

Paleoseismic history of faults ruptured in the 2019 Ridgecrest, California earthquake sequence

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Abstract The July 2019 Ridgecrest sequence ruptured two nearly orthogonal faults, the left-lateral, NE-striking Salt Wells Valley fault (M_w 6.4) and the right-lateral, NW-striking Paxton Ranch fault (M_w 7.1), highlighting the hazard of multi-fault earthquakes in the Walker Lane. To test whether similar conjugate ruptures occurred previously, we excavated five paleoseismic trenches and constrained paleo-earthquake timing using luminescence ages. Salt Wells Valley exposures record the 2019 rupture and only one earlier surface-faulting earthquake (17–27 ka), indicating infrequent activity. In contrast, Paxton Ranch strata preserve two Holocene events (4.4–8.7 ka and 10.6–14.6 ka) and up to three late Pleistocene events (17 ka and older) in addition to 2019. These records indicate that rupture along the Paxton Ranch fault commonly occurs independently of the Salt Wells Valley fault. Slip rates based on 2019 displacements and these event intervals are 0.2–1.3 mm yr^{-1} for Paxton Ranch and 0.01–0.09 mm yr^{-1} for Salt Wells Valley. The 2019 sequence therefore represents an unusual pairing of an often-active dextral fault with a much less active sinistral fault. The contrasting recurrence and lack of overlap, together with regional paleoseismic patterns, indicate that synchronous rupture is not systematic but instead varies among faults within an evolving network. This suggests that seismic hazard reflects a fault system in which rupture is governed by time-dependent fault network interactions rather than independent, repeatable behavior of individual faults.

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1 Introduction

Multi-fault ruptures and earthquake sequences are not uncommon in historical and instrumental records (e.g., Hudnut et al., 1989; Rockwell et al., 2000; Bell et al., 2004; Reitman et al., 2023; Pierce et al., 2024). Such occurrences underscore the potential for temporally clustered ruptures along multiple, often kinematically linked fault strands, which can produce larger overall seismic moments and more complex surface deformation than single-fault events (Stirling et al., 2017; Dee et al., 2021; Yang et al., 2021). Despite the growing recognition of multi-fault ruptures, detailed paleoseismic analyses remain essential to discerning whether multiple faults have consistently ruptured together during past earthquake cycles or if co-rupture is a geologically infrequent phenomenon (Rockwell et al., 2000; Scharer and Yule, 2020; Pierce, 2022; Vadman et al., 2023).

For example, a comprehensive study of the 2016 M_w 7.8 Kaikoura earthquake in New Zealand revealed that although individual faults within the rupture complex exhibited evidence of multiple Holocene events,

the precise arrangement of more than a dozen faults rupturing together in 2016 likely had not occurred at any time over the last 13,000 years (Stirling et al., 2017). Similarly, in the Eastern California Shear Zone, the 1992 Landers earthquake ruptured five principal faults (Camp Rock, Emerson, Johnson Valley, Kickapoo, and Homestead Valley), yet paleoseismic data suggest the penultimate surface-rupturing events along these structures did not align in time (Rockwell et al., 2000). Paleoseismic data from the northern Lost River fault zone indicate that prehistoric ruptures crossed structural boundaries and linked multiple fault sections, producing rupture patterns that differed from the 1983 M_w 6.9 Borah Peak event (DuRoss et al., 2022). Such findings demonstrate that adjacent faults can fail independently, co-rupture, or interact through stress transfer in ways that are not always straightforward from single-fault paleoseismic records alone (Marchandon et al., 2020).

While most seismic hazard models assume time-independent, Poissonian earthquake occurrence, these examples show that the geometry, proximity, and rupture history of faults can strongly influence the timing and magnitude of future events. This highlights the limitations of time-independent models in capturing the heightened hazard posed by fault networks,

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where stress interactions and temporal clustering may increase earthquake probabilities. Paleoseismic data remain essential for identifying these patterns of fault behavior and informing time-dependent models that better account for multi-fault and multi-segment rupture scenarios.

Against this backdrop, we study paleoseismic data to determine whether the two main faults responsible for the 2019 Ridgecrest earthquake sequence, the northeast-striking Salt Wells Valley fault and the northwest-striking Paxton Ranch fault (Figure 1), have ruptured in tandem or independently in previous earthquakes. Because radiocarbon-datable material is commonly scarce in the region (e.g., Bacon et al., 2020), we employ optically stimulated luminescence (OSL) dating of faulted deposits to constrain the timing of these paleoseismic events. Clarifying the relationship between earthquakes along these conjugate structures sheds light on their mechanical and kinematic linkage and provides key constraints for time-dependent seismic hazard models that must account for multi-fault and multi-segment rupture scenarios. By refining our understanding of the interplay between these two faults over multiple earthquakes, we can better anticipate future large-magnitude events in the Walker Lane and Eastern California Shear Zone.

2 The 2019 Ridgecrest Earthquakes

The Ridgecrest sequence began on July 4, 2019, when a M_w 6.4 earthquake ruptured ~14 km of the northeast-striking, left-lateral Salt Wells Valley fault (Figure 1). One day later, a M_w 7.1 event broke ~45 km of the nearly orthogonal, northwest-striking right-lateral Paxton Ranch fault (DuRoss et al., 2020; Ponti et al., 2020; Pierce et al., 2020; Thompson Jobe et al., 2020; Rodriguez Padilla et al., 2021; Gold et al., 2021). Seismologic and geodetic studies (Barnhart et al., 2019; Ross et al., 2019; Xu et al., 2020; Magen et al., 2020) demonstrated that the two faults are kinematically linked, forming a conjugate fault system accommodating complex rupture processes. Geomorphically, the Salt Wells Valley fault is expressed as a sinuous, low-relief lineament through granitic bedrock hills and pediments, whereas the Paxton Ranch fault trends across the western part of Searles Valley, the Spangler Hills, and into the China Lake basin (Figure 1). The 2019 Ridgecrest earthquakes emphasize the potential for multi-fault ruptures in the Walker Lane and Eastern California Shear Zone, echoing previous and subsequent large multifault events like the 1932 M_s 7.3 Cedar Mountain, 1992 M_w 7.3 Landers, 1999 M_w 7.1 Hector Mine, and 2020 M_w 6.5 Monte Cristo Range earthquakes (Sieh et al., 1993; Bell et al., 1999; Fialko et al., 2001; Dee et al., 2021, Figure 1).

3 Geologic Setting

The 2019 Ridgecrest earthquake sequence occurred within the southern portion of the Walker Lane, an approximately 100–150 km wide zone of discontinuous and distributed faulting that accommodates 10–12

mm/yr of northwest-directed dextral shear (Dixon et al., 2000; Unruh et al., 2003; Wesnousky, 2005a; Pierce et al., 2021, Figure 1). The Walker Lane merges with the Eastern California Shear Zone (ECSZ) to the south, here divided across the Garlock fault, and roughly follows the California–Nevada border northward beyond the Lake Tahoe region. This broad domain absorbs approximately 15–25% of the total northwest directed shear of the Pacific–North America plate boundary, while the San Andreas system carries the remainder (Wesnousky, 2005b). Throughout the Walker Lane/ECSZ corridor, multiple fault systems display a mix of right-lateral, left-lateral, and normal to oblique slip, reflecting the complex kinematics of transtensional shear (Dokka and Travis, 1990; Wesnousky et al., 2012; Pierce et al., 2021). Conjugate fault systems are common throughout the Walker Lane (e.g., Hatch et al., 2019; Pierce and Koehler, 2023).

The southern Walker Lane is characterized by a series of major north-northwest trending basins including Owens, Searles, Panamint, and Death Valleys. Each of these basins contains both north-striking normal faults (primarily west dipping aside from the eastern margin of the Sierra Nevada) and northwest-striking strike-slip faults. Collectively, these major fault systems—Owens Valley, Panamint Valley, Searles Valley, and others—accommodate the transtensional motion between the Sierra Nevada microplate, the Garlock fault, and the southern Basin and Range province.

3.1 Major Nearby Faults

The faults in the area surrounding the Ridgecrest ruptures are a mix of range bounding normal faults, including the Panamint Valley and Searles Valley/Tank Canyon faults, and both left- and right-lateral strike-slip faults, including the Garlock, Owens Valley, and Airport Lake fault (Figure 1). To provide context these faults are described in detail below.

The Garlock fault divides the southern Walker Lane from the Eastern California Shear Zone (ECSZ) and is one of the most prominent left-lateral strike-slip faults in California. Extending for over 250 km from near the San Andreas fault in the west to the southern Basin and Range in the east, it generally strikes east–west, although local bends and stepovers occur (Dawson et al., 2003; Rittase et al., 2014). Slip-rate estimates vary along strike, and have dramatically varied in time through the Holocene from ~3–13 mm/yr (Dolan et al., 2016; Fougere et al., 2024). Paleoseismic trenching studies have documented multiple Holocene surface-rupturing earthquakes, but the Garlock fault has not produced a major historical event (Dawson et al., 2003). Static and dynamic triggering of small earthquakes along the Garlock fault by nearby large ECSZ events, including the 1992 Landers and 2019 Ridgecrest sequences (Hill et al., 1993; Ramos et al., 2020).

Northwest of Ridgecrest, the Airport Lake–Little Lake fault system is a ~55-km-long NW-striking zone of dextral, normal, and oblique faulting in the southern Coso and Indian Wells Valley region. The Little Lake fault, together with the right-oblique Owens Valley fault to

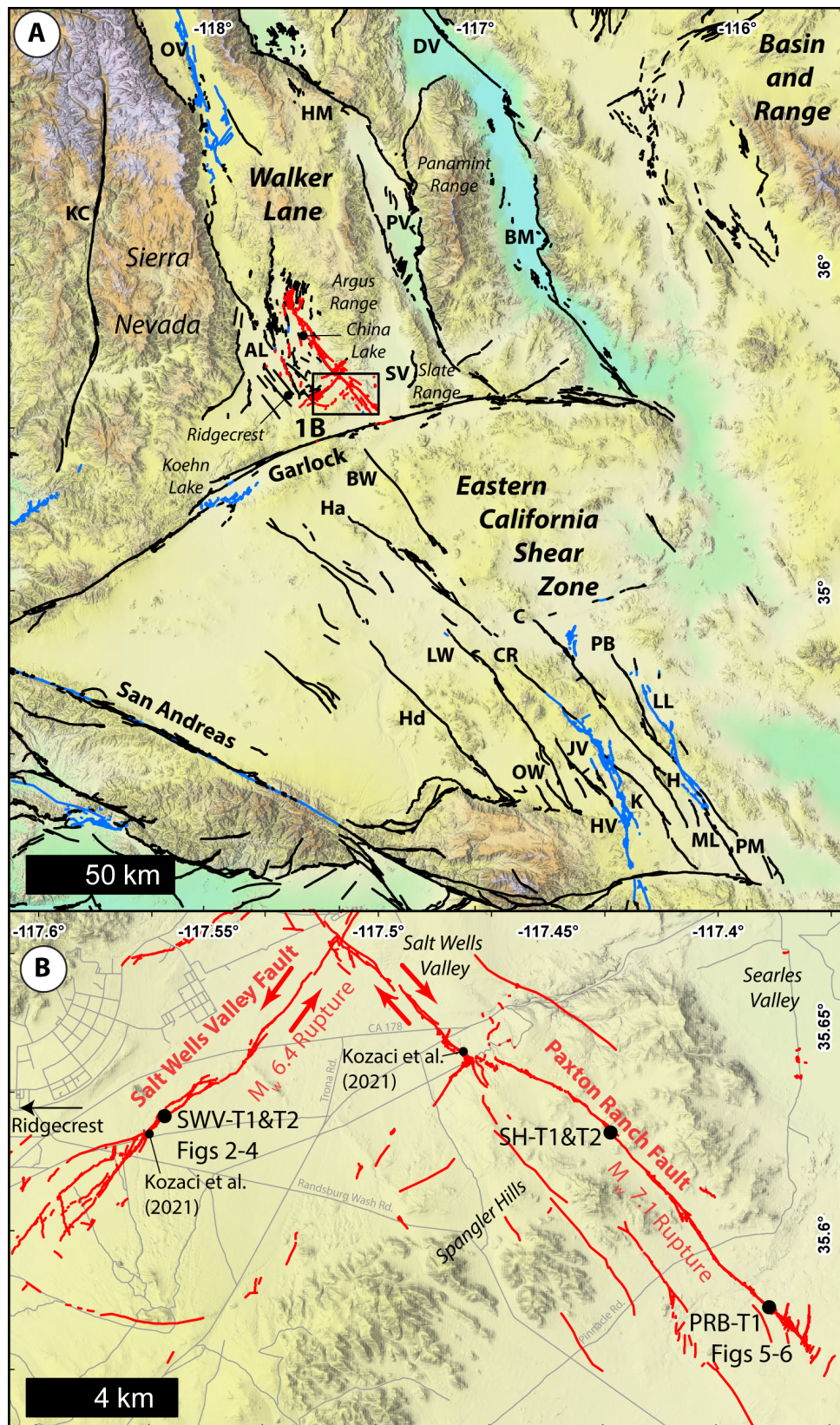


Figure 1 Upper: Quaternary faults of southeastern California plotted on a 10-m elevation colored hillshade. Black are Late Quaternary and blue are historical ruptures from the USGS Quaternary Fault and Fold Database. Red are the 2019 Ridgecrest surface ruptures (Ponti et al., 2020). The Garlock fault divides the Southern Walker Lane belt from the Eastern California Shear Zone. Lower: Location map of the southern portion of the Ridgecrest ruptures showing the 3 trench sites. Fault labels: OV: Owens Valley, KC: Kern Canyon, HM: Hunter Mountain, PV: Panamint Valley, DV: Death Valley-Fish Lake Valley, BM: Black Mountains, AL: Airport Lake-Little Lake, SV: Searles Valley-Tank Canyon, BW: Blackwater, Ha: Harper, Hd: Helendale-South Lockhart, LW: Lenwood-Lockhart, CR: Camp Rock-Emerson-Copper Mountain, C: Calico-Hidalgo, PB: Pisgah-Bullion, LL: Lavic Lake, HV: Homestead Valley, JV: Johnson Valley, OW: Old Woman Springs, ML: Mesquite Lake, PM: Pinto Mountain, K: Kickapoo, H: Hidalgo.

the north, forms an extensional relay across the Coso Range, while southward the Little Lake and Airport Lake faults merge into a highly segmented shear zone across Indian Wells Valley, and form a right-stepover to the Paxton Ranch fault. Geomorphic and geochronologic data indicate a late Quaternary dextral slip rate on the Little Lake fault of ~ 0.6 – 1.3 mm/yr (Amos et al., 2013). The most recent surface rupturing earthquake on the Little Lake fault occurred $<2,500$ years ago (Roquemore, 1981).

Farther north, the Owens Valley fault system trends roughly north–south along the eastern side of the Sierra Nevada. This zone famously ruptured in 1872 during the M 7.4–7.9 Owens Valley earthquake (Beanland and Clark, 1994). The fault is predominantly right-lateral strike-slip, though it also exhibits local normal or oblique components in places, with a late Quaternary slip rate of 0.6 – 1.6 mm/yr (Haddon et al., 2016). Paleoseismic and historical investigations indicate multiple late Pleistocene to Holocene events, including the 1872 rupture that formed prominent scarps visible along much of the valley (Bacon and Pezzopane, 2007; Kirby et al., 2008; Amos et al., 2013; Haddon et al., 2016).

The Panamint Valley fault is a major range-bounding normal and oblique-slip fault that defines the eastern margin of the Panamint Range and the western margin of Panamint Valley. It trends broadly NW–SE, parallel to other Walker Lane structures. Although large historical events on the Panamint Valley fault are not documented, geomorphic and paleoseismic evidence indicates multiple late Quaternary fault scarps and associated earthquake activity with a slip rate of 1.75 – 2 mm/yr (Hoffman, 2009; McAuliffe et al., 2013; Choi, 2016).

Immediately east of the Paxton Ranch fault lies Searles Valley, bounded by the southern Slate Range to the east, and the Argus Mountains and the Spangler Hills to the west and southwest, respectively (Figure 1). The Searles Valley–Tank Canyon fault system includes a set of subparallel and oblique-slip faults that cut across the eastern margin of the basin and exhibit both strike-slip and normal displacement at a rate of 0.2 – 0.3 mm/yr (Nunel et al., 2007).

3.2 Relationship of the 2019 Ruptures to Regional Structures

The two faults that ruptured during the 2019 Ridgecrest sequence—the NE-striking Salt Wells Valley fault and the NW-striking Paxton Ranch fault—are immediately north of the Garlock fault (Figure 1). Notably, the Paxton Ranch fault trends toward the broader Walker Lane and Eastern California Shear Zone (including the Airport Lake, Blackwater, Lenwood, and Helendale faults), whereas the Salt Wells Valley fault aligns more closely with the western part of the Garlock fault, prior to its more eastward bend near Koehn Lake (Dawson et al., 2003). In contrast with the other major faults in this part of the Southern Walker Lane, the Paxton Ranch fault is not associated with a major fault-bounded mountain range. The conjugate geometry of the Salt Wells Valley and Paxton Ranch faults highlights the complex stress regime that persists in the region, influenced by the

oblique plate boundary motion and the interaction of multiple fault systems with varying orientations.

3.3 Pluvial Lake Basins

During wetter climate periods of the late Pleistocene, the Owens River spilled into a chain of connected lakes, including Owens Lake, China Lake, Searles Lake, and Panamint Lake, eventually reaching Lake Manly in Death Valley (Bacon et al., 2020). The elevations of these basins and their sill points dictate overflow thresholds: China Lake overflows into Searles Lake at ~ 665 m, while Searles Lake spills into Panamint Lake at 690 m (Rosenthal et al., 2017). Five spillover events (where the elevation of China Lake exceeded the basin and flowed into Searles Lake) between China and Searles Lake from 13–18 ka are documented by Rosenthal et al. (2017). These repeated highstand events left behind beach bars, shoreline scarps, and lacustrine deposits that now serve as important stratigraphic markers in paleoseismic studies. Fault strands crossing these basins commonly offset these geomorphic features, providing opportunities to constrain Quaternary slip rates and fault activity.

4 Methods

4.1 Field Methods

We excavated five paleoseismic trenches in November 2020 to investigate the past behavior of the Salt Wells Valley and Paxton Ranch faults. Two trenches were placed across the Salt Wells Valley fault between Highway 178 and Randsburg Wash Road (SWV–T1 and –T2), two trenches were located across the Paxton Ranch fault in the Spangler Hills (SH–T1 and –T2), and one was sited in southwestern Searles Valley, near the Trona Pinnacles (Basin trench) (Figure 1). We targeted areas where pre-2019 tectonic geomorphology suggested potential for well-preserved paleoearthquake evidence.

We generated high-resolution orthophotos at each trench site using a DJI Phantom 4 Pro v2.0 equipped with a TEOKIT dGPS, following the methods described in Pierce et al. (2024). Flights were conducted at ~ 30 -m AGL, providing sub-centimeter-scale ground resolution. Each flight plan maintained ~ 75 – 80% forward and 65 – 70% sidelap. An Emlid Reach RS2 base station collected raw GNSS data, allowing post-processed kinematic (PPK) corrections for accurate camera positions. Images were processed in Agisoft Metashape to produce ~ 8 mm/pixel resolution orthophotomosaics. The resulting orthophotos were used to provide precise documentation of surficial fault features at the three trench sites.

Standard paleoseismic field protocols (e.g., McCalpin, 2009) were followed. Trench walls were photographed, gridded, and logged using both in-field mylar drafting and digital photogrammetry. We used Agisoft Metashape to create orthophotomosaics of each trench wall (Pierce and Koehler, 2023). Sedimentary units were distinguished based on grain size, sorting, color, primary structures, and cross cutting relationships. Luminescence samples were collected by ham-

mering opaque metal tubes into undisturbed trench wall sediments and capping packed tubes for transport.

4.2 OSL Measurements and Analysis

Samples were prepared and analyzed at the Desert Research Institute Luminescence Research Laboratory in Reno, Nevada. Potassium-rich feldspar grains (180–250 μm) were isolated from bulk sediment and measured using single-grain infrared stimulated luminescence (IRSL) on a Risø TL-DA-20 reader. Equivalent dose (D_e) values were determined using a modified single-aliquot regenerative dose (SAR) protocol for the IR₅₀ signal (Murray and Wintle, 2000, 2003; Wallinga et al., 2000). A dose recovery test yielded a measured-to-given dose ratio of 0.95 ± 0.01 , indicating that the measurement protocol was appropriate for these samples.

Equivalent dose distributions exhibited moderate overdispersion (>40%). Most samples displayed broadly symmetrical D_e distributions without clear evidence of discrete grain populations and were therefore modeled using the Central Age Model (CAM; Galbraith and Green, 1990). In contrast, samples OV001, OV028, and OV029 showed evidence of post-depositional mixing, characterized by elevated overdispersion and the presence of low-dose grain populations. These samples were therefore analyzed using the Finite Mixture Model (FMM; Galbraith et al., 1999) to isolate the dominant depositional D_e population. Anomalous fading rates (g -values) were measured following Auclair et al. (2003), and final ages were corrected using the model of Huntley and Lamothe (2001). Environmental dose rates were calculated from U, Th, and K concentrations measured by ICP-MS/AES. Dose rate and age calculations follow Durcan et al. (2015).

Detailed sample preparation procedures, instrumentation parameters, grain rejection criteria, fading measurements, and D_e distributions for all samples are provided in the Supplementary Material.

5 Results

5.1 Salt Wells Valley Fault Trenches

Two trenches (SWV-T1 and SWV-T2) were excavated at one location across the surface ruptures of the Salt Wells Valley fault (Figure 2). At this location the 2019 M_w 6.4 surface ruptures cut across low relief alluvial/pediment surfaces and anastomosing active channels. The low-relief alluvial/pediment surfaces are ~ 0.5 m above the active channels and are clear in aerial imagery from their vegetated appearance forming sharp contrast with the unvegetated active channels. Shallow granitic bedrock outcrops generally follow the trace of the fault. The site was chosen as we suspected that the alluvial surfaces at this site may preserve evidence of previous earthquakes. The SWV-T1 trench (117.5627°W 35.6276°N, Figure 3) was excavated across a pediment surface and the SWV-T2 trench (117.5625°W 35.6277°N; Figure 4) was excavated in the center of a sandy wash with a left-lateral offset of the northeast bank of ~ 124 cm from the 2019 M_w 6.4 earthquake.

5.2 Salt Wells Valley Trench 1 (SWV-T1)

SWV-T1 (Figure 3) was a 10-m-long, 1.9-m-deep trench oriented N45°W across the M 6.4 surface rupture in a pediment surface. The trench primarily exposed heavily sheared and weathered granitic bedrock overlain by thin colluvial and alluvial sediments.

The lowest unit on the southeast end of the trench (Unit 6) is a heavily sheared and weathered light-blue to gray and brown granitic bedrock unit. In places, the faulting in this unit forms pulverized fault gouge. The top of Unit 6 has characteristics consistent with a weathered C horizon, with blocks of material surrounded by finer grained sands filtering in from above forming a wavy to irregular gradational contact.

Abutting Unit 6 across the fault zone to the northwest is Unit 5, a sedimentary unit comprised primarily of light tan sandy grus with scattered cobbles. Unit 5 is moderately cemented (Stage 2 carbonate) and contains numerous carbonate-lined fractures and faults. The top of part of Unit 5 has a blocky texture, interpreted to be a buried Bt soil horizon. Above Unit 5 is a sharp contact with Units 3 and 4.

Unit 4 is an undifferentiated assemblage of massive, loose gray sandy deposits with scattered pebbles and cobbles. It overlies Units 5 and 6 across a sharp, irregular nonconformable contact.

Unit 3, Unit 2, and Unit 1 are sandy deposits with scattered gravels and cobbles of varying color and gradational contacts. Unit 3 is reddish, unstratified, and ~ 10 –30 cm thick. Unit 2 is brown, also unstratified, and ~ 20 –30 cm thick. Unit 1 caps the deposit and is lighter gray, weakly bedded, and ~ 10 –30 cm thick.

We interpret Units 1–3 to be Holocene/latest Pleistocene alluvial/slope wash deposits. Unit 4 is interpreted to be a mixture of sheared and bioturbated materials derived from the surrounding units. Unit 5 is interpreted to be a late Pleistocene alluvial deposit that was stable long enough to develop a soil prior to the younger depositional episodes. Unit 6 is weathered bedrock.

Steeply dipping faults were identified throughout the exposure. Overall, the faults form a broad positive flower structure with most faults dipping slightly towards the center of the exposure. No discrete vertical displacements were observed across units due to the irregularity of contacts and difficulty correlating units across fault zones. Unit 5 contains numerous carbonate-lined fractures, and Unit 6 contains gouge-lined faults.

The 2019 surface ruptures are confined to the central part of the trench along 4 primary fault strands. Carbonate- and gouge-lined fractures in Units 5 and 6 that terminate at the base of Units 2, 3, and 4 provide evidence of one or more pre-2019 earthquakes, while the pulverized bedrock in Unit 6 provides evidence for additional older events.

Two luminescence samples (OV029 and OV028) were collected from the northwest side of the exposure in Units 3 and 5, respectively. Both yielded late Pleistocene ages— 14.51 ± 1.85 and 22.17 ± 2.92 , respectively using the central age model (Tables 1 and 2). These ages place upper and lower limits on the timing of at least one

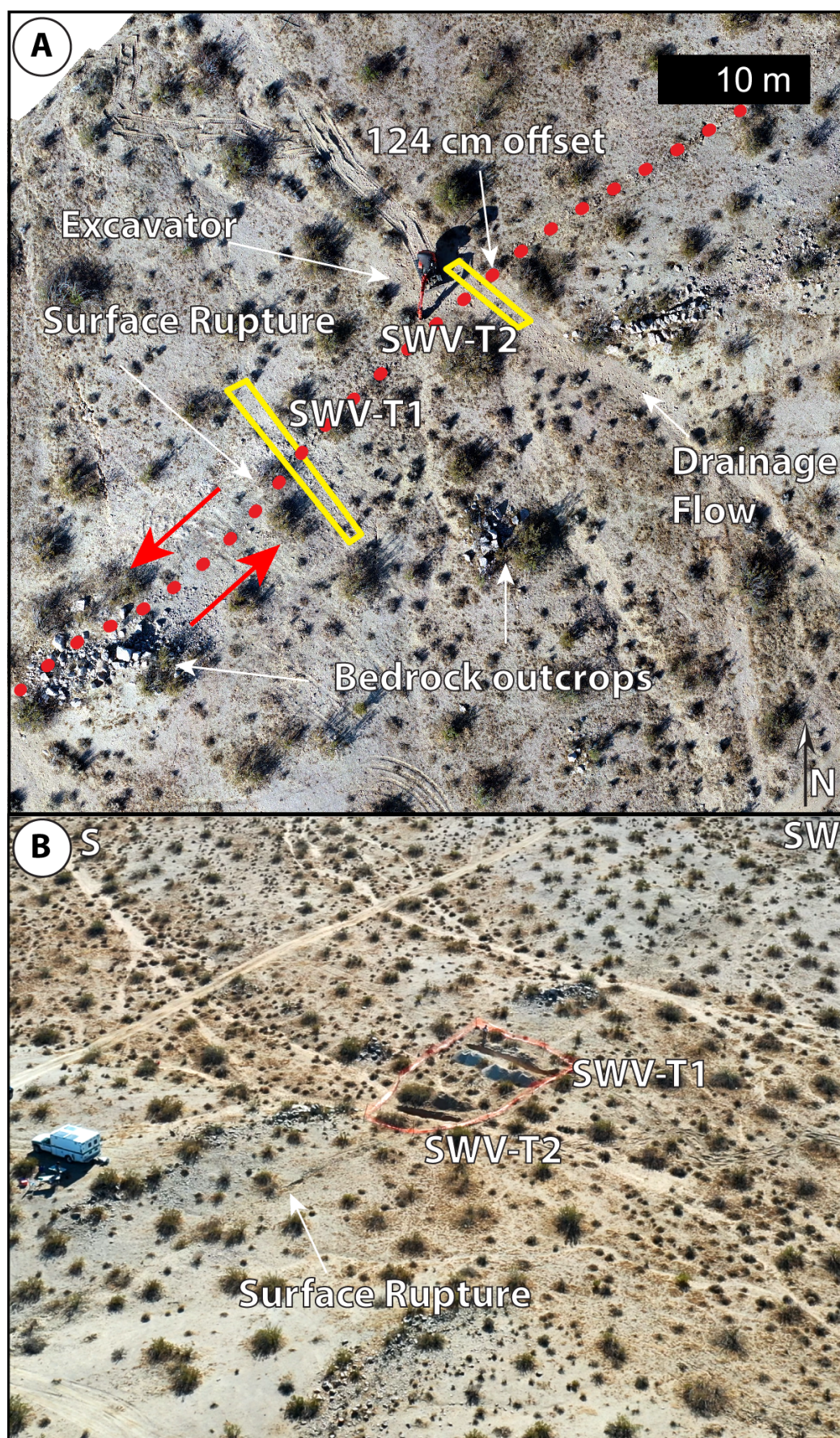


Figure 2 Salt Wells Valley (SWV-T1/2) trench sites. A: UAV orthophotomosaic from November 2020 showing the two trench outlines (yellow) prior to excavation. Note the shallow bedrock outcrops at the surface and sharp surface rupture (red dashed line). Drainages flow to the northwest. B: Oblique aerial photo looking southward showing opened trenches. Coordinates: 35.6277, -117.5625.

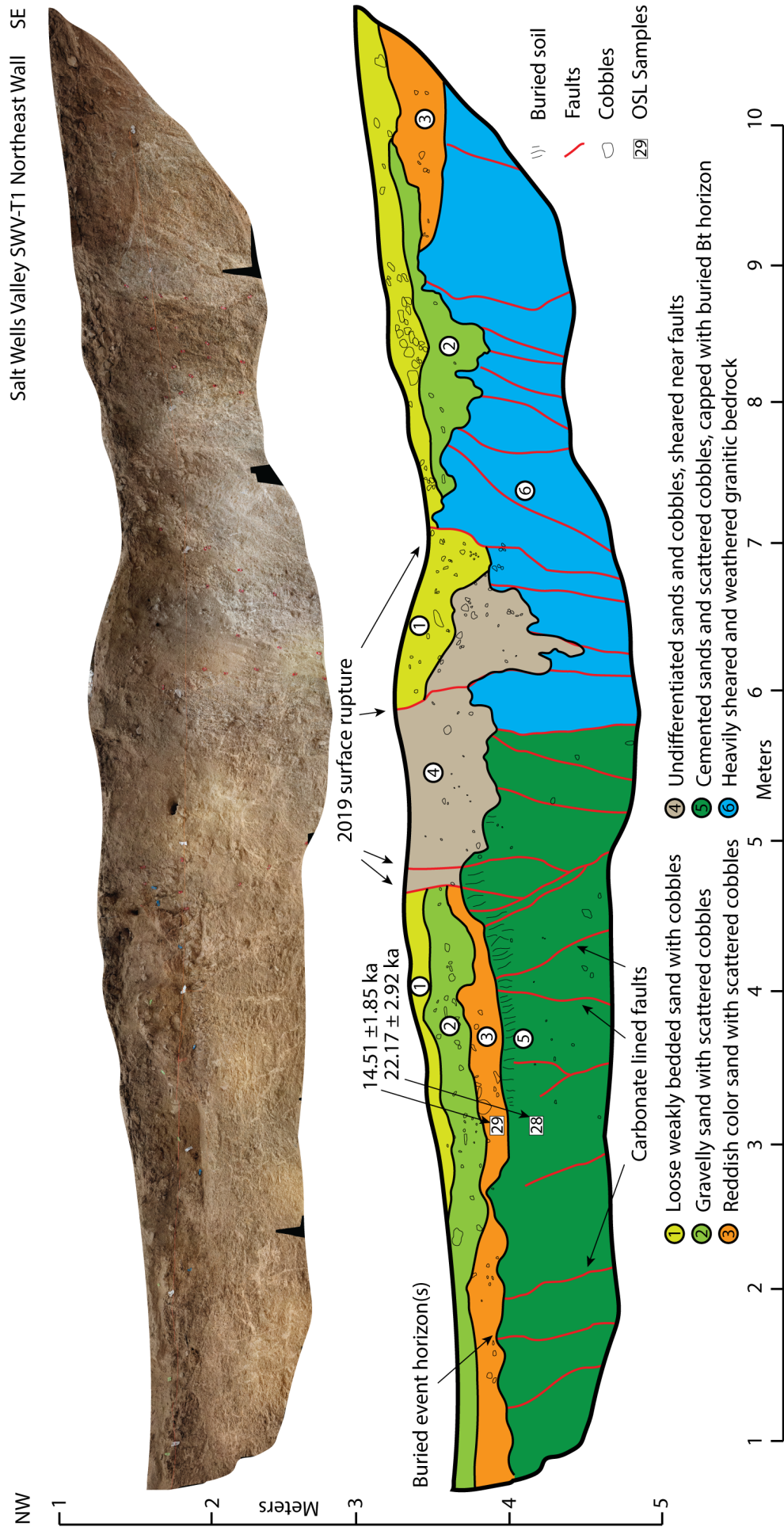


Figure 3 Salt Wells Valley fault trench SWV-T1 (northeast wall). This trench revealed heavily sheared granitic bedrock in fault contact with Pleistocene alluvium and all capped with thin Late-Pleistocene to Holocene alluvium. Two luminescence samples limit the event horizon above faults that terminate at the Unit 3-5 contact on the northwest end of the trench. Sample numbers are the same as Tables 1 and 2 with the ‘OV0’ prefix omitted.

Sample ID	Depth (m)	N ^a	Over-dispersion (%)	Equivalent Dose (Gy) ^b	Fading rate (%/decade) ^c	Total dose rate (Gy/ka)	Un-corrected age (ka)	Fading-corrected age (ka) ^d
OV001	0.20	22	195 ± 33	11.92 ± 1.00	6.42 ± 0.39	4.57 ± 0.33	2.61 ± 0.29	4.68 ± 0.66
OV002	0.85	160	55 ± 3	22.84 ± 1.00	6.09 ± 0.42	4.45 ± 0.34	5.14 ± 0.45	9.15 ± 1.05
OV003	0.95	86	52 ± 7	24.36 ± 1.40	4.81 ± 0.55	4.57 ± 0.34	5.33 ± 0.50	8.25 ± 0.94
OV004	1.00	106	51 ± 4	28.47 ± 1.47	5.82 ± 0.51	4.54 ± 0.33	6.27 ± 0.55	10.90 ± 1.27
OV005	1.05	106	52 ± 8	30.50 ± 1.46	5.39 ± 0.48	4.18 ± 0.31	7.30 ± 0.64	12.16 ± 1.50
OV006	2.10	126	63 ± 6	27.73 ± 1.59	7.48 ± 0.46	4.40 ± 0.32	6.30 ± 0.58	13.49 ± 1.59
OV007	2.50	130	64 ± 4	36.21 ± 2.09	6.66 ± 0.33	3.98 ± 0.30	9.10 ± 0.86	17.83 ± 1.78
OV008	2.60	100	54 ± 5	45.43 ± 2.55	4.98 ± 0.38	4.04 ± 0.31	11.25 ± 1.07	18.15 ± 1.79
OV009	1.40	122	64 ± 9	36.68 ± 2.17	5.82 ± 0.41	4.79 ± 0.37	7.66 ± 0.74	13.43 ± 1.46
OV020	0.60	87	49 ± 4	26.11 ± 1.44	3.54 ± 0.29	5.37 ± 0.35	4.86 ± 0.41	6.61 ± 0.56
OV021	0.20	82	42 ± 4	28.16 ± 1.39	4.82 ± 0.31	6.04 ± 0.38	4.66 ± 0.37	7.19 ± 0.58
OV028	0.75	54	92 ± 10	75.37 ± 4.08	6.87 ± 0.56	6.92 ± 0.42	10.90 ± 0.89	22.17 ± 2.92
OV029	0.50	76	63 ± 6	57.84 ± 2.56	6.30 ± 0.55	7.41 ± 0.45	7.81 ± 0.59	14.51 ± 1.85

^a. N is the number of D_e determinations accepted after screening.

^b. D_e values were calculated using the Central Age Model (CAM) (Galbraith et al., 1999), except for OV001, OV0028, and OV029, where the Finite Mixture Model (FMM) of Galbraith and Green (1990) was applied. For FMM-based calculations, only the dominant component is reported.

^c. Fading rates (g-values, t_c = 2 days) were measured over the course of ~24 hours on all single grain discs using the approach of Auclair et al. (2003) after D_e measurements were conducted. The reported single grain g-values reflect the weighted mean of all single grain discs.

^d. Luminescence ages, rounded to the nearest 10 years, are expressed as thousands of years before AD 2024. The age uncertainty is reported at 1 sigma.

Table 1 Summary of single grain K-feldspar luminescence age results.

penultimate earthquake on the Salt Wells Valley fault.

5.3 Salt Wells Valley Trench 2 (SWV-T2)

SWV-T2 (Figure 4) was a 6-m-long, 1.5-m-deep trench oriented N50°W across the M6.4 rupture in the active channel. The trench primarily revealed sandy grus units overlying an indurated Pleistocene paleosol cut by a simple fault zone.

The lowest unit, Unit 5, is a fine-grained, light-gray, indurated sedimentary unit with scattered pebbles. The excavator created clay smears in this unit. It exhibits a blocky/prismatic structure, most pronounced on the southeast side of the fault zone, and we interpret it as a mid-Pleistocene paleosol based on its degree of induration and pedogenic structure. The top of Unit 5 is a sharp, wavy to irregular contact with the unconformably overlying Unit 4.

Units 4 through 1 are composed of sandy, decomposed granitic grus with infrequent scattered pebbles and cobbles. They show increasing rubification with depth:

- Unit 4 is reddish-brown and massive, ~25-30 cm thick, with a gradational contact with overlying Unit 3;
- Unit 3 is a darker red-brown massive unit, ~35-50 cm thick, in sharp contact with Unit 2;
- Unit 2 is dark brown with cross-bedded laminations, ~25 cm thick, thinning across the fault zone to the northwest to ~4 cm thick, in sharp contact with Unit 1;
- Unit 1 is a light gray, loose, cross-bedded laminated sand at the top of the section, ~15 cm thick.

We interpret Units 1–4 as Holocene channel deposits, each conformably overlying the previous, and based on the lack of stratigraphy we interpret moderate bioturbation of Units 3 and 4.

Two steeply dipping primary fault strands, F1 and F2, merge in Unit 5 at the trench base, forming a ~45-cm-wide negative flower structure (graben) in the overlying sediments. Units 1–4 are downdropped between F1 and F2, with Unit 2 being thickest in the graben block. The Unit 2–3 and 3–4 contacts are down-dropped by ~20 cm between faults F1 and F2. Each fault strand is 2–4 cm wide and creates local fissures in the upper units. F1 is vertical in Units 1–4 and dips 72°SE in Unit 5, while antithetic F2 dips 75°NW. A minor fault, F3, branches from F1 with a 48°SE dip through Units 1–3. No vertical fault terminations, colluvial wedges, or other distinct event horizons were observed. Apparent thickness change of units across faults, particularly of Unit 2 between faults F1 and F2 is likely a result of lateral slip among channel deposits with spatially variable thicknesses.

Based on the relatively simple fault zone structure and lack of discrete paleoearthquake markers, we infer that Units 1–4 experienced only the 2019 earthquake rupture. Although the vertical displacement of the Unit 1–2 contact is clearly less than that of the Unit 2–3 and 3–4 contacts, we attribute this to lateral unit thickness variations and predominantly strike-slip motion.

Two luminescence samples (SWV-T2, OV021 and OV020) were collected from the southeast side of the fault zone in Units 3 and 4, respectively (Figure 4). Both yielded mid-Holocene ages—7.19 ± 0.58 ka and 6.61 ± 0.56 ka (Table 1), respectively, using the central age model. These ages are inverted but overlap within their 1-sigma error bounds. Since these units were only

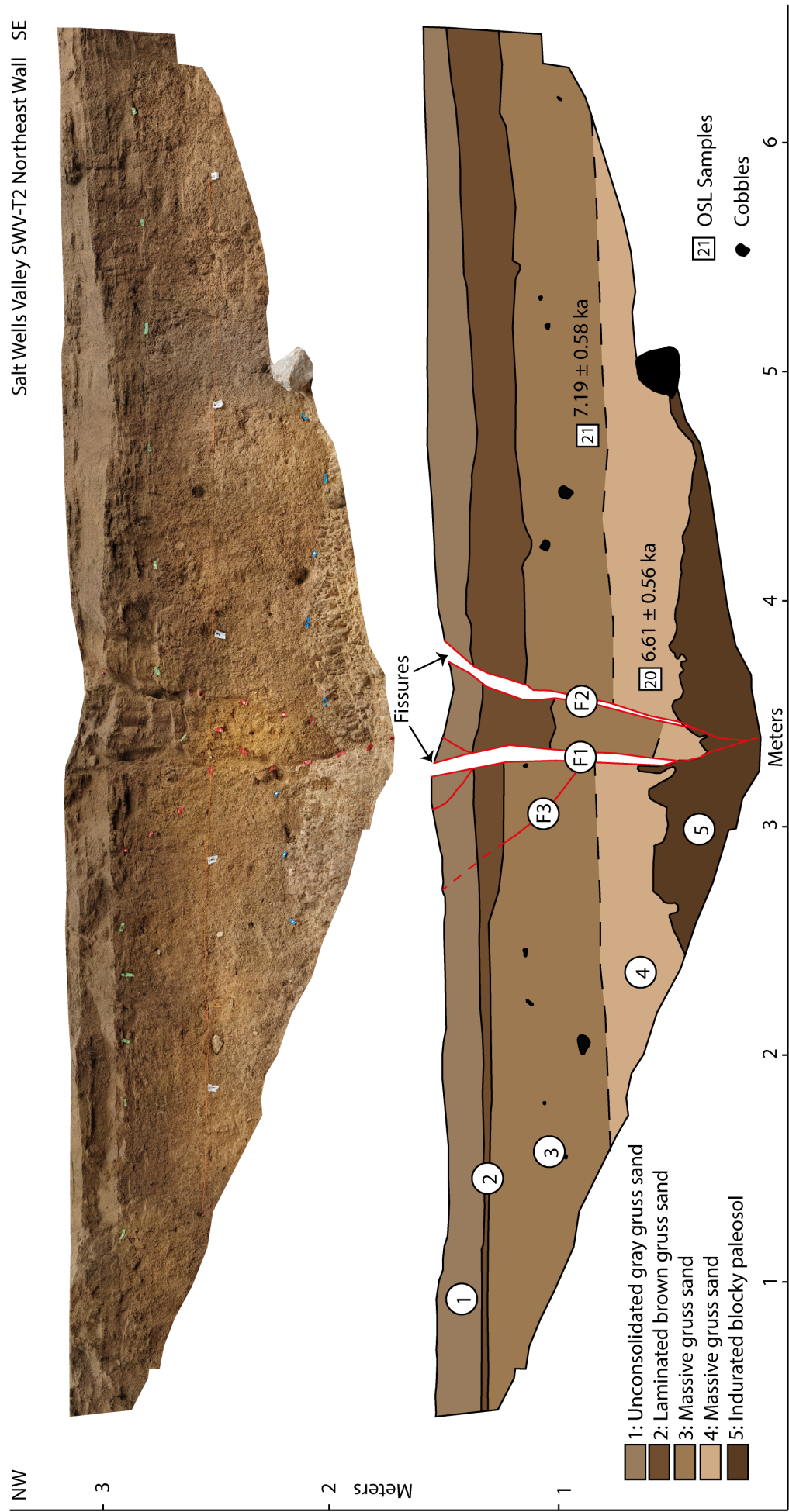


Figure 4 Salt Wells Valley fault trench SWV-T2 (northeast wall). A simple fault zone in Holocene sands only displays evidence of the 2019 M 6.4 earthquake. Sample numbers are the same as Tables 1 and 2 with the ‘OV0’ prefix omitted.

Sample ID	Depth (m)	U (ppm) ^a	Th (ppm) ^a	K (ppm) ^a	Moisture content (%)	External alpha dose rate (Gy/ka) ^b	External beta dose rate (Gy/ka) ^c	External gamma dose rate (Gy/ka)	Cosmic dose rate (Gy/ka) ^d	Total dose rate (Gy/ka) ^e
OV001	0.20	1.85	5.37	2.83	1 ± 5	0.00 ± 0.00	2.41 ± 0.26	1.12 ± 0.10	0.27 ± 0.03	4.57 ± 0.33
OV002	0.85	1.19	4.21	2.97	1 ± 5	0.00 ± 0.00	2.41 ± 0.27	1.07 ± 0.10	0.21 ± 0.02	4.45 ± 0.34
OV003	0.95	1.37	4.79	3.01	1 ± 5	0.00 ± 0.00	2.47 ± 0.27	1.12 ± 0.11	0.21 ± 0.02	4.57 ± 0.34
OV004	1.00	2.05	6.52	2.71	1 ± 5	0.00 ± 0.00	2.37 ± 0.25	1.21 ± 0.11	0.21 ± 0.02	4.54 ± 0.33
OV005	1.05	1.8	5.46	2.51	2 ± 5	0.00 ± 0.00	2.14 ± 0.23	1.07 ± 0.10	0.21 ± 0.02	4.18 ± 0.31
OV006	2.10	1.53	5.05	2.96	1 ± 5	0.00 ± 0.00	2.53 ± 0.28	1.14 ± 0.11	0.18 ± 0.02	4.40 ± 0.32
OV007	2.50	1.49	4.93	2.45	2 ± 5	0.00 ± 0.00	2.05 ± 0.22	0.99 ± 0.09	0.17 ± 0.02	3.98 ± 0.30
OV008	2.60	1.04	3.63	2.67	1 ± 5	0.00 ± 0.00	2.16 ± 0.24	0.95 ± 0.09	0.17 ± 0.02	4.04 ± 0.31
OV009	1.40	1.18	3.65	3.38	1 ± 5	0.00 ± 0.00	2.69 ± 0.30	1.14 ± 0.11	0.20 ± 0.02	4.79 ± 0.37
OV020	0.60	2.19	12.10	2.99	1 ± 5	0.26 ± 0.08	2.81 ± 0.29	1.56 ± 0.13	0.23 ± 0.02	5.37 ± 0.35
OV021	0.20	2.94	17.4	3.0212	1 ± 5	0.36 ± 0.11	3.05 ± 0.30	1.84 ± 0.15	0.28 ± 0.03	6.04 ± 0.38
OV028	0.75	3.66	29.80	2.66	1 ± 5	0.56 ± 0.17	3.14 ± 0.29	2.48 ± 0.21	0.22 ± 0.02	6.92 ± 0.42
OV029	0.50	3.76	26.50	3.38	1 ± 5	0.52 ± 0.16	3.62 ± 0.35	2.51 ± 0.21	0.24 ± 0.02	7.41 ± 0.45

^a. Radionuclide concentration measurement uncertainties are 10% for U, Th, K. Dose rates were calculated using the conversion factors of Liritzis et al. (2013) and are shown rounded to two decimal places; ages were calculated using values prior to rounding.

^b. Samples OV001-OV009 were HF etched prior to measurements to remove the outer alpha-irradiated surface of the grains. The remaining samples were not HF etched. The alpha dose rate assumes an a-value of 0.15 ± 0.05 and alpha grain size attenuation factors from Brennan et al. (1991).

^c. Beta dose rates were calculated using the grain size attenuation factors of Guérin et al. (2012).

^d. Cosmic dose rates (Gy/ka) were calculated according to Prescott and Hutton (1994).

^e. The total dose rate incorporates an internal dose rate based on an assumed internal K concentration of $10 \pm 2\%$, based on the work of Smedley et al. (2012). The total dose rate has been adjusted for an estimated moisture content over the course of burial history.

Table 2 Summary of dose rate data used for luminescence age calculation.

faulted in 2019, these mid-Holocene ages place a minimum bound on any earlier rupture. Hence, the penultimate event on this segment of the Salt Wells Valley fault predates ~ 7.2 ka.

5.4 Paxton Ranch Fault Trenches: Spangler Hills

In the Spangler Hills, two trenches were opened across a ~ 0.5 -m-high fault scarp on a bedrock platform incised by southwest-draining fans (SH-T1 & -T2 on Figure 1B). Although both trenches revealed clear evidence of the 2019 rupture as well as fractures and faults consistent with older events, correlation of specific event horizons was difficult due to thin Holocene stratigraphy and shallow bedrock. Moreover, low tufa platforms at higher elevations indicate this site was submerged under Searles Lake highstands in the late Pleistocene, but the sedimentary record was not sufficiently continuous to bracket distinct events. These trench logs are included in the electronic supplement.

5.5 Paxton Ranch Fault Basin Trench (PRB-T1)

A single 21-m-long, 2-m-deep trench was excavated across an uphill-facing scarp formed by the 2019 earthquake in a wash south of Pinnacle Road at ~ 579 m elevation (117.3845°W , 35.5825°N ; Figure 5). The trench was oriented $\text{N}20^\circ\text{E}$, roughly perpendicular to the scarp, and was selected because post-earthquake ponding on

the downthrown, upstream side of the scarp had begun depositing a thin silt/clay layer, suggesting potential for well-preserved buried event horizons. Right-lateral displacement of ~ 120 cm was measured in this area following the 2019 event (Ponti et al., 2020). The right-bank terrace riser at this site appears offset by ~ 7 -13 m (Figure 5C), suggesting cumulative displacement from repeated late Pleistocene-Holocene surface ruptures. The terraces are underlain by lacustrine sediments.

The trench exposes fluvial deposits that cap late Pleistocene lacustrine sequences, and a prominent fault zone uplifts the downstream (northeast) reach (Figure 6). Units 3-9 are interpreted as nearshore lacustrine deposits. Units 2-7 warp upward toward the fault zone from the southwest, dipping $\sim 5^\circ$ NE at a distance but locally up to 25° SW near the fault zone, forming a gentle syncline geometry.

- Unit 9 is exposed only on the northeast side of the fault zone and is >1.2 m thick. Most of Unit 9 is a light gray massive fine sand with several coarser sand interbeds in the lower part, and several thin, intermittent white silty-clay stringers.
- Unit 8 is also only exposed on the northeast side of the fault zone, is ~ 50 cm thick, and is an interbedded sequence of well sorted medium sands, coarse sands, fine pebbles, and a ~ 3 -cm-thick light-brown clay bed. It conformably overlies Unit 9 on the northeast side of the fault zone, and is interpreted to be a nearshore/beach deposit.

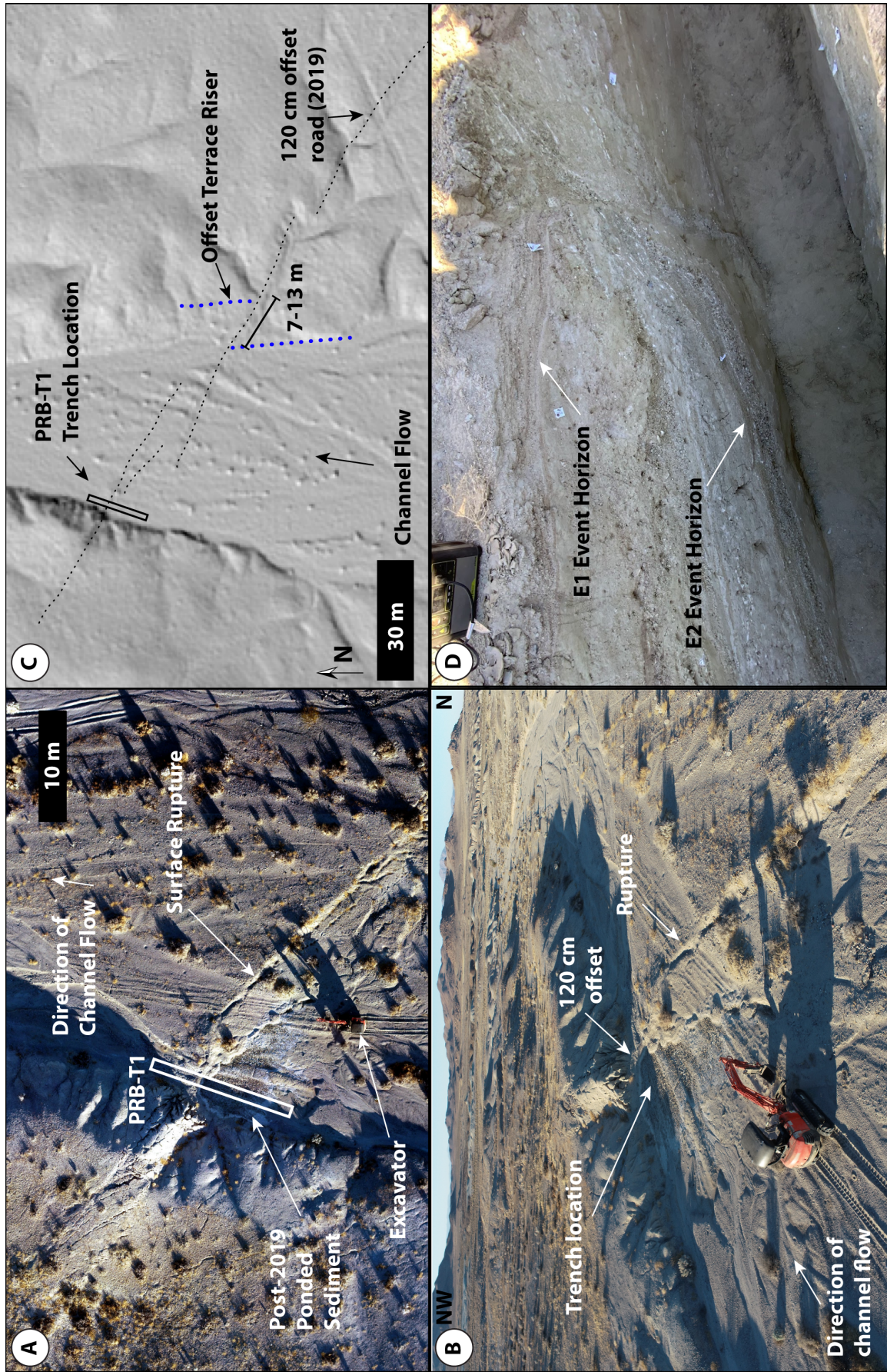


Figure 5 A: Orthophotomosaic (Pierce et al., 2020) showing the Paxton Ranch (M 7.1) Basin trench location on edge of wash. Wash flows from south to north (indicated by arrow). Note the dried ponded sediment deposited behind the scarp. B: Oblique drone image of site before excavation showing echelon faulting and small mole-track. C: Post-event lidar hillshade (Hudnut et al., 2020) showing possible 7-13 m right-lateral offset of the right bank terrace riser (blue dotted lines). Dashed black lines show the 2019 surface rupture trace. 120 cm of right-lateral displacement was measured at a road margin (Ponti et al., 2020) D: Field photo of northwest trench wall showing event horizons and fault zone. Coordinates: 35.5825, -117.3846.

- Unit 7 is only on the southwest side of the fault zone on the northwest wall, but on the southeast wall it conformably caps Unit 8 on the northeast side of the fault zone. Unit 7 is a massive light-gray fine sand with thin, white silty-clay stringers, similar to Unit 9, and is >50 cm thick.
- Unit 6 is a light-gray massive fine sand, ~20 cm thick, conformably overlying Unit 7, and also restricted to the southwest side of the fault.
- Units 4 and 5 consist of cross-laminated coarse sand (Unit 4) to fine pebble layers (Unit 5) that conformably overlie Unit 6. Their backset laminations and well-sorted coarse texture suggest a beach or nearshore environment. Unit 5 extends only ~2 m from the fault zone and pinches out, while Unit 4 is ~35 cm thick near the fault but pinches out ~14 m to the southwest.
- Unit 3 is a well-bedded sequence of clay, silt, sand, and thin pebble layers. It conformably overlies Unit 4 and likely represents a back-beach playette environment where a small, closed basin accumulated clay.
- Unit 2 forms a sharp, wavy erosional boundary above Unit 3. It is ~80 cm thick, composed of moderately sorted sands, pebbles, and occasional cobbles in cross-bedded lenses. This fluvial deposit transitions abruptly from the underlying lacustrine facies. Near the top of Unit 2 is a thin (2–3 cm) clay layer.
- Unit 1 is a loose, gray, laminated sand capping the exposure on both sides of the fault. It forms an angular unconformity above Units 2 and 8 and has a maximum thickness away from the fault of ~10 cm. Unit 1 represents modern fluvial wash deposition.

Stratigraphy in this trench is consistent with the regional climatic history of repeating Pleistocene lacustrine sequences followed by a drier mid-Holocene climate. Unit 9 is a nearshore lacustrine deposit, capped by Unit 8, a beach deposit, left behind as the pluvial lake receded. Units 6/7 are a younger sequence of pluvial nearshore deposits, subsequently capped by another beach sequence comprised of Units 4/5. Unit 3 is the result of deposition within a small, closed basin that possibly formed behind a fault scarp. Following regional Holocene desiccation, fluvial units 1 and 2 eroded into the lacustrine sequence and formed the channel we see today.

Faulting at this site is dominated by a 60° NE-dipping primary strand (F1), creating an asymmetric (NE-side up) positive flower structure with multiple splays. Near the surface, F1 forms a ~90 cm-wide mole track that tapers to ~10–15 cm width at ~35 cm depth. To the northeast of the fault zone sediments are permeated by a network of cross-cutting fractures. To the southwest of F1 are two additional faults, F2 (52° NE dip) and F3 (32° NE dip), each producing apparent vertical offsets of 8–30 cm on various unit contacts. F2 terminates at the Unit 2–3 boundary, while F3 dies out in Units 4 and 5. Overall, Units 2–7 are warped upward, thinning or pinching

out across the fault zone, and units 8 and 9 warp downward across the fault, disappearing to the southwest of F1. Units 8 and 9 are likely older lacustrine units that are being faulted into the channel from beneath the adjacent terrace (Figure 5).

Paleoearthquake evidence reveals as many as five events preceding the 2019 rupture. E1, the penultimate event, breaks faults F1 and F2, postdating Unit 2 but predating the deposition of Unit 1. E2, the antepenultimate event breaks faults F1 and F3, postdating or within upper Unit 4 and predating the deposition of Unit 3. As E2 occurred during or shortly after Searles Lake was depositing the Unit 4 beach deposits, it is stratigraphically plausible that this event created accommodation space behind the fault scarp for Unit 3 (consisting of back-beach slack-water facies) to be deposited. While some thin clay layers in Units 1, 2, and 3 could reflect additional intervening scarp-derived ponding events, we do not interpret them as discrete paleoearthquake horizons due to the lack of additional evidence for intervening events such as the clear upward terminations and deformation associated with the other ruptures.

A possible earlier event (E3): Breaks F4 (on the northwest wall), postdating Unit 8 and predating Unit 5. On the southeast wall this event is less clear, but it possibly terminates below Unit 7. The timing of upward terminations on the northeast side of the F1 fault zone is uncertain due to Unit 1 fluvial sediments unconformably eroding Units 5, 7, and 8. As the Unit 5 sediments on the northeast side of the fault zone are close to the main F1 fault zone, it is unclear if they are capping F4 or are faulted, and it is also possible this fault is part of the E1 or E2 ruptures. Evidence supporting E3 and other possible earlier events (E4, E5) includes: (1) the apparent vertical offset of Units 8 and 9 is more than double the apparent vertical offset of Units 1–5 (though this could be a result of laterally discontinuous units being laterally faulted together), (2) Units 6, 8, and 9 cannot be traced across the fault zone, (possibly due to cumulative lateral slip or erosion of the uplifted side by the stream channel) (3) Units 8 and 9 have significantly more tilting and deformation near the fault zone than younger units, (4) upward terminations of faults within Units 8 and 9. The lack of age control in Units 8 and 9 precludes estimating ages for E4 and E5.

Nine luminescence sample (OV001–OV008) from Units 1–7 provide temporal constraints (Table 1). Ages range from 4.68 ± 0.66 (OV001 in Unit 1) to 18.15 ± 1.79 ka (OV008 in Unit 7). Lacustrine units 3, 4, and 5 date to ~11–13 ka, while Units 6–7 cluster around ~17–18 ka, consistent with documented spillovers of Owens Lake that would have generated lakes in Searles Valley (Bacon et al., 2020).

The overall stratigraphic sequence is in chronological order and constrains the earthquake history as follows (Figure 7): the most recent event is the 2019 Ridgecrest Mw 7.1 earthquake; E1 is bracketed between Unit 1 at 4.68 ± 0.66 ka and Unit 2 at 8.25 ± 0.94 ka; E2 is constrained between 12.16 ± 1.50 ka in Unit 3 and 13.43 ± 1.46 ka in Unit 4; and a possible E3 occurred at approximately 18 ka, based on faulting of Unit 8 and burial by either Unit 5 or Unit 7. Older events E4 and E5 are less well

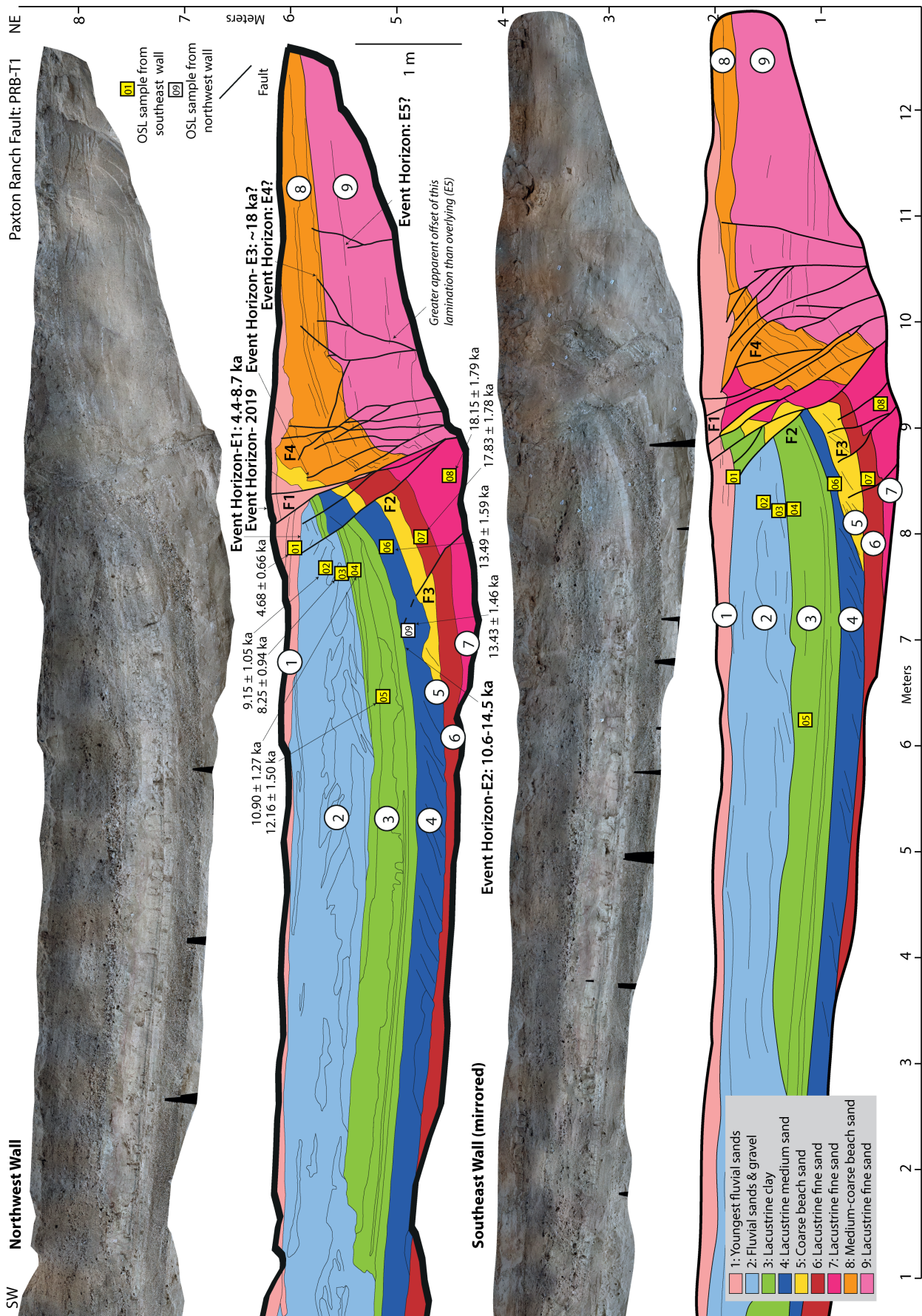


Figure 6 (Previous page.) Northwest Wall (upper) and mirrored southeast wall (lower) of Paxton Ranch fault Basin trench (PRB-T1). Western 10-m of trench is omitted from the figure for space requirements. Fluvial sediments cap two late Pleistocene lacustrine sequences. A positive flower structure has uplifted sediments to the northeast (right-side of figure) and two vertical fault terminations provide clear event horizons for the most recent two E1 and E2 events. Third, fourth, and fifth possible events (E3, E4, E5) are based on terminations and deformation within and above Units 8 and 9. Sample numbers are the same as Tables 1 and 2 with the 'OV0' prefix omitted. Event horizons are based on results of OxCal model (Figure 7).

constrained, but may date to Owens Lake spillover intervals ~23–28 ka (Bacon et al., 2020). Combined, these ages place two to five late Pleistocene–Holocene surface ruptures along this section of the Paxton Ranch fault prior to the 2019 event.

6 Discussion

6.1 Trench Interpretations on the Salt Wells Valley Fault (M_w 6.4 2019 earthquake)

Our trenches reveal infrequent surface ruptures on the Salt Wells Valley fault. At SWV-T2 (Figure 4), uniform deformation in the youngest deposits (Units 1–4) indicates only the 2019 M_w 6.4 event was preserved. Luminescence ages suggest any earlier rupture must predate ~7 ka. The stratigraphy and faulting relationships in SWV-T1 (Figure 3) are consistent with this result and provide evidence of at least one pre-2019 event between 14.51 ± 1.85 (OV029) and 22.17 ± 2.92 ka (OV028). In a nearby trench ~600 m to the southwest (Figure 1), Kozaci et al. (2021) documented at least one event older than 25.34 ± 2.91 ka but could not exclude the possibility of a younger Holocene rupture. These results confirm at least one pre-2019 surface rupture along the Salt Wells Valley fault, with no clear evidence for a penultimate event younger than ~14.5 ka. Combining the ages from the Kozaci et al. (2021) and the SWV-T1 and -T2 trenches into an OxCal model (Bronk Ramsey, 1995) limits the timing of a penultimate event from 17.7–27.2 ka (Figure 7, Table 3). The bounding ages (OV028 and Kozaci) have large uncertainties and partially overlapping probability distributions, and their central values are not clearly separated in stratigraphic order. As a result, the modeled age of E1 is derived largely from the tails of these distributions, producing a broad age range.

6.2 Trench Interpretations on the Paxton Ranch Fault (M_w 7.1 2019 earthquake)

In the Paxton Ranch Basin trench (PRB-T1, Figure 6), the timing of two paleoearthquakes (E2 and E1) predating the 2019 M_w 7.1 rupture is well constrained by fault terminations and bracketing luminescence ages. Earlier events (E3–E5) lack direct age control; therefore, a basal boundary age of 23–28 ka is applied to Unit 9 based on regional correlation with earlier spill-over events of

Owens Lake that may have reached Searles Valley (Bacon et al., 2020). The OxCal sequence model yields ages of 4.4–8.7 ka for E1 and 10.6–14.5 ka for E2. In contrast, the timing of E3–E5 remains weakly constrained and is dependent on the assumed basal boundary, with possible occurrence between ~17.2–28.4 ka.

Our findings confirm at least two, and possibly five late Pleistocene–Holocene ruptures on the Paxton Ranch fault prior to 2019. Inter-event intervals for the two most recent earthquakes are ~4–8 kyr (E1–2019) and 2–10 kyr (E1–E2), 3–15 kyr (E2–E3), whereas earlier intervals (E2–E3 and older) are poorly constrained due to limited age control.

6.3 Multifault Rupture Behavior of the Salt Wells Valley and Paxton Ranch Faults

The 2019 Ridgecrest sequence shows that the Salt Wells Valley and Paxton Ranch faults can rupture in close temporal succession, but the paleoseismic record indicates that this is not the dominant long-term behavior of the fault pair. Salt Wells Valley trenches preserve only one pre-2019 surface-rupturing earthquake at 17.7–27.2 ka, whereas the Paxton Ranch record contains at least two earthquakes since 10.6–14.5 ka and additional older events that may extend the record to ~17–28 ka. The two best-constrained pre-2019 events on the Paxton Ranch fault do not overlap in age with the Salt Wells Valley event, and although overlap among older events cannot be excluded, the contrasting number of ruptures over the same interval indicates that most Paxton Ranch earthquakes occurred without corresponding rupture on Salt Wells Valley. Repeated paired rupture would require both faults to approach failure during the same interval, whether through coincidence in long-term loading or short-term stress transfer between adjacent faults. The 2019 sequence demonstrates that such short-term interactions can produce closely spaced failure, and modeling and seismological studies generally interpret the sequence in terms of stress transfer and triggering between adjacent faults (Chen et al., 2020; Lozos, 2022; Lozos and Harris, 2020; Ross et al., 2019). While short-term stress transfer may influence rupture timing, the larger rupture geometry still reflects the structure and stress state of the fault system. Accordingly, the paleoseismic record suggests that the fault configuration expressed in 2019 was uncommon over the interval preserved by the trenches, rather than the dominant long-term behavior of the fault pair.

The lack of overlapping event ages between the Salt Wells Valley and Paxton Ranch faults does not preclude multifault rupture involving either structure and other nearby faults. Because paleoseismic data are inherently local, trenches record only earthquakes that rupture a given site and cannot resolve rupture extent; conversely, partial ruptures that do not reach a trench site may be missed. Our interpretation of the paleoseismic records and discussions in this study assumes that the trench sites record the principal rupture history of each fault. If rupture extent or fault participation varied through time, trench records may both miss events or record only part of larger rupture sequences.

Fault	Event	Event Interval ¹	Event Age with Uncertainty ¹	Event Evidence
Paxton Ranch	E1	4.4-8.7 ka	6.6 ± 2.2 ka	Upward fault termination & age brackets
Paxton Ranch	E2	10.6-14.5 ka	12.6 ± 2.0 ka	Upward fault termination & age brackets
Paxton Ranch	E3 ²	17.2-25.8 ka	21.5 ± 4.3 ka	Upward fault termination, no lower age bracket
Paxton Ranch	E4 and/or E5 ²	19.5-28.4 ka	24.0 ± 4.5 ka	Deformation and possible fault terminations, no directly measured age brackets
Salt Wells Valley	E1	17.7-27.2 ka	22.5 ± 4.8 ka	Upward fault termination, event bracketed across trenches

¹Modeled with OxCal v4.4 (Bronk Ramsey, 1995) showing 95.4% uncertainty.
²Modeled with lower bounding age of 23-28 ka correlated from regional lacustrine history.

Table 3 Event Horizons modeled with OxCal v4.4.

6.4 Slip Rates from Paleoseismology

Slip-rate estimation from paleoseismic data is limited by the small number of observed earthquake cycles, recurrence irregularity (e.g., Styron, 2019), uncertain slip per event, and a mismatch between recurrence intervals measured at specific trench sites and displacement measured over different spatial scales. In this study, slip rates are calculated using displacement measured at the trench sites, as well as average and maximum displacement observed across the 2019 ruptures (DuRoss et al., 2020). These approaches are not equivalent: site-specific displacement is internally consistent with trench-based recurrence but assumes repeatable slip at that location, whereas rupture-scale displacement incorporates broader observations but mixes local recurrence with fault-scale slip. All of these estimates also assume that the displacement pattern observed in 2019 is representative of earlier earthquakes, which may not be true if slip varies between events (DuRoss et al., 2022; Hecker et al., 2013) because of changing rupture extent or fault participation. Accordingly, the slip rates presented here are preliminary and are best treated as end-member estimates that bracket the plausible range permitted by the available data.

6.5 Paxton Ranch Fault

Our data document two closed seismic cycles between E2 and 2019 in the last 10.6-14.5 ka. Using the 1.2–1.7 m mean and 4.3–7.0 m maximum slip distributions measured following the 2019 earthquakes (DuRoss et al., 2020), a total of ~2.4–3.4 m mean slip and 8.6–14.0 m maximum slip may have accumulated over these two cycles. The slip at the trench site in 2019 was 1.20 m. These values result in the rates presented in Table 4. The maximum slip measurements in 2019 were obtained farther north along the fault near China Lake and may not be representative of slip at our trench site.

The 2019 rupture occurred as part of a multifault sequence and followed rupture of the Salt Wells Valley fault by ~1 day, indicating that the Paxton Ranch fault was apparently already near failure. Stress transfer may have influenced the timing of rupture, although coincident failure cannot be excluded. Multifault rupture may also have affected slip magnitude, such that the observed displacement may not represent typical single-

fault behavior. These uncertainties cannot be resolved with the available data, and the Paxton Ranch fault slip rate is best expressed as a broad range of ~0.2–1.3 mm/yr.

6.6 Salt Wells Valley Fault

In contrast, the Salt Wells Valley fault is constrained by a single closed interval of 17.7–27.2 ka since the penultimate event. In 2019, the Salt Wells Valley fault produced a mean displacement of 0.3–0.5 m and a maximum of 0.7–1.6 m (DuRoss et al., 2020). Slip measured at the trench site was 1.24 m. Assuming these displacements represent the total slip accumulated over the duration of the single closed interval yields the rates presented in Table 4.

Because this estimate is based on a single closed interval, it does not resolve whether slip accumulates steadily or is released in infrequent, larger events. The apparent slip rate therefore reflects limited sampling of fault behavior and may vary through time with changes in rupture mode and fault participation. As such, this estimate should not be interpreted as a robust long-term slip rate.

6.7 Summary of Slip-Rate Implications

Slip-rate estimates presented here are based on a limited number of earthquake cycles and should be considered end-member values that bracket plausible fault behavior rather than precise long-term rates (Styron, 2019). Slip rate depends on how displacement and recurrence are defined: in this study, recurrence is constrained locally at trench sites, whereas displacement can be represented by slip at those locations or by average and maximum values across the full ruptures. Because slip varies along strike and between earthquakes, these approaches are not directly equivalent, and the resulting range reflects both definitional differences and uncertainty associated with sparse event records.

This distinction is important when comparing regional datasets. Slip rates derived from offset landforms integrate displacement over multiple earthquake cycles but are subject to preservation and selection biases that may favor larger offsets, and may therefore be more comparable to maximum displacement esti-

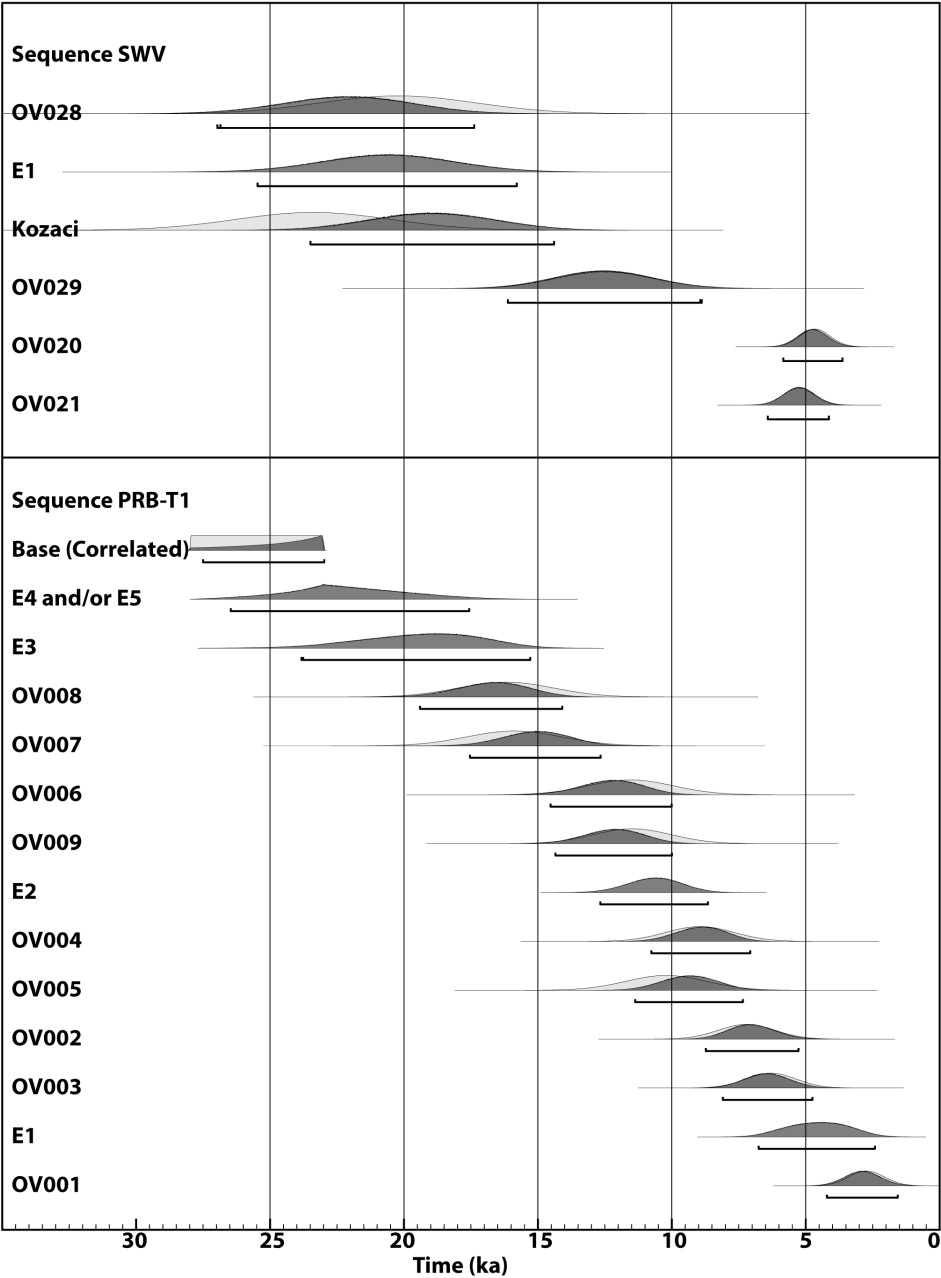


Figure 7 Stratigraphic sequence models for the Salt Wells Valley trenches (upper) and Paxton Ranch Basin trench (lower). OxCal models integrate stratigraphic ordering with luminescence ages to estimate the timing of paleoearthquakes (E1–E5). Dark and light shaded distributions show modeled and unmodeled age probability densities, respectively, and horizontal bars indicate 95.4% confidence intervals. At Salt Wells Valley, the age of E1 is weakly constrained by broad, overlapping OSL ages. In contrast, at Paxton Ranch Basin, E1 and E2 are more tightly bracketed, whereas older events (E3–E5) remain dependent on the assumed basal boundary.

Fault	Time Interval (kyr)	# of Closed Intervals	Slip at Trench (2019) (m)	Mean (2019) Event Slip ¹ (m)	Max (2019) Event Slip ¹ (m)	Slip Rate (from 2019 at trench) (mm/yr)	Slip Rate (from 2019 mean) (mm/yr)	Slip Rate (from 2019 max) (mm/yr)
Paxton Ranch	10.6-14.5	2	1.2 m	1.2-1.7	4.3-7.0	0.17-0.23	0.17-0.19	0.59-1.3
Salt Wells Valley	17.7-27.2	1	1.24	0.3-0.5	0.7-1.6	0.05-0.07	0.008-0.01	0.03-0.09

¹Mean and Max Event Slip from 2019 surface ruptures from DuRoss et al. (2020).

Table 4 Summary of slip rate calculations.

mates. In contrast, mean displacement across a rupture may better approximate long-term moment release, whereas trench-based estimates reflect site-specific behavior. Apparent differences in slip rate therefore reflect not only uncertainty but also both methodology and definition.

Slip-rate estimates for the Paxton Ranch fault ($\sim 0.2\text{--}1.3$ mm/yr) are consistently higher than those for the Salt Wells Valley fault ($\sim 0.01\text{--}0.09$ mm/yr) across all approaches. Paxton Ranch rates are similar to those of the Little Lake fault ($0.6\text{--}1.3$ mm/yr; Amos et al., 2013) and fall within the range of geologic estimates for dextral faults in the southern Walker Lane ($\sim 0.5\text{--}2$ mm/yr; Pierce et al., 2021), whereas Salt Wells Valley rates are substantially lower than most mapped structures contributing to regional shear. This order-of-magnitude difference suggests that the Salt Wells Valley fault plays a subordinate role within the regional strain field, consistent with its antithetic orientation within a dominantly right-lateral shear system. These estimates remain limited by sparse event records and do not distinguish between kinematic partitioning, incomplete sampling, temporal variability in slip, or variable participation in multifault rupture.

6.8 Regional Context, Temporal Clustering, and Network Behavior

To evaluate whether earthquakes on the Paxton Ranch and Salt Wells Valley faults occurred in isolation or during broader periods of regional activity, we compare their event timing with paleoseismic records from across the southern Walker Lane/ECSZ (Figure 8), which shows event ages and uncertainties alongside a kernel density estimate highlighting intervals of elevated earthquake occurrence.

The 2019 Ridgecrest sequence occurred within a broader pattern of surface-rupturing earthquakes along the Walker Lane/ECSZ over the past ~ 150 years, including Owens Valley (1872), the Central Nevada Seismic Belt (1915, 1932, 1954), Landers (1992), Hector Mine (1999), and Monte Cristo Range (2020) earthquakes. Many of these events ruptured multiple faults and, when considered together, define a sequence of earthquakes separated by decades, far shorter than the 3–10 kyr recurrence intervals typical of individual faults (Figure 8). Considered in this context, the historical record is more consistent with temporally clustered behavior at the scale of the fault system than with independent recurrence on individual faults.

Although historical clustering within the Central Nevada Seismic Belt (Bell et al., 2004) and ECSZ (Rockwell et al., 2000; Scholz, 2010; Vadman et al., 2023) inclusion of the Owens Valley, Ridgecrest, and Monte Cristo Range ruptures within this interval suggests that these events may not represent separate regional clusters, but part of a broader episode of earthquake activity spanning much of the Walker Lane/ECSZ. This interpretation suggests that clustering may extend beyond individual regions and be expressed at the plate boundary scale.

Paleoseismic compilations further show that such clustering is expressed as broad intervals of elevated

activity rather than discrete or periodic episodes (e.g. Rockwell et al., 2000; Vadman et al., 2023). In our dataset (Figure 8), kernel density estimates show weak clusters of events. Consistent with prior work (Rockwell et al., 2000; Scholz, 2010), these intervals involve different combinations of faults through time. The Paxton Ranch record overlaps with several periods of elevated regional activity, whereas the Salt Wells Valley and other faults show no clear evidence of participation in the same intervals. This variability indicates that participation in regional clusters is not fixed, even among geometrically linked faults, and that periods of elevated activity reflect shifting patterns of fault interaction rather than repeated rupture of the same fault combinations.

Interpretations of past clustering are subject to several limitations. Many faults in the southern Walker Lane/ECSZ lack detailed paleoseismic records, including the Death Valley, Searles Valley, Hunter Mountain–Saline Valley, Tin Mountain, Kern Canyon, southern Sierra frontal, Airport–Little Lake, Harper, Blackwater, Ash Hill, Towne Pass, Deep Springs, and Tank Canyon faults, leaving large portions of the network poorly constrained. Existing datasets are biased toward locations with favorable stratigraphic preservation and toward larger, more easily recognized events, and event ages are commonly tied to depositional units that may reflect regional climatic signals. Age uncertainties further limit the ability to distinguish closely spaced rupture from broader millennial-scale overlap, and individual trench sites may only record a subset of ruptures on a given fault. Comparisons of recurrence between faults are limited by differences in record length and resolution. As a result, non-uniform event ages do not resolve the presence or structure of temporal clustering at the scale of the fault network.

Despite these limitations, patterns in Figure 8 support broader evidence that rupture behavior across the Pacific–North America plate boundary is not stationary, but contains both isolated events and periods of temporally clustered, multi-fault activity, with clusters that shift in space and time rather than recurring on fixed structures (e.g. Bell et al., 2004). Paleoseismic and historical records provide multiple lines of evidence for this behavior, including past clusters in the Walker Lane ($\sim 800\text{--}500$ years ago; Pierce, 2022), switching between independent and clustered modes of rupture in the southern San Andreas system (e.g., Scharer and Yule, 2020), and a period of closely spaced, multi-fault rupture in the San Francisco Bay Area (A.D. $\sim 1600\text{--}1776$), followed by a large, system-spanning rupture in 1906, illustrating a transition from clustered to isolated modes of faulting (Schwartz et al., 2014).

The Walker Lane/ECSZ is therefore best interpreted as a geometrically complex fault network in which rupture is redistributed among different structures through time. Over multiple earthquake cycles, deformation is redistributed across the network and contributes to long-term permanent changes in fault geometry, including evolving linkage, segmentation, and localized rotation of crustal blocks (e.g., Fialko and Jin, 2021; Pierce et al., 2021). Superimposed on this longer-term structural evolution, the paleoseismic record indicates

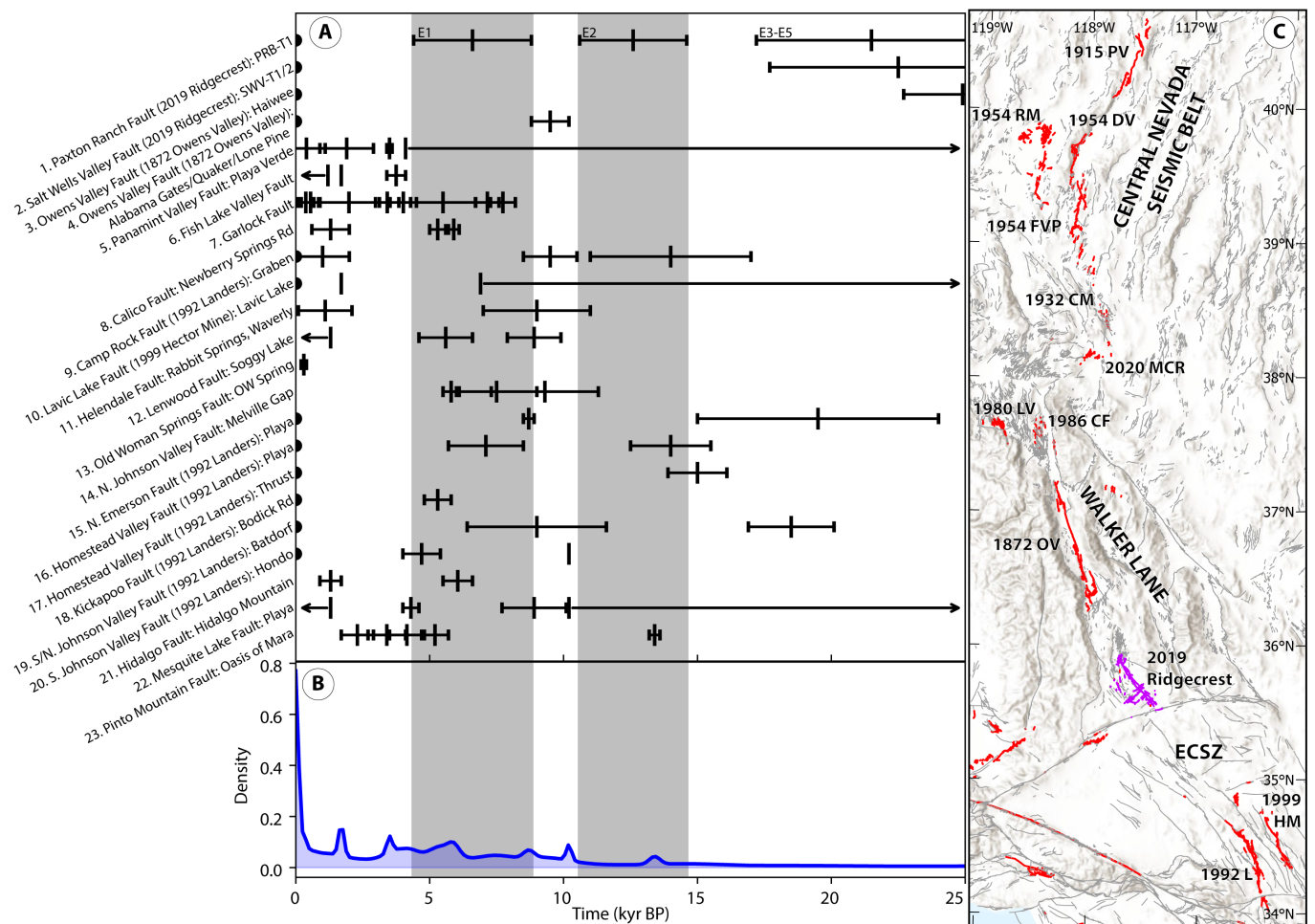


Figure 8 A: Results of paleoseismic studies of faults in the Southern Walker Lane and Eastern California Shear Zone from 0-25 ka. Sites are generally organized from north to south and west to east. See Figure 1 for fault locations. Tall vertical bars show midpoints, and shorter bars indicate uncertainties. Arrows indicate open intervals. Grey bars highlight the intervals of the 2 most recent events on the Paxton Ranch fault. B: Kernel Density Plot showing relative density of events over time including uncertainties, excluding open-interval events. References: 1,2: this study. 3: [Amos et al. \(2013\)](#); 4: [Bacon and Pezzopane \(2007\)](#); 5: [McAuliffe et al. \(2013\)](#); 6: [Sawyer \(1988\)](#); 7: [Peña \(2018\)](#); 8: [Ganev et al. \(2010\)](#); 10: [Rymer et al. \(2002\)](#); 9, 12-20: [Rockwell et al. \(2000\)](#); 21: [Vadman et al. \(2023\)](#); 22: [Madden et al. \(2006\)](#); 23: [Cadena](#). C: Map of the Central Nevada Seismic Belt, Walker Lane and Eastern California Shear Zone with historical surface ruptures in red ([USGS, 2022](#)), other faults in grey, and the 2019 Ridgecrest ruptures in purple ([Ponti et al., 2020](#)) PV: 1915 M_s 7.7 Pleasant Valley, RM: 1954 M_s 6.3/7.0 Stillwater/Rainbow Mountain, FVP: 1954 M_s 7.2 Fairview Peak, DV: 1954 M_s 6.8 Dixie Valley, CM: 1932 M_s 7.2 Cedar Mountain, MCR: 2020 M_w 6.5 Monte Cristo Range ([Dee et al., 2021](#)), LV: 1980 M 6.0 Mammoth Lakes/Long Valley, CF 1986 M_w Chalfant, OV: M_w 7.6 1872 Owens Valley, L: 1992 M_w 7.3 Landers, and HM: 1999 M_w 7.1 Hector Mine earthquake.

that periods of elevated activity involve different combinations of faults through time rather than repeated rupture of the same structures.

6.9 Time-Dependent Fault Interaction and Implications for Seismic Hazard

Typical seismic hazard models represent earthquake occurrence as either time-independent (Poisson) or time-dependent (renewal) behavior on individual faults. In renewal models, rupture probability depends on time since the last event and long-term slip rate, implying a fault-specific history of loading and release. At the scale of the Walker Lane/ECSZ, however, regional paleoseismic compilations indicate that earthquake occurrence is strongly temporally clustered, with different combinations of faults participating in different intervals. This behavior is better interpreted at the

scale of an interacting fault network than at the scale of individual faults. Time dependence in the system therefore appears to reflect episodic stress release and redistribution across the broader network, rather than recurrence on a fixed set of independently cycling structures ([Scholz, 2010](#)). Because the participating faults change through time, these clusters do not represent repetition of fixed rupture pathways ([Field et al., 2015](#); [Quigley et al., 2019](#)), but intervals in which activity is elevated or reduced and slip is distributed across different parts of the system.

Our paleoseismic record of the Paxton Ranch and Salt Wells Valley faults illustrates this process at the scale of an individual fault pair. The 2019 Ridgecrest sequence shows that these adjacent, kinematically linked faults can rupture in close succession, but the paleoseismic record indicates that the Paxton Ranch fault rup-

tured repeatedly without corresponding rupture of the Salt Wells Valley fault. Although large uncertainties in the older events prevent confident evaluation of overlap, the available data do not indicate that paired rupture was the most frequent mode of behavior for this fault pair. Instead, the results indicate that even kinematically linked faults can participate variably through time, consistent with the broader Walker Lane/ECSZ pattern of clustered activity and changing fault participation. In this sense, the Paxton Ranch and Salt Wells Valley records provide a local expression of the broader Walker Lane/ECSZ pattern, in which short-term rupture sequencing between adjacent structures is superimposed on a longer-term history of clustered activity and changing fault participation across the network.

The results of this work have an important implication for hazard assessment. If a substantial part of the time-dependent behavior emerges at the scale of the fault network, then hazard cannot be fully described by treating faults as independent sources with separate recurrence clocks. Paleoseismic records remain critical because they reveal past intervals of clustered activity and variable fault participation, but they also have important limitations. Local fault records cannot resolve rupture extent, so past multi-fault ruptures may have involved changing combinations of structures that are not fully resolved at individual sites (Morell et al., 2020). In addition, many paleoseismic records are too short to distinguish persistent behavior from intermittent participation within a clustered network. Slip rates are also of limited utility in this context because they average slip over many earthquake cycles and lack the temporal resolution needed to identify changing network behavior. The larger limitation, however, is that few physical models explain why rupture rate varies through time at the scale of the network (Kenner and Simons, 2005; Milodon et al., 2022), or how to determine whether the system is currently in a relatively active or quiescent state. Hazard may therefore be expressed not only through larger multi-fault ruptures, but also through intervals of elevated regional activity in which different parts of the network participate through time. In distributed plate-boundary systems such as the Walker Lane/ECSZ, the central challenge for time-dependent hazard models may therefore be not simply estimating elapsed time on individual faults, but determining the current state of the interacting fault network.

7 Conclusions

The paleoseismic data presented here constrain the earthquake history of the Paxton Ranch and Salt Wells Valley faults over the late Pleistocene–Holocene. Both faults ruptured during the 2019 earthquake sequence. The Paxton Ranch fault records well constrained earthquakes at 4.4–8.7 ka and 10.6–14.6 ka, defining two closed seismic cycles, with additional, more poorly resolved events potentially extending the record to ~17–28 ka. In contrast, the Salt Wells Valley fault preserves a single event 17.7–27.2 ka with no additional resolved earthquakes. No high-confidence temporal overlap is observed between events on the two faults.

Slip-rate estimates are substantially higher along the Paxton Ranch fault (~0.2–1.3 mm/yr) than on the Salt Wells Valley fault (~0.01–0.09 mm/yr). This one to two orders-of-magnitude difference is consistent with a subordinate role for the Salt Wells Valley fault within the regional strain field, consistent with its antithetic orientation, although these estimates are based on numerous assumptions.

Synchronous rupture is not the dominant mode of behavior for this fault pair. Contrasting paleoseismic records indicate that multifault rupture between the Paxton Ranch and Salt Wells Valley faults is intermittent, requiring coincidence between structures with different earthquake frequencies. Overlap of Paxton Ranch event ages with earthquakes on multiple regional faults is consistent with temporally clustered earthquakes across the broader fault network, indicating that rupture behavior is scale-dependent, with asynchronous behavior at the fault-pair scale but clustering at the network scale.

These results indicate that rupture in distributed plate-boundary systems is not adequately described by simple renewal on independent, repeating fault sources. Paleoseismic data constrain long-term earthquake histories and may capture broad temporal clustering, but they generally cannot resolve the short-term interactions that influence rupture timing, fault participation, and rupture extent. In systems such as the Walker Lane/ECSZ, seismic hazard therefore reflects the combined effects of long-term loading, fault geometry, and time-dependent interactions across a geometrically complex fault network.

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Data Availability

High resolution trench orthomosaics are available in an online repository (Pierce, 2026). Luminescence tables and methodology, and trenches not shown in text are provided in the supplementary materials. Photogrammetric products were generated with Agisoft Metashape v1.8 (commercial software). All other data used are publicly available.

Competing Interests

The authors declare no financial or non-financial competing interests.

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