The San Andreas Fault Paleoseismic Record at Elizabeth Lake: Why are There Fewer Surface-Rupturing Earthquakes on the Mojave Section?

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ABSTRACT

The structural complexity of active faults and the stress release history along the fault system may exert control on the locus and extent of individual earthquake ruptures. Fault bends, in particular, are often invoked as a possible mechanism for terminating earthquake ruptures. However, there are few records available to examine how these factors may influence the along-fault recurrence of earthquakes. We present a new paleoearthquake chronology for the southern San Andreas fault at Elizabeth Lake and integrate this record with existing paleoearthquake records to examine how the timing and frequency of earthquakes vary through a major restraining bend. This restraining bend features a mature, throughgoing right-lateral strike-slip fault, two major fault intersections, proposed subsurface fault dip changes, and a >200 km long section of fault misaligned with the regional plate motion. The Frazier Mountain, Elizabeth Lake, Pallett Creek, Wrightwood, and Pitman Canyon paleoseismic sites are located on this relatively linear surface trace of the San Andreas fault between fault bends. Our paleoseismic investigations at Elizabeth Lake document 4–5 earthquakes, since ~1100 C.E., similar to the number of earthquakes recorded at Pallett Creek. In contrast, the Frazier Mountain and Wrightwood sites each record 8–9 earthquakes during this same time period. Differences in earthquake frequency demonstrate that fewer earthquakes rupture the central portion of the restraining bend than occur near the fault bends and intersections. Furthermore, the similarity of earthquake records from the Bidart Fan paleoseismic site northwest of the restraining bend and the Frazier Mountain paleoseismic site suggests that the broad, 30° curve of the Big Bend section of the San Andreas fault exerts less influence on fault rupture behavior than the 3D geometry of the Mojave sections of the fault.

KEY POINTS

- We examine the timing of ground-rupturing earthquakes on a straight section of the southern San Andreas fault.
- The Elizabeth Lake site shows 4–5 paleoearthquakes in 900 yr, versus about 8 on adjacent fault sections.
- Along-fault differences in earthquake frequency appear to correspond with major structural complexities.

Supplemental Material

INTRODUCTION

What permits seismic rupture to traverse barriers? Empirical and numerical modeling studies of earthquake rupture propagation examine the parameters that allow an earthquake rupture to propagate through a barrier (e.g., Barka and Kadinsky-Cade, 1988; Acharya, 1997; Harris, 1998; Duan and Oglesby, 2005; Wesnousky, 2008; Elliott *et al.*, 2009, 2015;

Lozos *et al.*, 2011; Biasi and Wesnousky, 2017; Douilly *et al.*, 2020). These barriers are typically structural complexities, such as stepovers and bends, in the trace or plane of the fault. Dynamic rupture models of earthquake propagation through bends in strike-slip faults show a common association between bends and rupture termination/initiation (Douilly *et al.*, 2020) and the critical role of inherited stress state from prior earthquakes for the propagation of ruptures through structural complexities (Duan and Oglesby, 2005). Empirical studies (e.g., Biasi and Wesnousky, 2016, 2017) examine surface rupture

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maps of historical earthquakes to characterize the size and geometry of structural complexities associated with the ruptures. From these data, the frequency with which past ruptures propagated through or terminated at bends, gaps, and stepovers can be used to calculate probabilities that, in turn, can be used to constrain potential fault parameters that control rupture propagation or termination. Although, these efforts offer a synoptic view of rupture characteristics and propagation behavior, structural complexity is typically limited to the surface trace of the rupture, rather than the geometry of the fault at seismogenic depths.

The southern San Andreas fault (SSAF) is a long-lived, right-lateral strike-slip fault that accommodates 50%–70% of the total relative motion between the Pacific and North American plates. Among the most prominent, first-order structural features of this fault system are the two major restraining bends that form a ~250 km long left step in the SSAF fault surface trace. The northern end of this left step—the Big Bend section of the San Andreas fault (SAF; Fig. 1)—exhibits a broadly curved surface trace with ~30° of total curvature. The southern end of the restraining bend displays more surface trace complexity where the fault exhibits oblique slip for ~40 km in the San Geronio Pass area. Between these fault bends, the SSAF is rotated ~25° to the motion of the Pacific plate, which contributes to greater compressional stress in the region around the fault (e.g., Yang and Hauksson, 2013). The third Uniform California Earthquake Rupture Forecast (UCERF3; Field et al., 2017) divides the SAF in the restraining bend into four sections: The Big Bend, Mojave north, Mojave south, and San Bernardino north (Fig. 1). Two models for the subsurface geometry of the SAF through the restraining bend differ primarily in the dip of the fault plane through the Big Bend and San Bernardino north sections. The current version of the Southern California Earthquake Center’s Community Fault Model (CFM 5.2; Plesch et al., 2007; Nicholson et al., 2017) implements a near-vertical fault plane through the restraining bend. An alternative model, presented by Fuis et al. (2012) and based largely on potential field modeling, depicts a moderately south-dipping

Figure 1. The southern San Andreas fault (SSAF) system and the location of the Elizabeth Lake paleoseismic site. Inset map illustrates the position and orientation of the main figure within southern California. This section of the fault is relatively straight between major restraining bends of the San Andreas fault (SAF). Underlined labels provide the fault section names as defined in the third Uniform California Earthquake Rupture Forecast (UCERF3) (Field et al., 2017), with section boundaries shown by “I” across the fault trace. The Mojave north (N) and south (S) sections are distinguished by a boundary corresponding to a ~4° bend in the surface trace of the fault near Lake Hughes. Triangles show the location of well-established paleoseismic sites. “x” shows locations where the Los Angeles region seismic experiment (LARSE) 1 and 2 transects cross the SAF. Fuis et al. (2012) present geophysical models constraining the subsurface geometry of this portion of the SAF, with the shaded boxes depicting where they identify changes in fault dip, from vertical to southwest-dipping on the Mojave north section and vertical to northeast-dipping on the Mojave south section. Quaternary fault traces derived from the 2010 Fault Activity Map of California produced by the California Geological Survey (Jennings and Bryant, 2010). The color version of this figure is available only in the electronic edition.

SAF fault plane for the Big Bend and Mojave north sections, and a moderately north-dipping fault plane for the southeastern Mojave south section and San Bernardino north section. This model requires relatively short along-strike zones for the fault dip to change, with the south-dipping to vertical transition occurring over ~15 km at the Mojave north–Mojave south section boundary, and the vertical to north-dipping transition occurring over 20–25 km across the Mojave south–San Bernardino north section boundary (Fig. 1). The CFM 5.2 and the Fuis et al. (2012) models agree on a vertical dip for the Mojave south section between the two Los Angeles Region Seismic Experiment (LARSE) transects (Fig. 1). Although several recent studies provide interpretations of fault dip that are consistent with the Fuis et al. (2012) model (Barak et al., 2015; Lee and Chen, 2017; Forand et al., 2018), ambiguity as to whether the modeled fault represents the active fault plane remains. If the interpretations of dipping sections of the SAF

correspond with the active fault plane, these constraints suggest there are significant changes in the fault geometry at depth that are not illuminated by the surface trace (Fig. 1).

The SSAF has generated two known historic surface-rupturing earthquakes, the 1812 $\sim M_w$ 7 Wrightwood earthquake and the 1857 $\sim M_w$ 7.9 Fort Tejon earthquake (Sieh, 1978; Jacoby *et al.*, 1988). Paleoseismic and dendrochronologic data show the 1812 Wrightwood earthquake ruptured through the Pallett Creek, Wrightwood, and Pitman Canyon sites (Jacoby *et al.*, 1988; Seitz *et al.*, 1997; Fumal *et al.*, 2002), with the northern rupture extent uncertain over the 100 km gap between the Pallett Creek and Frazier Mountain paleoseismic sites (Toppozada *et al.*, 2002; Scharer *et al.*, 2017). The rupture extent of the subsequent Fort Tejon earthquake overlapped much of the Wrightwood earthquake and extended an additional ~ 200 km northwest to Parkfield, California (Sieh, 1978; Scharer *et al.*, 2017). The paleoearthquake record preceding these historic events is well constrained at several widely spaced sites, including the Frazier Mountain paleoearthquake chronology (Scharer *et al.*, 2014, 2017) established at the southernmost end of the Big Bend section, and the Pallett Creek and Wrightwood paleoseismic sites on the Mojave south section (Sieh, 1978; Fumal *et al.*, 2002; Weldon *et al.*, 2002; Scharer *et al.*, 2011) (Fig. 1). The 100 km gap between these sites is long enough to produce earthquakes as large as M_w 7.3, based on magnitude-scaling relationships (e.g., Hanks and Bakun, 2008). Models of paleoruptures that have assumed that earthquakes traverse this gap (Scharer *et al.*, 2017; Scharer and Yule, 2020) could overestimate magnitude of paleoearthquakes due to potential miscorrelation of events between sites. Given its position, filling this gap allows us to use the along-fault paleoearthquake records to test ideas of earthquake behavior relative to fault geometry and prior earthquake history.

Major fault geometric features such as bends in the fault trace, changes in the amount and direction of fault dip, and overall obliquity of the SSAF in the restraining bend, influence how the regional stress field is resolved onto the fault plane. This static state of stress on the fault plane can then interact

Figure 2. The Elizabeth Lake paleoseismic site. (a) The uphill-facing SAF scarp occurring upslope from Elizabeth Lake. Semitransparent polygons depict alluvial fan deposits from the north-flowing drainages dammed by the fault scarp. The black rectangle shows the extent of (b). White arrows highlight the trace of the SAF. (b) Detailed map of the southwestern portion of the Elizabeth Lake trench site, with each trench colored according to the level of documentation (a 1998 exploratory trench, not shown for clarity, was approximately coincident with the shallow portions of T4). Exploratory trenches were primarily used to test for faulting beyond the primary fault zone and are not detailed further here. Our excavations span the entire width of the prospective fault zone in multiple locations, ultimately limiting the fault zone to within ~ 10 m of the fault trace shown (black dotted line). Contour interval = 2 m. Topographic data derived from the B4 light detection and ranging (lidar) dataset (Bevis and Hudnut, 2005). The color version of this figure is available only in the electronic edition.

with the dynamic behavior of earthquake ruptures to impede or promote rupture propagation (e.g., Douilly *et al.*, 2020). To examine how these geometric changes might influence earthquake ruptures through this restraining bend, we established the new Elizabeth Lake paleoseismic site on the Mojave south section of the SAF (Fig. 1). This site is located about halfway between the Frazier Mountain and Pallett Creek paleoseismic sites (Fig. 1). We describe the evidence for up to five SAF ground-rupturing earthquakes during the past ~ 900 yr at the Elizabeth Lake site, based on observations from six trenches excavated across the fault. When compared with the paleoseismic record at neighboring sites, the new chronology of paleoearthquake ruptures at Elizabeth Lake demonstrates that the Mojave south section of the SSAF ruptures less frequently than adjacent fault sections. The along-fault changes in earthquake frequency appear to correspond with large-scale geometry changes of the SAF, and these geometry changes are likely acting to limit the propagation of some earthquake ruptures.

THE ELIZABETH LAKE PALEOSEISMIC SITE

Along the northern end of the Mojave south section, the active trace of the SAF occupies the southwestern margin of a long axial valley that traps sediment shed northeastward from the San

Figure 3. Elizabeth Lake paleoseismic site stratigraphic section and cross-site unit correlations. Key examples of the lower stratigraphy from (a) T5 and the upper stratigraphy from (b) T9, with lines showing our interpretation of unit correlations between trenches. These correlations between eastern and western trenches are based on textural observations and supported by radiocarbon dating. (c) Basic sedimentologic descriptions for each unit include the most common characteristics of each unit, although, there are minor grain-size variations across the site and a general increase in grain

size upslope (southward) from the fault. (d) Fault-parallel unit correlations. Unit contacts and thicknesses are representative values measured between 1 and 3 m south from the main fault zone. White rectangles with enclosed numbers show the stratigraphic location of evidence for earthquakes EL1-4. The persistent trend of northwest-dipping units records the alluvial character and typical source of these deposits. The color version of this figure is available only in the electronic edition. (Continued)

Gabriel Mountains (Figs. 1 and 2). Along this reach, the fault zone forms an uphill-facing scarp that dams and offsets north-flowing drainages emanating from the adjacent mountains. Geomorphic and vegetation patterns indicate that shallow groundwater is present along much of the valley. We targeted a large fault-parallel depression that is situated in an undeveloped zone between Blue Hills Drive and Ranch Club Road

(Fig. 2). Satellite imagery since 1994 shows fluctuations in the amount of surface water in this depression, with a drying trend between 2008 and 2012 prior to beginning our work at the site. Alluvial fans and channels show that most sediment at the site is derived from three small catchments (<0.3 km² each). Given the topography, the site may also episodically receive sediment from a larger catchment (2.2 km²) to the southeast (Fig. 2a). The

Figure 3. Continued

southeastern portion of the site was covered in ~1 m of sediment during the 1998 El Nino event (Figs. 3 and 4), and a 10 cm thick deposit of sand and gravel in storms following the 2013 Powerhouse fire, which burned the hills above the site.

In total, our paleoseismic investigations consist of 10 fault-perpendicular trenches that cross the depression (Fig. 2) and expose a >2000 yr long depositional record. These trenches reveal that the thickest section of young stratigraphy is preserved at the southeastern end of the site where the fault zone crosses through a northeast-flowing ephemeral drainage. Correspondingly, this southeastern end of the depression best preserves the stratigraphic record associated with recent earthquakes and is the primary focus of this article.

Of the 10 trenches at the Elizabeth Lake paleoseismic site, seven provided well-defined stratigraphy that could be readily correlated to nearby trenches. The westernmost of these trenches (T5, T6, and T7) were excavated through the deepest portion of the modern fault-parallel depression, extending northward from the geomorphic fault scarp across the middle of the depression (Fig. 2). The other four trenches (T3, T4, T4b, and T9) and associated extensions (T4E ext, T4S ext) were excavated into an alluvial fan that extends across the fault trace at the southeastern end of the fault-parallel depression. These

southeastern trenches reveal transpressional and transtensional structures within the fault zone, providing juxtaposition of stratigraphic units and soils.

TRENCH STRATIGRAPHY

The stratigraphy of trenches T3–T9 is characterized primarily by fine-grained, organic-rich deposits with intermittent coarser-grained alluvial deposits (Fig. 3; Table 1). The alluvial input varies across the site, with T5–T7 containing generally finer-grained deposits due to a small hill blocking direct sediment input from the north-flowing drainages (Fig. 2). An ephemeral drainage that passes immediately southeast of this small hill is the source of the greater alluvial input to the T3, T4, T4b, and T9 area. The uppermost unit in these trenches was deposited following heavy precipitation associated with the 1998 El Nino climatic event. The basal contact of the 1998 deposits is locally defined by an asphalt road surface (partially exposed in T4 ext) or a thin layer of bentonite (in the east wall of T4 and T4b). The 1998 deposits do not appear in T5–T7. Below the 1998 deposits in the closely spaced T3, T4, T4b, and T9 trenches, the upper stratigraphic section (units 40–60.3) increases in thickness from 2 to 3 m toward the southeast (Fig. 3). In T3 and T4, unit 50 varies in thickness from ~30 to 70 cm and typically thins across structural highs

(Figs. S4–S8, available in the supplemental material to this article). Southeastward from T4, unit 50 thickens across T4b and T9, expanding to 1.5 m thick with nine well-defined subunits (Figs. 3 and 4, Figs. S1 and S9). Cross-trench elevation differences of subunits within unit 50 indicate a gentle dip to the southeast from T4 to T9; this dip decreases upsection such that the basal contact of 45.3 is close to horizontal from T3 to T9 (Fig. 3). Unit 50 thins from ~0.5 to <0.2 m over 3–4 m north of the fault zone (Figs. 4 and 5), and farther north becomes indistinguishable from the adjacent units. The thickness and relative grain sizes of unit 60 vary between trenches, but the sequence of a coarser-grained layer between two finer-grained layers is persistent. The basal contact of unit 60 occurs as a consistently sharp boundary between sandy sediments above and clayey silt below within the fault zone, and extends >10 m to the north (e.g., T3). This stratigraphic contact becomes less distinct ~7 m south of the fault zone, as the entire stratigraphic sequence becomes generally coarser-grained in the upslope direction. Units below 60.3 are not as stratigraphically distinct and consequently exhibit unclear correlations across fault zones and between trenches. The relationships between units 70,

Figure 4. Portion of the east wall of T9 showing key faulting and stratigraphic relationships. The stratigraphic thickness of unit 50 increases markedly to the south across the main fault zone between 1 and 2 m. Horizontal distances on the trench logs are measured relative to a line fit through the location of ELx evidence in each trench, with positive distance values to the south and negative distance values to the north. The ELx/2 label corresponds with the location of earthquake evidence described in Table 3 and is used to indicate that this evidence is correlated with either ELx and/or EL2. The color version of this figure is available only in the electronic edition.

80, and 90 are the best preserved within downdropped portions of the fault zone, whereas, where these units occur structurally higher, the contacts and sedimentological characteristics are overprinted by soil-forming processes.

The upper stratigraphic section in trenches T5 and T6 exhibits a sequence of units that is correlative with T3, T4, and T9; however, the deposits in T5 and T6 are generally finer-grained and exhibit an overall fining-upward sequence (Figs. 3 and 6; Figs. S10–S13). The sediments are separated from sheared bedrock across two subvertical fault zones and

TABLE 1
Descriptions of Stratigraphic Units at the Elizabeth Lake Paleoseismic Site

Units of T3, T4, T4b, and T9		Units of T5 and T6	
Unit	Description	Unit	Description
1998	50–100 cm thick; poorly sorted gravelly sand; deposited by storms in the winter of 1998–1999		
40	10–50 cm thick; discontinuous horizons of gravelly sand, sand, and sandy silt; sediments coarsen with distance south of fault zone (i.e., upslope)	40	Bioturbated, clayey, organic-rich silt topped with a thin O horizon
45.1	5–10 cm thick; locally bioturbated, moderately sorted, fine-grained sand; sharp basal contact	45	~10 cm thick fine-grained sand; extensively bioturbated; subunits indistinguishable; clear basal contact
45.2	~0 cm thick across structural highs, up to 30 cm thick in depressions; sand- and organic-rich silt near-fault zone, coarser grained >5 m south of fault zone		
45.3	5–10 cm thick; well-sorted, fining upward sand; sharp basal contact		
50.1	Bioturbated clayey silt; diffuse basal contact	50	20–30 cm thick; massive to locally bedded clayey silt and sand; clear basal contact
50.2	Strongly bioturbated, fine-grained sand; mottled tan-orange		
50.3	Bioturbated clayey silt		
50.4	5–15 cm thick fine-grained sand; numerous krotovina (filled animal burrows)		
50.5	15–40 cm thick; massive organic-rich clayey silt; irregularly shaped lenses of orange-tan fine sand		
50.6	15–40 cm thick; massive organic-rich clayey silt		
50.7a	5–10 cm thick; silty fine-grained sand; local bioturbation		
50.7b	5–15 cm thick; clayey silt and fine-grained sand; thin charcoal-rich horizon		
50.7c	10–15 cm thick; silty fine-grained sand; krotovina; thin, dark, charcoal-rich horizon at base, with sharp basal contact		
60.1	Fine- to medium-grained sand; thickness varies between trenches, locally absent; clear basal contact	60.1	~10 cm thick; well-sorted, very fine- to fine-grained sand
60.2	20–50 cm thick; massive, coarse-grained sand	60.2	~10 cm thick; well-sorted, fine- to medium-grained sand
60.3	10–30 cm thick; moderately sorted fine- to medium-grained sand; sharp basal contact	60.3	~10 cm thick; well-sorted, very fine- to fine-grained sand; sharp basal contact
70	10–30 cm thick; clayey silt with local cm-scale sandy silt interbeds	70	~50 cm thick; well-bedded sequence of clayey silt and sandy silt horizons; internal contacts diffuse, but individual beds continuous
80	10–20 cm thick; well-sorted fine- to medium-grained sand	80	15–20 cm thick; well-sorted fine- to medium-grained sand; sharp basal contact; upper portion of unit contains extensive bioturbation and Fe-Mn oxide nodules, lower section unaltered
90	Silty sand to clayey silt with diffuse, decimeter-scale bedding	90	Alternating 2–5 cm thick beds of clayey silt with sharp contacts in upper portion of unit; lower portion has thicker beds with more diffuse contacts
100	Silty sand with 5–10 cm scale internal bedding defined by variations in silt content; sharp basal contact	100	Very fine- to medium-grained sand; no internal bedding
110	Massive, silty, very coarse-grained sand	110	Well-sorted coarse-grained sand; increasing silt and clay content near top of unit
		120	Massive clay to clayey silt; base of unit not exposed

an intervening 2–3 m wide zone of relatively homogeneous gravelly silt and clay (Fig. 6). The fault zones occur at the base of the ~2 m tall, 10–12 m wide, gently sloped fault scarp face (Fig. 2). No stratigraphic units cross the fault zone. Bedrock is exposed to the northeast of the fault zones, and exhibits pervasive shears and fractures.

EARTHQUAKE EVIDENCE

Our investigations exposed the full width of the fault zone in two locations—the directly overlapping trenches T5 and T7

and the T3, T4, and T9 set of trenches (Fig. 2). The long exposure of undeformed bedding in the southern end of T5 and T7 demonstrate that recent deformation is localized within a few meters of the main fault zone in T5. Similarly, stratigraphic offsets associated with the fault zone are captured entirely in T4, with the southern extension of T4 exposing undeformed sediments (Fig. 2, Figs. S2 and S3) south of the fault zone and T3 containing the unfaulted basal contact of unit 60 extending northward from the fault zone (Figs. S4 and S5). The upper stratigraphic section across the fault zone, from unit 60 to

the historical 1998 deposit, is ~3.7 m thick in T9 and thins northwestward to ~2.3 m in T4 (Fig. 3). Most of this thickness change occurs within unit 50, which is a ~0.5 m thick, massive organic-rich clayey silt in T4 that expands to a 1.4 m thick succession of interbedded sand and clayey silt in T9. Complete details on locations of event evidence on the individual trench walls are presented in Table 2. Locations of trench wall features mentioned in the text are described by their horizontal position on the trench log (e.g., meter 8; or between meters 7 and 9).

Event 1—EL1

The most recent event recorded at Elizabeth Lake (EL1) is defined by a southwest-side-up vertical separation of units 45.3 and younger on faults extending up to within 50 cm of the 1998 deposit basal contact (Figs. 4 and 5, Figs. S1, S6, S8, and S9). Deformation associated with this earthquake forms a low amplitude (~20–30 cm high) pop-up structure in the southeasternmost trenches (T4b, T9), transitioning to a simple vertical separation to the west at T4. Unit 45.3 exhibits a consistent thickness where present on both sides of the zone of faulting, except where it is truncated by the fault and absent for ~2 m on the upthrown side of the fault. On the south side of the pop-up, unit 45.3 is gently tilted to the south. Above this, unit 45.2 appears to cross-cut 45.3, forming a very subtle angular unconformity. However, these contacts are partially overprinted by bioturbation and soil development, making this relationship indistinct. In all exposures, 45.2 is significantly thicker on the north side of the fault zone. Although, the basal contact of unit 45.1 is indistinct across the EL1 fault trace in T9 and T4b, it is clearly unfaulted across the fault zone in T4E ext (meters 0.5 to 1 in Fig. S8).

We interpret EL1 as having occurred during the deposition of unit 45.2 based on: (1) no cross-fault thickness change of 45.3,

Figure 5. Photomosaic and log of the T4b east wall. The southern end of the trench wall is shown rotated 90° into the same perspective as the main wall. North–south and east–west indicate the approximate orientations of the originally perpendicular wall sections. The lower subunits of unit 50 exhibit increasing dip, with depth to the southeast in the trench. The main fault zone bounds a 1–2 m wide pop-up structure. Below unit 45.3, contacts cannot be traced continuously across the pop-up structure, preventing correlation of ELx deformation with the higher-resolution stratigraphy of unit 50 preserved south of the pop-up. The top of the photomosaic is below the ground surface, because the 1998 deposits were disturbed during excavation of prior, adjacent trenches. The color version of this figure is available only in the electronic edition.

despite localized erosion across a structural high; (2) apparent folding of 45.3; (3) thickness change of 45.2 across the fault; (4) apparent stratigraphic onlapping relationships within 45.2; (5) thickness change in 45.1, consistent with accumulation across minor surface relief associated with the fault zone; and (6) lack of faulting across the base of 45.1. The relief produced during the earthquake led to localized erosion at the top of the pop-up, redepositing the sediments of units 45.3 and lower 45.2 in the thickened section of 45.2 on the north side of the fault. The swale on the downthrown side was largely filled prior to the deposition of 45.1.

The stratigraphically highest evidence for this rupture appears near meters 1 and 2 in T5 (Fig. 6) and meters –1 and 0 in T6 (Figs. S12 and S13), in which the fault zone that separates bedrock from sheared sediments appears to penetrate up into the base of modern soil horizons. In both the trenches, there is a package of coarser-grained sediment (labeled “CW?”) immediately south of and downslope from the prospective surface rupture that is consistent with the occurrence of a recent rupture on the geomorphic scarp. Organic-rich sediments overlying the clastic deposit appear to be consistent with unit 40.

TABLE 2

Radiocarbon Sample Data and Ages from the Elizabeth Lake Site

Sample Name	CAMS Lab ID	Trench	Wall	Unit*	Sample Type	¹⁴ C age (yr B.P. at 1σ) [†]	δ ¹³ C [‡]	Trench Log Code
EL9E-B5.1	169930	9	E	50.1	Charcoal	220 ± 30	-25	B5
EL9E-B9	174953	9	E	50.4 – 9	Charcoal	655 ± 25	-26.3	B9
EL9E-B9A	174848	9	E	50.4 – 9	Seed	425 ± 25	-26.3	B9
EL9E-B13A	174850	9	E	50.6 – 9	Plant remains	750 ± 25	-24.6	B13
EL9E-B11B	174954	9	E	50.6 – 1	Charcoal	715 ± 25	-27.1	B11B
EL9E-B11B1	174952	9	E	50.6 – 1	Plant remains	570 ± 35	-25	B11B
EL4.2-M2	174955	4b	S	50.5 – 2	Charcoal	760 ± 25	-26.5	M2
EL4.2-M2	174852	4b	S	50.5 – 2	Charcoal	750 ± 25	-26.5	M2
EL4.2-M3.5	169927	4b	S	50.7c	charcoal	935 ± 30	-25	M3
EL4.2-M3.8	169929	4b	S	50.7c	Charcoal	865 ± 30	-25	M3
EL4.2-M3.7	169928	4b	S	50.7c	Charcoal	785 ± 35	-25	M3
EL4.2-M3.2	169924	4b	S	50.7c	Stem	675 ± 35	-25	M3
EL4.2-M3.4	169926	4b	S	50.7c	Seed	655 ± 30	-25	M3
EL4.2-M3.1	169923	4b	S	50.7c	Monocot stem	605 ± 30	-25	M3
EL4.2-M3.3	169925	4b	S	50.7c	Charcoal	820 ± 30	-25	M3
EL3EW-03	163380	3	E	60.1	Charcoal	590 ± 80	-25	03
EL4.2S-05	166877	4b	S	60.2	Charcoal	965 ± 50	-25	05
EL4.2W-06	166878	4b	W	60.1 – 8	Charcoal	790 ± 25	-24.5	06a
EL3WW-06	163378	3	W	90 or 100?	Charcoal	1740 ± 20	-24.0	06b
EL4.2W-10	169917	4b	W	60.1 – 8	Charcoal	920 ± 35	-25	9-12
EL4.2W-12	169918	4b	W	60.1 – 8	Charcoal	865 ± 30	-25	9-12
EL4.2S-13	166882	4b	S	50.7c	Bulk soil + charcoal	820 ± 35	-25	13
EL4.2S-14	169919	4b	S	50.7c	Charcoal	1470 ± 60	-25	14
EL4.2S-15	166883	4b	S	50.7c	Charcoal	625 ± 25	-26.2	15
EL4-16	163000	4	W	Unknown	Charcoal	1540 ± 25	-22.6	n/a
EL3WW-16	163379	3	W	90	Charcoal	1330 ± 40	-22.6	16b
EL4.2E-18	166879	4b	E	60.1 – 2	Charcoal	845 ± 30	-24.2	18
EL4WW-22	163382	4	W	40-9	Charcoal	245 ± 30	-25	22
EL4.2S-23	166892	4b	S	50.4	Charcoal	155 ± 25	-24.6	23
EL4-24	163119	4	W	60.3 – 1	Charcoal	825 ± 30	-25	24
EL4EW-25	163381	4	E	50.1	Bulk sediment	445 ± 35	-25	25
EL4.2S-26	166893	4b	S	50.1	Charcoal	260 ± 30	-23.8	26a
EL4-26	162998	4	W	45.2 – 2	Charcoal	625 ± 35	-25	26b
EL4.2S-28	166896	4b	S	45.2	Charcoal	180 ± 70	-22.6	28
EL4-29	162997	4	W	60.3	Charcoal	890 ± 20	-27.6	29
EL4-31	162999	4	W	40-1	Charcoal	190 ± 25	-23.8	31
EL4-36	163001	4	W	45.2 – 2	Charcoal	525 ± 30	-25	36
EL4WW-37	163383	4	W	40-9	Charcoal	80 ± 30	-25	37
EL4.2E-43	169916	4b	E	70	Charcoal	830 ± 35	-25	43
EL9W-57	169921	9	W	50.4	Charcoal	105 ± 30	-25	57
EL9W-59	166888	9	W	50.3	Charcoal	230 ± 40	-25	59
EL9W-60	166890	9	W	50.3	Charcoal	200 ± 25	-24.6	60
EL9W-61	166891	9	W	50.2	Charcoal	350 ± 30	-25	61
EL9W-62	169922	9	W	50.4	Charcoal	405 ± 30	-25	62
EL9W-64	166895	9	W	45.3	Charcoal	410 ± 110	-25	64
EL9W-65	166894	9	W	45.3	Charcoal	660 ± 40	-25	65
EL9W-66	166897	9	W	45.2	Charcoal	140 ± 30	-25.9	66
EL9E-71	166889	9	E	50.2	Charcoal	180 ± 25	-23.7	71
EL9E-73	166887	9	E	50.3 – 2	Charcoal	185 ± 25	-24.7	73
EL9E-74	166886	9	E	50.4 – 9	Charcoal	360 ± 25	-24.6	74
EL9E-75	169953	9	E	50.7c	Charcoal	1110 ± 40	-25	75
EL9E-77A	174849	9	E	50.5 – 9	Plant remains	420 ± 30	-28.2	77
EL9E-78	166884	9	E	50.7c	Charcoal	885 ± 35	-25	78
EL9E-79	169920	9	E	50.7b – 1	Charcoal	1010 ± 45	-25	79
EL9E-81	166880	9	E	50.7c	Charcoal	735 ± 30	-25.5	81
EL9E-83	166881	9	E	50.7c	Charcoal	925 ± 40	-25	83

(continued)

TABLE 2 (Continued)

Sample Name	CAMS Lab ID	Trench	Wall	Unit*	Sample Type	¹⁴ C age (yr B.P. at 1σ) [†]	δ ¹³ C [‡]	Trench Log Code
EL9E-85	166885	9	E	50.7c	Charcoal	610 ± 25	-25.4	85
EL3-100	162996	3	W	Undiff.	Bulk sediment	1750 ± 40	-25	100
EL5WW-101	163393	5	W	90 – 8	Charcoal	1675 ± 25	-24.2	101
EL5WW-104	163392	5	W	90 – 9	Bulk sediment	1720 ± 35	-25	104
EL5WW-113	163394	5	W	90 – 2	Charcoal	1475 ± 25	-23.9	113
EL5WW-122	163395	5	W	70	Charcoal	2830 ± 230	-25	122
EL5WW-124	163396	5	W	60.3	Charcoal	805 ± 25	-27.4	124
EL5EW-144	163398	5	E	60.2	Charcoal	530 ± 45	-25	144
EL5WW-148	163397	5	W	60.2	Charcoal	735 ± 35	-25	148
EL6WW-150	163384	6	W	120 – 8	Charcoal	2380 ± 25	-24.9	150
EL6WW-152	163385	6	W	120 – 5	Charcoal	2415 ± 30	-24.7	152
EL6WW-154	163386	6	W	120 – 3	Charcoal	2350 ± 25	-23.9	154
EL5EW-160	163390	5	E	100 – 1	Charcoal	1710 ± 25	-26.5	160
EL5EW-162	163389	5	E	100 – 7	Charcoal	1780 ± 25	-24.1	162
EL5EW-166	163388	5	E	100 – 9	Charcoal	1800 ± 30	-24.8	166
EL5EW-167	163391	5	E	100 – 1	Charcoal	1720 ± 35	-25	167
EL6WW-179	163387	6	W	110 – 1	Charcoal	2040 ± 25	-25.3	179

Undiff., sample from stratigraphy where we were unable to confidently correlate units to known stratigraphy; n/a, not applicable; sample not labeled on trench logs.

*Numbers following the hyphen (-) indicate relative position within unit. 1 = upper contact to 9 = basal contact.

[†]Radiocarbon years using Libby half-life of 5568 yr and following conventions of [Stuiver and Polach \(1977\)](#).

[‡]When given without decimal places, δ¹³C values are assumed values according to [Stuiver and Polach \(1977\)](#). Values measured on the sample itself are given with a single decimal place.

being of high quality. T9W exhibits a consistent pattern of a downdropped and tilted unit 50.7, but most of the apparent causative faults are also associated with EL2, and it is unclear if these overprint older structures are associated with EL3 (Fig. S1). The limited occurrences of evidence for EL3 are likely a result of limited observation of the expanded stratigraphic section of unit 50, which is restricted to the eastern edge of our field site—only appearing in T9 and T4b (Figs. 4 and 5).

Event 4—EL4

Evidence for EL4 appears as faulting in T4b and T4E that offsets the finer-grained basal unit 60.3 and terminates within the coarse-grained sand to pebbly sand unit 60.2 (evidence occurs near meters 2.5 and 3.5 in Fig. 5, and between meters 2 and 3 in Fig. S7). Where preserved, unit 60.1 appears to not be offset by these faults. Unit 60.2 also changes thickness across these faults, suggesting it filled an irregular ground surface and then was juxtaposed by lateral separations. Unit 60.1 does not show this variation (Fig. 5).

In T6, thickness changes of unit 60 gives the appearance of sediment that filled a broad trough (between meters 6 and 10 in Figs. S12 and S13). If this trough predated the deposition of unit 60, it would record an event prior to EL4. However, the basal horizon of unit 60 in T6 does not change thickness across the trough, suggesting that it may have been deposited prior to creation of the trough, placing this deformation at a stratigraphic level consistent with the other evidence for EL4. Similar evidence is not present in T5, or the evidence has been overprinted by smaller-scale folding associated with EL2, EL3, and/or ELx.

Event x—ELx

A distinctive stratigraphic feature within unit 50 persists across T3, T4W, T4E ext, T4b, and T9, located at meter 0 in each of these trenches (Figs. 4, 5, Figs. S1, S4–S6, and S8). This feature consists of thin (0.2–2 cm) laminae of clean fine-grained sand interbedded with clayey silt, forming a unique 0.5–0.8 m wide trough-shaped feature. This feature occurs between meters 1 and 2 north of the main fault zone associated with EL1 and EL2, and the top of the feature is consistently within the middle to upper section of unit 50. The base of the feature cuts across the lower portion of unit 50 and locally into the underlying unit 60.1. In all occurrences, fault traces occur next to and/or below the trough-shaped feature, and none of these faults can be traced above unit 50 (e.g., Figs. 4 and 5). Because the feature is persistently on the north side of the pop-up, can be connected for 30 m along the fault zone, and is typically bounded by or just above vertical faulting, we interpret the feature as a narrow fissure formed some time during the deposition of unit 50. Unfortunately, unit 50 is relatively thin and massive north of the EL1 fault zone and the lack of internal stratigraphy prevents possible correlation with the other events identified within the expanded stratigraphy of unit 50 south of the EL1 fault zone (EL2 and EL3) based on stratigraphic relationships. Therefore, the event that produced this trough-shaped feature could have occurred during EL2, EL3, or as an additional, separate earthquake during the deposition of unit 50.

In detail, the stratigraphic position of this event evidence suggests that the earthquake occurred during deposition of the upper section of unit 50. Notably, we expect that the

fine-scale layering within the trough is unlikely to be preserved through many ruptures and, especially, near the surface with active soil-forming processes and bioturbation. Trenches T5 and T6 do not contain similar evidence for ELx.

EVALUATION OF RECORD COMPLETENESS

Table 2 provides a description of each observed piece of evidence of ground deformation and the associated earthquake horizon. Earthquakes EL1–4 and ELx are qualified as probable-to-very likely to be paleoearthquakes following [Scharer et al. \(2007\)](#), in that each is characterized by clear structural and sedimentologic deformation that indicate faulting disturbed a paleoground surface, and subsequent deposition preserved that surface rupture. Within the stratigraphy, and outlined in Table 2, are a few horizons that are associated with weak or inconclusive evidence of ground deformation. We designate these as possible events, following arguments in [Scharer et al. \(2007\)](#), and describe the deformation in these intervals that may be of use to subsequent studies.

Possible event—ELy

Two lines of evidence from T9, labeled ELy in Table 2, Figure 4, and Figure S1, permit the interpretation of an earthquake between EL1 and EL2. On the east wall of T9 (Fig. 4), there is sufficient stratigraphic resolution within unit 50 to identify a fault that may truncate the base of unit 50.2 in meter 2. Units 50.1–50.2 thicken across the fault, resulting in a southward-tapering wedge of sediment that is capped by the unit 45.3 basal contact. A similar wedge of sediment appears on the west wall of T9, but this stratigraphy is not as clearly associated with a pre-EL1 fault trace (Fig. S1). Below the wedge of sediment on the west wall of T9 are two cryptic fault traces that appear to cut the base of 50.2 but do not exhibit vertical separation above unit 50.4. In the other trenches, several faults penetrate into the uppermost part of unit 50 (50.1–50.3), but the association of these faults with EL1 or another event is ambiguous. For example, T4 and T4b both exhibit faults that terminate within 10–15 cm of the 45.3 basal contact, but, due to the massive nature of unit 50 in those trenches, more precise constraints on the timing and stratigraphic relationships are not possible. Unfortunately, due to the massive nature of upper unit 50, we are unable to differentiate the ELy evidence from the evidence for EL1 and ELx, leading to the possibility that the ELy evidence is actually part of an earthquake we have already documented.

Additional possible event evidence

Multiple weak lines of evidence exist in stratigraphy below unit 70 for earthquakes preceding EL4 (Table 2). Several fault traces exhibit upward terminations within unit 90 (near meter 8 in T5 and meter 7 in T6; Fig. 6; Figs. S10–S13); in T5 and T6 east, this deformation cannot be clearly distinguished from deformation of younger units, because the associated folding is similar through the base of unit 60.3 (i.e., EL4). In T6 west, however, the steeply south-dipping fault between meters 7 and 8

separates a two-fold thickness change in unit 90 that suggests substantial lateral slip that did not deform unit 80, providing some discrete evidence for an earthquake. There is similar weak evidence of older events. For example, a single fault strand vertically offsets the base of unit 110 by 40 cm at meter 10 on the west wall of T5 (Fig. 6) and produces a lateral mismatch in the thickness of unit 110 across the fault. The interaction of this fault with the diffuse basal contact of unit 100 is unclear, but unit 100 gradually thickens to the north, suggesting some relative lowering of the ground surface is preserved. The basal contact of unit 90 is not deformed. Unfortunately, the basal contact of unit 110 is not exposed on the east wall of T5, and no faulting was documented, so we lack corroborating lines of evidence for this event.

RADIOCARBON AGE CONTROL

We collected samples of organic material from trenches T3, T4, T4b, T5, T6, and T9 (Table 2, sample locations shown on Figs. S1–S13). Individual samples were examined under a dissecting microscope to identify primary sample components and remove potential contaminants before chemical pretreatment. Four bulk-sediment samples were processed by PaleoResearch Institute to isolate and identify macrofloral components for additional dating targets. All samples were chemically pretreated at Lawrence Livermore National Laboratory Center for Accelerator Mass Spectrometry, with most undergoing standard acid–alkali–acid (HCl and NaOH) washes. Several small or delicate samples (noted on Table 3) were pretreated with only HCl, to avoid possible sample destruction. Of 73 total samples, 35 were large enough to provide a split for $\delta^{13}\text{C}$ measurement. Sample ages are calibrated to the IntCal 13 curve ([Reimer et al., 2013](#)) with OxCal 4.3 ([Bronk Ramsey, 2009](#)) with ages at 2σ (95% confidence limits) and reported as calendar years C.E./B.C.E. (Table 3).

EARTHQUAKE AGES

We modeled the age ranges for paleoearthquakes at the Elizabeth Lake site, using Bayesian methods implemented through the OxCal 4.3 sequence model framework ([Bronk Ramsey, 2008](#); [Lienkaemper and Bronk Ramsey, 2009](#)). This method incorporates individual sample ages and uncertainties with a priori observations regarding stratigraphic order and unit boundaries, to model statistically robust age ranges for events within the model. Figure 7a provides the age range of 57 dated samples from T3, T4, T4b, and T9 in stratigraphic order. As is common for sequences dated with detrital charcoal, in several layers (e.g., 45.2, 50.7c) there is an ~ 400 yr spread in the ages of individual samples. Furthermore, samples in different layers have overlapping probability distribution functions (PDFs) that make assessing the representativeness of their sample ages more difficult. To address issues of inheritance in modeling earthquake age ranges, we iteratively removed the oldest samples from each layer, until an agreement

TABLE 3

Summary of Event Evidence in Trenches T3, T4, T4b, T9, T5, and T6

Event	Trench	Trench Location*	Oldest Unaffected Unit	Youngest Affected Unit	Quality†	Evidence
EL1	T4W	0–0.5	45.1	45.2	3	Units 45.3 and 45.2 truncated across tip of fault and absent on upthrown side within ~2 m of the fault. On the downthrown side, 45.3 maintains thickness, whereas, 45.2 is substantially thicker. Unit 45.1 is continuous across fault projection, thickening slightly across the swale formed over the downthrown side of the fault.
EL1	T4E ext	0–3	45.1	45.3	4	On the downthrown side, unit 45.3 appears folded in a swale, but remains constant thickness where preserved. Unit 45.2 is much thicker on the downthrown side with internal stratigraphy forming a weak onlapping geometry toward the fault zone. Units 45.2 and 45.3 are absent across the crest of the pop-up that forms the upthrown side of the fault. On the south side of the pop-up, 45.2 and older units tilt to the south. The base of unit 45.1 is not faulted and maintains nearly constant thickness across the fault zone.
EL1	T4b	1	40	45.2	2	Base of unit 45.3 is offset by over 40 cm at fault zone, and unit 45.2 is twice as thick on south side of pop-up. Unit 45.1 not directly mappable across the fault zone.
EL1	T4b	–1 to 5	45.3	45.2	3	Unit 45.1 appears broadly folded, but does not exhibit substantive unit thickness change throughout the trench. Units 45.2 and 45.3 exhibit similar broad folding to unit 45.1, but only 45.2 exhibits a significant thickness change across the fault zone. However, the basal contact of 45.1 appears more gently folded than the underlying contacts, suggesting that folding occurred prior to that unit. The contacts of 45.3 are parallel folded, suggesting that folding occurred after this unit.
EL1	T9E	1–1.4	40	45.2	1	Thickness changes across the pop-up may reflect ground deformation event (s) between units 45.3 and the lower portion of unit 40. The greatest thickness change appears to occur during unit 45.2, which doubles in thickness compared to the south side of the pop-up. However, the 45.1/40 contact becomes quite diffuse here, so some additional thickening may occur as late as the base of unit 40.
EL1	T9E	0–5	45.3	40	3	Units 45.3 and 45.2 pinch out across the fault-cored pop-up structure. The basal contact of 45.1 is sharp and distinct south of the pop-up, but diffuse and difficult to identify to the north. A wedge of sandier material wipossthin 45.2 occurs north of the fault, suggesting infill of a depression with reworked sediment eroded from the adjacent pop-up following its formation.
EL1	T9W	1–1.4	40	45.2	2	Unit 45.3 is truncated at the fault zone on the north side of the pop-up and absent across crest of pop-up. The basal contact of unit 45.2 does not appear significantly offset where 45.3 is truncated; however, given the absence of 45.3 on one side, the basal contact of 45.2 is likely older north of the fault. The basal contact of 45.1 is diffuse, thus does not provide a robust marker for limiting the upward termination of the fault.
EL1	T9W	0–5	45.2	45.1	1	On the south side of the fault-cored pop-up structure, unit 45.3 pinches out toward the crest of the pop-up, appearing to be truncated by the basal contact of 45.2. Unit 45.2 also thins across the pop-up structure and thickens significantly on the north side of the pop-up, with a sandier interval in the middle of the unit. Unit 45.1 is bioturbated across the crest of the pop-up, but the basal contact is weakly defined by the transition from sand dominated above and organic-rich silt dominated below. This contact becomes more diffuse north of the pop-up, limiting the clarity of the structural and stratigraphic relationships.
EL1	T9W	1	45.2	45.1	0	No discrete fault trace reaches the basal contact of 45.3. However, due to offsets, warping, and erosion of 45.3 corresponding with underlying faults, the lack of discrete faulting is likely due to healing of fault traces in a clayey, organic-rich soil and/or ductile warping of the ground surface.

(continued)

TABLE 3 (Continued)

Event	Trench	Trench Location*	Oldest Unaffected Unit	Youngest Affected Unit	Quality†	Evidence
Ely	T9E	2–3.5	50.2	45.2	0	Within meters 2 to 3, a north-dipping fault appears to truncate unit 50.2; the upper extent is difficult to define and may extend into unit 45.3. South of the fault, a gentle wedge shape is apparent between the flat-lying unit 50.2 and the gently south-dipping 45.3 above. It is unclear if the dip of 45.3 is due to faulting during the deposition of 45.2 (EL1) or if displacement during 50.1 created the south-dipping wedge surface on which unit 45.3 subsequently overlapped. Relationships north of the pop-up do not clarify this relationship.
Ely	T9W	2.4–2.6	45.3	50.2	1	Two cryptic fault traces appear to cut the basal contact of unit 50.2 and lower, but these faults only exhibit vertical unit offsets below 50.4. The upward terminations of these faults are not well expressed in the organic and clay-rich units 50.2 and 50.1, but unit 45.3 is not present north of these faults until the depression north of the pop-up structure. It is possible that these faults moved prior to deposition of 45.3 and that unit overlies a scarp, or the faults may have moved later (in EL1), and erosion across the top of the pop-up produced the stratigraphic relationships.
EL1(?)	T6E	–1 to 2	Undiff.	Undiff.	0	Faults approach surface through undifferentiated, organic-rich sediments near base of geomorphic scarp. A wedge-shaped deposit of pebbly colluvium extends downslope from the fault zone and is buried by deposits at the same stratigraphic level as unit 45.
EL1(?)	T6W	–1 to 2	Undiff.	Undiff.	0	Faults approach surface through undifferentiated, organic-rich sediments near base of geomorphic scarp. A wedge-shaped deposit of pebbly colluvium extends downslope from the fault zone and is buried by deposits at the same stratigraphic level as unit 45.
EL1(?)	T5E	0–1	Undiff.	Undiff.	0	Fault zone juxtaposes sheared gravel against sheared bedrock, fault is clear to within 40 cm of ground surface, but the stratigraphy in this zone is uncorrelated with documented units.
EL1(?)	T5E	0–1	Undiff.	Undiff.	0	Fault zone juxtaposes sheared gravel against sheared bedrock, individual fault planes cut basal contact of a surficial organic-rich sediment. A wedge-shaped deposit of gray, silty coarse sand occurs downslope from where these faults approach the surface.
EL2	T4b	3–3.6	50.3	50.6	3	North-dipping fault cuts unit 50.6 and likely 50.5. Covered by unit 50.2 and, possibly, poorly differentiated 50.3/50.4. The fault trace is partially obscured by krotovina, but thickness change and sediment texture indicate displacement that produced accommodation space for 50.5, or lateral translation roughly midway through the deposition of unit 50.
EL2	T9E	2–4	50.4	50.6	1	Minor, broad folding of basal unit 50.5 and below, that is not expressed in the top of 50.4, suggests deformation in the main fault zone between units 50.6 and 50.4.
EL2	T9E	2–3	50.4	50.6	0	A single fault juxtaposes unit 60 against unit 50.6 (north side up). The upper termination of this fault is not clear due to massive stratigraphy and a younger, cross-cutting fault.
EL2	T9W	2–4	50.4	50.7	1	Units 50.4–50.7 double in thickness across a series of faults. Shearing makes the exact stratigraphic location of the thinning difficult to identify, but most of the faults appear to extend through unit 50.7c. Faulting could be during the deposition of 50.7 or later and capped by 50.4.
EL3	T9E	2–4	50.7a	50.7c	4	Unit 50.7c and older are downdropped about 50 cm across a series of faults. The top of unit 50.7a is not faulted. Overall, 50.7 thins toward the main fault zone, suggesting the ground surface was deformed during the deposition of 50.7, likely within 50.7b or 50.7a.
EL3	T4b	4–5.3	50.7a	50.7c	4	From fault at meter 3.8 to the south, unit 50.7c and 60.1 are tilted to the southeast (also seen in south wall of trench). They appear to be partially eroded where upthrown. Unit 50.7b and 50.7a thicken to southwest, recording gradual filling of the trough formed when 50.7c was at the ground surface or early in the deposition of unit 50.7b.

(continued)

TABLE 3 (Continued)

Event	Trench	Trench Location*	Oldest Unaffected Unit	Youngest Affected Unit	Quality†	Evidence
ELx	T9E	0	Upper 50	Lower 50	1	Bowl-shaped feature cuts unit 60.1 and the base of unit 50. Although, unit 50 is attenuated here, the fissure like feature appears to have been produced during deposition of the older section of unit 50.
ELx	T9W	0	Upper 50	Lower 50	1	Stratigraphically, the top of the bowl is midway through the unit 50 deposit, suggesting this could have occurred during EL3 or EL4.
ELx	T4b	0	Upper 50	Lower 50	0	Bowl-shaped, interbedded, thin, clean fine sand and clayey silt bounded by faults that truncate units up to 50 cm below the basal contact of 45.3.
ELx	T4b	0.5	Upper 50	Lower 50	0	Series of faults that reach the base of unit 50. These could be associated with the event that produced the bowl-shaped feature, as upward termination is not clear in massive character of unit 50.
ELx	T4W	−0.5	50.1	Lower 50	1	Trough-shaped interbedded thin, clean fine sand and clayey silt bounded by faults that truncate units up to 10 cm below the basal contact of 50.1.
ELx	T3	0–1	50	60.2	1	Trough-shaped wedge of unit 50 containing a 1–2 cm thick sandy horizon. Bounded by faults that juxtapose units 50 and 60.
ELx/2/3	T4W	−1.5	50.1	60.1	1	South-dipping fault exhibits 30 cm offset of the base of unit 50; however, lack of internal stratigraphy within 50 limits timing to between 60.1 and 50.1. Possible correlation to EL2, EL3, or ELx.
EL4	T4b	2.5	60.2	60.3	2	Narrow fissure formed in unit 60.3, filled with 60.2. If fault extends higher, it is not apparent in the gravel units. Low quality due to small size of feature and coarse units above.
EL4	T4b	3.5	60.1	60.3	2	Faulting offsets base of 60.2 but does not appear to cause offset in unit 60.1. Low quality due to gradational contacts in upper units that could obscure offset.
EL4	T4E	2–3	50	60.2	1	Two subparallel faults cut across 60.2. Unit 60.1 largely absent, with a wavy basal unit 50 contact suggestive of an erosional contact.
EL4	T6W	8–10	50	60.3	1	Unit 60.3 maintains constant thickness across broad fold. Unit 60 above 60.3 appears to thicken into a depression.
EL4	T6E	8–10	50	60.3	1	Unit 60.3 maintains constant thickness across broad fold. Unit 60 above 60.3 appears to thicken into a depression.
EL1/2	T3	1.6	45.1	50.2	1	Fault appears to truncate a silty unit interpreted to be 50.2 and terminates above this within organic-rich silt. Unit 45.3 is not preserved across this zone, and the fault does not offset unit 45.1 above. This could represent faulting during either EL1 or EL2.
EL1/2/3/x	T4b	1.6	50.5	45.1	0	Multistranded fault zone with over 50 cm of vertical separation on unit 50 and lower. Fault at 1.6 m is cryptic above the lower portion of unit 50, ending about midway in the organic-rich silt. Above the fault termination, unit 50 is massive, and there is no obvious offset of unit 45.1. Units 45.3 and 45.2 are not preserved at this location. Faulting could be associated with any of the other clearer faulting events that occurred during or after deposition of unit 50.
EL1/2	T9W	1.6–1.9	45.1	50.1	1	Multistranded fault zone produces significant vertical separation, juxtaposing unit 60.1 against a silt layer interpreted to correlate with unit 50.2. Above this truncation, the fault is cryptic or healed within the soil layers of (upper) 50. There is no offset of unit 45.1, and units 45.2–45.3 are not present at the crest of the moletrack. If unit 50.2 is correctly mapped, the southward thinning wedge of unit 50.1 from meters 2 to 3 could indicate that faulting may have occurred when 50.1 was at the ground surface, producing a high across, which 45.3 overlapped. Alternatively, this faulting could be associated with EL1, occurring after 45.3 was deposited (if it has eroded off the top of the pop-up and the variation in unit 50.1 thickness is not related to earthquake surface rupture).
EL1/2/3/x	T5E	4–5	Undiff.	Lower 50	0	Fault zone juxtaposes the entire section below unit 50 against undifferentiated gravelly deposits. Very weak stratigraphy at top of fault zone limits event possible event correlations.

(continued)

TABLE 3 (Continued)

Event	Trench	Trench Location*	Oldest Unaffected Unit	Youngest Affected Unit	Quality†	Evidence
EL1/2/3/x	T5W	4–5	Undiff.	Lower 50	0	Fault zone juxtaposes the entire section below unit 50 against undifferentiated gravelly deposits. Very weak stratigraphy at top of fault zone limits event possible event correlations.
EL1/2/3/x	T6E	3–4	Undiff.	Undiff.	0	Fault zone juxtaposes units 60 and below against older, undifferentiated gravel deposits. Lack of internal stratigraphy above the fault zone restricts more precise correlation of event evidence.
EL1/2/3/x	T6E	2.5–3.5	Undiff.	Undiff.	0	Fault zone juxtaposes units 60 and below against older, undifferentiated gravel deposits. Lack of internal stratigraphy above the fault zone restricts more precise correlation of event evidence.
EL2/3/x	T9E	0–1	60	Upper 50	0	Three faults cut through unit 60 and terminate within unit 50. Unit 50 is only 10–30 cm thick here and is limited to diffuse internal stratigraphy that cannot be correlated to the subdivisions of unit 50 that occur south of the fault zone in meter 2. Thus, the stratigraphic position of this event between EL1 and EL4 is unclear.
EL2/3/x	T9W	0–1	60	Upper 50	0	Three faults cut through unit 60 and terminate within unit 50. Unit 50 is ~40 cm thick here and only contains weak internal stratigraphy that cannot be correlated to the subdivisions of unit 50 that occur south of the fault zone in meter 2. However, compared to similar faults in T9E, these faults appear to terminate lower within unit 50. The stratigraphic position of this event between EL1 and EL4 is unclear.
EL2/3/x	T5E	6–11	45	60.1	2	Unit 60 is folded between meters 5 and 11. This deformation incorporates portions of lower unit 50. Unit 45 is horizontal and undeformed across the deformed lower units.
EL2/3/x	T5W	6–11	45	60	2	Unit 60 is folded between meters 5 and 11. This deformation incorporates portions of lower unit 50. Unit 45 is horizontal and undeformed across the deformed lower units.
EL2/3/x	T6E	6–8	45	60	2	Unit 60 and lower unit 50 are cut by two faults that converge into a single fault zone in the base of the trench. Unit 45 appears undeformed.
EL2/3/x	T6W	6–8	45	60	2	Unit 60 and lower unit 50 are cut by two faults that converge into a single fault zone in the base of the trench. Unit 45 appears undeformed.
EL3/4	T3	5.6–7.5	Base 50	60.1	1	Unit 60.1 is absent across multiple faults and tilted to south at meter 7.5. Unit 50 has massive character with apparent erosional base. Appears similar to subunits above 50.6 in T4b and T9.

*Locations and intervals containing evidence are listed based on the horizontal grid distance (in meters) on the respective trench log.

†Relative quality factor, estimated based on the clarity and ambiguity of the event evidence; 0 = low clarity or high ambiguity, 5 = clear features, unambiguous.

index of 50% was achieved, slightly lower than recommended in [Bronk Ramsey \(2009\)](#). In general, soils and other fine-grained deposits interpreted to have accumulated gradually are permitted to retain a broader range of sample ages than coarser-grained episodic deposits, which should be the best represented by the youngest ages. Ultimately, we retained 25 of 57 samples dated from T3, T4, T4b, and T9. We did not include the 15 samples from T5 and T6 in the earthquake age models, due to the potential uncertainty from correlating units between different portions of the site.

In the stratigraphy at Elizabeth Lake, some earthquake horizons are broadly constrained to an interval containing multiple dated units (e.g., EL3 in the interval defined by 50.7a, 50.7b, and 50.7c). To assess the impact of different interpretations regarding the placement of earthquake timing between or within units, we developed two separate sequence models using the same 25 radiocarbon ages in each. The “traditional” model

employs the common strategy of calculating earthquake ages, as if they are between two discrete layers that may contain multiple dated samples (i.e., phases; [Lienkaemper and Bronk Ramsey, 2009](#)). With this approach, EL1 is modeled as occurring between units 45.2 and 40 (1790–1890 C.E.), EL2 between units 50.5 and 50.4 (1450–1610 C.E.), EL3 within subunits of 50.7c (1310–1400 C.E.), and EL4 between 60.3 and 60.1 (1170–1250 C.E.). The uncertainty on individual earthquake ages from this model (Table 4) has mean 2σ ranges of 80–100 yr (EL1, EL3, and EL4) and 160 yr (EL2).

We developed another model (the modified model; Fig. 7b) that recognizes that the exact paleoground surface of EL3 and EL4 occurred within a set of dated layers, and that age ranges for sequential layers are often overlapping. In this model, instead of deriving an earthquake age from two bounding layers, the age of the earthquake is determined by the age of the layers that encompass the earthquake horizon. With this

(a)

Figure 7. (a) Age plot of all calibrated radiocarbon dates from the southeastern trenches, T3, T4, T4b, and T9. The resulting radiocarbon ages document a significant detrital component to charcoal ages, with up to 400 yr variability for samples from the same layer. Sample names denoted with a double asterisk are not included in the earthquake age models. (b) Our modified earthquake age model used to define earthquake ages (red probability distribution functions [PDFs]; Table 3). This model results from our recognition that the paleoground surfaces for ELx, EL3, and EL4 are not well constrained between individual units or by the radiocarbon dates within proximal units. We, therefore, model the earthquake age as spanning a unit or sequence of units. An alternate age model, using a traditional structure of constraining earthquakes between units or phases, is presented in Figure S14. Sequence models run in OxCal version 4.3.2 (Bronk Ramsey, 2017), using the IntCal13 atmospheric curve (Reimer et al., 2013). The color version of this figure is available only in the electronic edition. (Continued)

approach, we allow the earthquake age to be defined by multiple layers, reflecting our uncertainty in the exact stratigraphic location of the ground surface at the time of the earthquake, in

in the overlying unit 50.7. We, therefore, model the age range of EL4 as spanning unit 60, allowing the timing of the earthquake to effectively be constrained by the suite of pre-

contrast to the traditional model in which earthquake age ranges are bound by the youngest age in the unit that predates the earthquake and the oldest age in the unit that postdates the earthquake.

The differences between the traditional and modified earthquake age models appear in how the earthquake age ranges for EL3 and EL4 are derived. Specifically, for EL3, the post-earthquake layer (upper unit 50.7c) and the stratigraphy does not definitively place the EL3 ground surface before or after the middle unit of 50.7c. Recognizing this uncertainty, we model the earthquake age as spanning unit 50.7, allowing two samples from 50.7b and the overlying unit 50.6 to contribute what we consider as a more representative stratigraphic uncertainty for EL3 of 150 yr (1260–1410 C.E.; Table 4). Similarly, we interpret EL4 as having occurred during deposition of unit 60.2, but most of the samples from this unit and the bounding units (60.1 and 60.3) produced similar ages without a clear association of the younger deposits having younger ages. Unit 60 is coarse grained and likely records storm events that entrained sediment from the larger catchment. Strong overlap in the youngest samples from layers in unit 60 suggests that charcoal generated during a single fire event was incorporated in all of the unit 60 sublayers and that our samples did not capture the intermediate ages between the charcoal produced before the earthquake and the charcoal that occurs

(b)

Figure 7. Continued

earthquake charcoal within unit 60 and postearthquake charcoal that occurs in unit 50.7 (1090–1290 C.E.; Table 3). We retain the traditional model format for EL1 and EL2, because those earthquakes are the best constrained between units containing age control.

The mean earthquake ages for EL1 (1830) and EL2 (1520) are identical between the traditional and modified age models, because they use the same model constraints (Table 4). For EL3 and EL4, the mean earthquake ages vary by only 30 and 10 years, respectively (Table 4), despite the different age model structure. The important result from the different model structures is in the ranges of the earthquake ages, in which the traditional model provides age ranges that are narrower than the modified model ages by 60 and 120 yr for EL3 and EL4, respectively. We argue that the traditional sequence model artificially narrows the EL3 and EL4 earthquake age ranges, and that our modified age model is more representative of the uncertainty inherent to the dating and stratigraphic uncertainty on likely earthquake timing.

Estimating an age for ELx provides a separate challenge, because the stratigraphic

TABLE 4
Earthquake Ages at Elizabeth Lake

Event	Modified Age Model (Calendar Years C.E.)			Traditional Age Model (Calendar Years C.E.)		
	95% Range		Mean	95% Range		Mean
EL1	1790	1890	1830	1790	1890	1830
EL2	1450	1610	1520	1450	1610	1520
EL3	1260	1410	1330	1310	1400	1360
EL4	1090	1290	1220	1170	1250	1210
ELx	1390	1790	1590	1390	1790	1590

Figure 8. Examples of plausible earthquake scenarios for the SSAF. Vertical bars encompass 95% confidence bounds for earthquake age ranges at each paleoseismic site, labeled with corresponding site-specific event codes assigned by previous studies. Thin horizontal lines show plausible rupture lengths for earthquakes based on correlations of contemporaneous earthquakes. Gray shaded fields highlight geometric complexities associated with the restraining bend; darker gray indicates more complexities operating in that zone. (a) Plot of earthquakes per century, calculated through 2000 C.E., for each paleoseismic site, illustrating how the frequency of earthquakes changes through the restraining bend. (b) This scenario correlates all contemporaneous earthquakes between adjacent sites, making earthquakes as long as permissible within the age constraints. In this version, we interpret that ELx occurred after EL2 and, thus, correlates with FM2. (c) Earthquake scenario assuming that the [Fuis et al. \(2012\)](#) fault dip changes are real and promote rupture termination. If ELx is the same event as EL2, as shown here, the number of ruptures spanning the Big Bend and Mojave south sections can be reduced. (d) An example scenario with no assumed controls on rupture endpoints and shorter ruptures are permitted. Rupture endpoints for (b) and (c) are placed halfway between paleoseismic sites, whereas, in (d) the endpoints are arbitrarily positioned between adjacent sites. Site names (and references): BF, Bidart Fan ([Akçiz et al., 2010](#)); EL, Elizabeth Lake (this study); FM, Frazier Mountain ([Scharer et al., 2017](#)); PC, Pallett Creek ([Scharer et al., 2011](#)); PT, Pitman Canyon ([Seitz et al., 1997](#)); LR, Littlerock; WW, Wrightwood ([Weldon et al., 2004](#)). Fault intersections: GF, Garlock fault; SJF, San Jacinto fault. The color version of this figure is available only in the electronic edition. (Continued)

constraints on the timing of ELx cannot be unambiguously correlated to the dated stratigraphy south of the fault zone. Given the uncertainty in the ground surface at the time of ELx relative to the dated samples, both models permit that it could have occurred any time between layers 50.6 and 50.2, inclusive. As a result, the age range of ELx is long; it overlaps slightly with EL3 and encompasses the full range of EL2 (Table 4).

The possible event, ELy, is not included in the age model framework, because the evidence for this event is weak.

Furthermore, it is possible that the minor deformation discussed is the product of mechanisms other than direct surface rupture, such as minor triggered slip or differential settling. The stratigraphic position of the ELy possible event, just preceding evidence of 1857 (EL1) could be consistent with the 1812 Wrightwood earthquake that is recorded at paleoseismic sites to the southeast along the fault, or with a slightly older event recorded to the northwest (i.e., the penultimate earthquake at Frazier Mountain).

Notably, the ELy evidence is discernible only in the thickest sedimentary section exposed in any of our trenches, in which the accelerated sediment accumulation rate would be the most likely to record a separate event that occurred closely spaced in time to another event. The absence of evidence for ELy in our other trenches, therefore, does not necessarily mean that this event did not cause deformation in those trenches, but rather that it might not be discernible in areas where sediment accumulation was slower than in trench T9. In summary, the ELy deformation could record rupture of the 1812 earthquake, the penultimate Frazier Mountain earthquake, or it could correspond with EL1 or ELx. Alternatively, the appar-

ent ELy offset and sedimentation could have been the result of strong shaking from an earlier earthquake, such as, 1812, and it may not necessarily record surface rupture at this site. Until better age control (e.g., pollen or tree ring evidence) and additional deformation evidence can be found, the northern extent of the 1812 rupture remains unclear.

RUPTURES ON THE MOJAVE SECTIONS OF THE SAF

The earthquake chronology at Elizabeth Lake provides evidence of four or, possibly, five surface ruptures of the SAF since

Figure 8. Continued

~1100 C.E. The most recent event at Elizabeth Lake is temporally and stratigraphically consistent with the historic 1857 Fort Tejon earthquake, which is known to have ruptured this portion of the SAF (e.g., Sieh, 1978; unattributed excerpt from Santa Barbara Gazette, 22 January 1857, see [Data and Resources](#)). To evaluate possible along-fault correlations for prehistoric earthquakes on the SSAF, we constructed several scenarios that represent different assumptions for earthquake rupture behavior (Fig. 8). The frequency of earthquakes at individual paleoseismic sites (Fig. 8a; calculated as number of earthquakes per 100 yr) further highlights persistent along-fault differences in earthquake recurrence that exert a first-order control on the rupture histories permitted. Bidart Fan and Frazier Mountain exhibit similar earthquake frequencies for the Big Bend and Carrizo sections, which contrasts with distinctly lower frequencies for earthquakes at Elizabeth Lake and Pallett Creek on the Mojave south section. A higher frequency is also associated with the Wrightwood and Pitman Canyon sites. Comparing the location of paleo-earthquake recurrence frequency changes with the geometric

complexities—the restraining bend, fault intersections, and changes in fault dip—allows us to examine which of these factors play roles in terminating rupture.

If long, large-magnitude earthquakes typify the SSAF, then we can build a model in which earthquakes correlate between sites if their ages are contemporaneous. Building off of the model in [Scharer et al. \(2017\)](#), Figure 8b provides one of several possible variations of this end-member scenario, in which we only terminate a rupture if there is no earthquake with an overlapping age range at the next adjacent paleoseismic site. For simplicity, ruptures are assumed to terminate half-way between noncorrelating sites. Ambiguity about the timing of ELx relative to EL2 creates different correlation options, depending on whether ELx is the same event as EL2, or if it is a separate event that occurred before or after. We illustrate ELx as occurring as a separate event after EL2 in

Figure 8b on the basis that the fine-scale laminations preserved as stratigraphic evidence for ELx would not survive a significant amount of time within a few decimeters of the surface in a marsh environment. The longest permissible ruptures include the 1857 earthquake, a rupture in the mid-1500s that extends from Bidart Fan to Pitman Canyon, and a rupture from, at least, Frazier Mountain to Pitman Canyon near 1200 C.E. In this model, Wrightwood and Pitman Canyon typically rupture together, with some ruptures extending to include additional sites to the northwest. Similarly, of the six ruptures that connect the Carrizo and the Big Bend sections, since 1300 C.E., only two extend across the Mojave south section at Elizabeth Lake. The five rupture terminations between Frazier Mountain and Elizabeth Lake could be attributed to the Big Bend, the intersection with the Garlock fault, or the proposed change in dip of the SAF ([Fuis et al., 2012](#)).

We develop another scenario in which we impose rupture endpoints that correspond with the zones of fault intersections and modeled subsurface fault dip changes of [Fuis et al. \(2012\)](#), assuming that these features exert a strong influence on

the propagation of ruptures along the SSAF. This scenario increases the total number of earthquakes and shortens average rupture lengths (Fig. 8c). The difference in the number of earthquakes between Frazier Mountain and Elizabeth Lake requires at least four rupture endpoints to occur between these sites, and, in this model, we infer the ELx and EL2 are the same earthquake, increasing this difference to five. Superposition constraints due to the close timing of earthquakes 3–6 at Frazier Mountain require an additional termination between Frazier Mountain and Elizabeth Lake. We create two additional endpoints in this zone by splitting the long rupture near 1550 C.E. in Figure 8b into two separate ruptures, leaving just one additional earthquake (about 1200 C.E.) besides 1857 to propagate across the proposed fault dip change. The southeastern dip change encompasses the location of the Wrightwood site, permitting rupture endpoints to occur either northwest or southeast of Wrightwood while being consistent with the zone of a fault dip change. This scenario requires that more ruptures have endpoints to the northwest of Wrightwood, because of the difference in the number of recorded earthquakes between Wrightwood (eight earthquakes) versus Pallett Creek (six earthquakes) (Fig. 8c). Compared to the maximum rupture length model of Figure 8b, Figure 8c shows that the paleoearthquake ages can be consistent with a model in which subsurface changes in fault dip control the extent of earthquakes.

A model in which each paleoearthquake represents a single event would produce over 30 ruptures in ~700 yr, producing a recurrence rate that we consider to be unrealistic, given the historical record. Consequently, our third correlation scenario (Fig. 8d) chooses arbitrary endpoints and does not assume a priori that geometric changes play a role. This scenario illustrates that some earthquakes can rupture a single paleoseismic site, but more often multiple sites are ruptured (Fig. 8d). There are many permutations of this scenario due to fewer assumptions constraining earthquake correlations; however, differences in the number of recorded earthquakes at individual sites force all scenarios to contain a minimum number of four ruptures at Frazier Mountain that terminate before reaching Elizabeth Lake.

Between all possible rupture scenarios, the fault geometry and the number of earthquakes per site remain unchanged (except for decisions on treating ELx as the same as EL2 or a separate event). What becomes apparent is that sites with more earthquakes since 1100 C.E. are located near major fault bends and intersections with other major active faults (Garlock fault, San Jacinto fault). Conversely, the sites with fewer earthquakes (Elizabeth Lake and Pallett Creek) occupy the central portion of a relatively straight section of the SAF. Sites outside the central portion have similar records. For example, the apparent cluster of earthquakes 3–6 at Frazier Mountain contains only one earthquake that cannot be correlated to earthquakes at the Bidart Fan site (e.g., Fig. 8b), leaving Frazier

Mountain and Bidart Fan with seven and six earthquakes since ~1300 C.E., respectively. The rate at Wrightwood is slightly higher than neighboring sites, which may be attributed to interaction with the San Jacinto fault (e.g., [Weldon et al., 2004](#); [Lozos, 2016](#); [Scharer and Yule, 2020](#)). Along-fault earthquake frequency and earthquake correlation scenarios (Fig. 8)—demonstrate that greater fault geometric complexity corresponds with where earthquakes are more frequent, in this case, where the fault bends and intersects with other major active faults. Our new paleoearthquake data from Elizabeth Lake do not discriminate which of the scenarios for earthquake ruptures on the SSAF is the most accurate. However, these scenarios illustrate how the lower number of earthquakes on the Mojave south section (Elizabeth Lake and Pallett Creek) requires that multiple rupture endpoints occur near the fault geometry changes at the ends of this fault section, regardless of specific earthquake behavior assumptions.

Several studies have examined how Coulomb stress changes are imparted at the major fault intersections in Figure 8a. At the Garlock intersection with the SAF, two studies have argued that Coulomb stress changes from an earthquake near the Garlock fault could trigger rupture of the Garlock fault, which, in turn, could trigger rupture of the Mojave sections of the SAF ([McAuliffe et al., 2013](#); [Toda and Stein, 2020](#)). Coulomb models of the SAF show that 1857-like events reduce stress on the Garlock ([Lin and Stein, 2004](#)). Events EL2 and ELx at Elizabeth Lake have a similar age to the cluster of events at Frazier Mountain and a rupture on the Garlock fault, which [McAuliffe et al. \(2013\)](#) propose, could be a series of triggered events about 1450–1550 C.E. Although, ~100 yr uncertainties in ages of paleoearthquakes cannot demonstrate potential triggering mechanisms between closely timed earthquakes, the record shows that syncopation of Garlock and SAF earthquakes is not a common mode of rupture, given the longer recurrence interval of Garlock fault earthquakes (e.g., [Madugo et al., 2012](#)) and the lower frequency of earthquakes on the Mojave south section of the SAF compared to the Big Bend.

The 1857 Fort Tejon earthquake ruptured through the Big Bend of the SAF and continued through the oblique restraining section to the southeast for ~150 km. In contrast, the 1812 Wrightwood earthquake and lower surface-rupture frequencies for paleoseismic sites on the Mojave sections of the SAF indicate that these throughgoing ruptures are not typical. Dynamic rupture modeling with multicycle effects ([Duan and Oglesby, 2005](#)) and complex 3D fault structure ([Douilly et al., 2020](#)) show that earthquake ruptures that encounter a bend in a strike-slip fault can continue through the bend, but often terminate within a short distance past it. Furthermore, integrating the 3D fault geometry in the dynamic rupture models demonstrates the sensitivity of rupture propagation to small changes in fault geometry and pre-existing fault stress ([Douilly et al., 2020](#)). In the case of the Big Bend and Mojave sections of the

SAF, this implies that either dynamic rupture processes drive ruptures through the Big Bend or, perhaps, a previously unmodeled effect, such as subsurface fault dip change, also contributes to terminating ruptures as they reach the Mojave sections. This study suggests that the fault geometry changes aid in terminating some ruptures, leading to a lower earthquake frequency for the Mojave south section of the fault and providing a specific behavior that can be used as a test on models of rupture propagation through the restraining bend.

CONCLUSIONS

Our studies document new paleoearthquake constraints from the Elizabeth Lake paleoseismic site on the SSAF. The most recent earthquake (EL1) is consistent with the 1857 Fort Tejon earthquake. The ages of the preceding surface ruptures—EL2 (1450–1610 C.E.), EL3 (1260–1410 C.E.), and EL4 (1090–1290 C.E.)—are well constrained within an expanded stratigraphic section at the southeasternmost edge of the study site. We also document an event we term “ELx” that may be a separate earthquake (1390–1790 C.E.) or another expression of EL2 deformation that we are unable to correlate across the primary fault zone. Along-fault correlation of the paleoearthquakes at Elizabeth Lake with chronologies from adjacent paleoseismic sites confirm the relative infrequency of 1857-sized ruptures and illustrate an abrupt change in the number of earthquakes recognized at paleoseismic sites through the SSAF over the past 900 yr. Elizabeth Lake and Pallett Creek record up to five and six earthquakes, respectively, on the linear, vertical portion of the SSAF. In contrast, the adjacent Frazier Mountain and Wrightwood sites, which are located on collinear but kinematically complex portions of the SAF, record eight or nine earthquakes. This pattern requires more frequent earthquakes that rupture through the Big Bend–Mojave north section and the San Bernardino north section than occur through the straight and vertical Mojave south section. Consequently, we suggest that the combined effect of greater plate motion obliquity, fault intersections, and possible fault dip changes exert a significant control on the initiation and/or propagation of SSAF earthquake ruptures, and that this effect may be more persistent than correlations of earthquake behavior with bends in the fault surface trace. This observation may improve the correlation between fault bends and the endpoints of strike-slip earthquakes documented by previous studies (e.g., *Biasi and Wesnousky, 2017*), such as, in this study, in which the proposed changes in fault dip at the ends of the Mojave south section (*Fuis et al., 2012*) are not evident in the fault surface trace but may be assisting to terminate ruptures. Dynamic rupture models will also be strongly influenced by these subsurface bends, but, will not be captured, if fault geometry is defined by surface trace alone.

DATA AND RESOURCES

All data used in this article came from published sources listed in the references or provided in the supplemental material. The supplemental

material consist of (1) high-resolution photomosaics and logs from the paleoseismic trenches used in defining the stratigraphic and structural relations in this study, (2) code and output for our OxCal sequence model. The Santa Barbara earthquakes from 1855 to 1860 are available at https://projects.eri.ucsb.edu/sb_eqs/SBEQCatlog/SBEQdescrips/SBEQs1855-1860.html (last accessed October 2020).

DECLARATION OF COMPETING INTERESTS

The authors acknowledge that there are no conflicts of interest recorded.

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