NW, Grant and Sieh, 1993). Our most recent event slip measurement is significantly lower than these other subsurface estimates (Grant and Sieh, 1993; Liu-Zeng et al., 2006) and older surficial measurements (Sieh, 1978) but fall at the low end of the range proposed for the 1857 earthquake by Zielke et al. (2010, based on surface slip measurements made in the B4 lidar data).

This discrepancy in slip for the 1857 earthquake can be explained several ways. First, it is possible that some portion
of total deformation is accommodated on other unseen fault strands or as off-fault deformation nearby and our measurement does not reflect the total slip in 1857. We evaluated the surrounding area using B4 lidar imagery and aerial photographs and although there are some subtle lineaments ∼1 km to the north and SE of our study area, they do not appear to be recently active. Additionally, the channel elements that we used as extended piercing lines (in trenches T1 and T10) do not appear to warp across the narrow fault zone that we exposed in trenches T9, T5, and T8.

Second is the possibility that we are observing true slip variability for the 1857 rupture. Other subsurface slip measurements are 15+ km to the NW and slip distributions commonly exhibit long-wavelength (tens of kilometers) spikes or troughs where the degree of diffuse off-fault deformation varies, surficial materials and depth to bedrock vary, where fault geometries change or complexity increases, or when nearing the ends of ruptures (Rockwell et al., 2002; Milliner et al., 2015). This low-frequency spatial variation easily explains the difference between our ∼4 m offset and the 7.9 and 6.7 m offsets seen at the distant northern end of the Carrizo Plain. Similarly, high-frequency variation in along-strike slip for young ruptures has been well-documented elsewhere (e.g., the 1999 Izmit and Düzce rupture, Rockwell et al., 2002; and the 2010 El Mayor–Cucapah rupture, Gold et al., 2013). Investigators use high-resolution air photos and terrestrial lidar surveys, respectively, to document up to 35% variability in slip measurements over only 100 m and found similarly large variations in slip at the 200 m scale.

Furthermore, paleoseismic evidence corroborates this type of variation in slip. The fourth earthquake at Bidart Fan (12 km to the NW; event D, 1510–1612), indicated by the development of a sag pond ∼10 m wide and several tens of centimeters deep, leads Akciz et al. (2010) to hypothetize that the fourth event was comparable to the 1857 event in terms of magnitude. However, if we argue that the datasets are comparable, the fourth event offset at Wallace Creek (∼18 km to the NW, WC4) was potentially as small as 1.4 m according to Liu-Zeng et al. (2006). Grant Ludwig et al. (2010) showed that the third through fifth events (earthquakes C, D, and E) collectively offset the northwestern Bidart Fan channel 5.6 m, with a minimum of 50 cm lateral slip in each event, thus suggesting that event D (1510–1612) had anywhere from 0.5 to 4.6 m of slip.

Conclusion

The results of this study compel a reconsideration of our interpretation of several topographic depressions previously interpreted as single-earthquake offsets in the southeastern Carrizo Plain, highlighting known limitations of measuring slip markers in surficial geomorphology by itself. It is likely that existing measurements of geomorphic offsets at VMR measure landforms that are not actually offset from the sources that were originally inferred, or if the reconstruction is correct, that the total offset is not from only a single earthquake.

We have shown that long-lived topographic depressions have the potential to be, but are not necessarily, reoccupied with continued slip and that small catchments (< 7000 m²) in the Carrizo Plain do not produce channel deposits as frequently as has been assumed. A high-confidence subsurface estimate of slip at VMR for the 1857 earthquake (3.8 m ± 50 cm) suggests that slip along strike in large events is variable and that slip at a point in successive earthquakes may also be variable. Slip in the penultimate event at the VMR site could be as much as 8 m, but we cannot discount that 8 m of slip may have been accommodated in two or three events prior to the 1857 earthquake. This and a similar study conducted at Bidart Fan (Akciz et al., 2014) highlight the need for similar studies involving subsurface excavations and high-precision geochronology as we build a database of surface slip measurements for fault-offset accumulation and earthquake hazard evaluation.

Data and Resources

B4 light ranging and detection (lidar) data are from the B4 Lidar Project (National Center for Airborne Laser Mapping [NCALM], U.S. Geological Survey [USGS], Ohio State University [OSU], and EAR Geophysics at National Science Foundation [NSF]) and are available at OpenTopography (http://www.opentopography.org, last accessed December 2017).

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