

PALEOSEISMOLOGY OF UTAH, VOLUME 24

Evaluating Surface Faulting Chronologies of Graben-Bounding Faults in Salt Lake Valley, Utah— New Paleoseismic Data from the Salt Lake City Segment of the Wasatch Fault Zone and the West Valley Fault Zone

by Christopher B. DuRoss and Michael D. Hylland



SPECIAL STUDY 149
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Cover photo: Research trench across the Granger fault (West Valley fault zone) at the Baileys Lake site, and the Wasatch Range 15 km to the east in the footwall of the Salt Lake City segment (Wasatch fault zone). The 1-m-high, east-facing Granger fault scarp marks the western margin of a graben between the Wasatch fault zone and antithetic West Valley fault zone.

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FOREWORD

This Utah Geological Survey Special Study, *Evaluating Surface Faulting Chronologies of Graben-Bounding Faults in Salt Lake Valley, Utah—New Paleoseismic Data from the Salt Lake City Segment of the Wasatch Fault Zone and the West Valley Fault Zone*, is the twenty-fourth report in the *Paleoseismology of Utah* series. This series makes the results of paleoseismic investigations in Utah available to geoscientists, engineers, planners, public officials, and the general public. These studies provide critical information regarding paleoearthquake parameters such as earthquake timing, recurrence, displacement, slip rate, fault geometry, and segmentation, which can be used to characterize potential seismic sources and evaluate the long-term seismic hazard of Utah's Quaternary faults.

The Salt Lake City segment (SLCS) of the Wasatch fault zone and the West Valley fault zone (WVFZ) comprise Holocene-active normal faults that together form a large intrabasin graben in the northern part of Salt Lake Valley. These faults trend through the most densely populated part of Utah and have evidence of recurrent, large-magnitude ($M \sim 6-7$) surface-faulting earthquakes, but because of urbanization, have received limited paleoseismic study. At the time of this investigation, significant questions remained regarding their paleoseismic histories and whether the WVFZ is seismically independent of or moves coseismically with the SLCS. Understanding these fault characteristics is necessary to quantify the seismic hazard of the heavily urbanized central Wasatch Front.

This *Paleoseismology of Utah* volume contains the results of two separate fault-trench investigations, which help improve the quality and resolution of paleoseismic data for the SLCS and WVFZ. In "Holocene and Latest Pleistocene Paleoseismology of the Salt Lake City Segment of the Wasatch Fault Zone, Utah, at the Penrose Drive Trench Site," DuRoss and others (this volume) present earthquake timing, displacement, and recurrence data from two trenches excavated at the Penrose Drive site on the East Bench fault of the Salt Lake City segment. In "Late Quaternary Paleoseismology of the West Valley Fault Zone—Insights from the Baileys Lake Trench Site," Hylland and others (this volume) discuss the timing, displacement, and recurrence of earthquakes exposed in three trenches at the Baileys Lake site on the Granger fault of the West Valley fault zone. Results from these trench investigations help refine the timing and recurrence of surface-faulting earthquakes on the SLCS and WVFZ, and support a model of coseismic fault movement. A separate paper (DuRoss and Hylland, in review) will present a more quantitative analysis and updated paleoearthquake history for the SLCS and include an expanded discussion of the seismogenic relation between the SLCS and WVFZ.

William R. Lund, Editor
Paleoseismology of Utah Series

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1. Fault behavior and earthquake recurrence on the Provo segment of the Wasatch fault zone at Mapleton, Utah County, Utah—Paleoseismology of Utah, Volume 1, 1991, by Lund, W.R., Schwartz, D.P., Mulvey, W.E., Budding, K.E., and Black, B.D.: Utah Geological Survey Special Study 75, 41 p., available online at http://ugspub.nr.utah.gov/publications/special_studies/SS-75.pdf.
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Holocene and Latest Pleistocene Paleoseismology of the Salt Lake City Segment of the Wasatch Fault Zone, Utah, at the Penrose Drive Trench Site

by

*Christopher B. DuRoss, Michael D. Hylland, Greg N. McDonald, Anthony J. Crone,
Stephen F. Personius, Ryan D. Gold, and Shannon A. Mahan*

Late Quaternary Paleoseismology of the West Valley Fault Zone—Insights from the Baileys Lake Trench Site

by

*Michael D. Hylland, Christopher B. DuRoss, Greg N. McDonald, Susan S. Olig,
Charles G. Oviatt, Shannon A. Mahan, Anthony J. Crone, and Stephen F. Personius*

Holocene and Latest Pleistocene Paleoseismology of the Salt Lake City Segment of the Wasatch Fault Zone, Utah, at the Penrose Drive Trench Site

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Holocene and Latest Pleistocene Paleoseismology of the Salt Lake City Segment of the Wasatch Fault Zone, Utah, at the Penrose Drive Trench Site

by Christopher B. DuRoss, Michael D. Hylland, Greg N. McDonald, Anthony J. Crone, Stephen F. Personius, Ryan D. Gold, and Shannon A. Mahan

ABSTRACT

The Salt Lake City segment (SLCS) of the Wasatch fault zone (WFZ) and the West Valley fault zone (WVFZ) comprise Holocene-active normal faults that bound a large intrabasin graben in northern Salt Lake Valley and have evidence of recurrent, large-magnitude ($M \sim 6-7$) surface-faulting earthquakes. However, at the time of this investigation, questions remained regarding the timing, displacement, and recurrence of latest Pleistocene and Holocene earthquakes on the northern SLCS and WVFZ, and whether the WVFZ is seismically independent of, or moves coseismically with, the SLCS.

To improve paleoseismic data for the SLCS, we conducted a fault-trench investigation at the Penrose Drive site on the northern SLCS. Two trenches, excavated across an 11-m-high scarp near the northern end of the East Bench fault, exposed colluvial-wedge evidence for five or six (preferred) surface-faulting earthquakes postdating the Provo-phase shoreline of Lake Bonneville ($\sim 14-18$ ka). Radiocarbon and luminescence ages support earthquake times at 4.0 ± 0.5 ka (2σ) (PD1), 5.9 ± 0.7 ka (PD2), 7.5 ± 0.8 ka (PD3a), 9.7 ± 1.1 ka (PD3b), 10.9 ± 0.2 ka (PD4), and 12.1 ± 1.6 ka (PD5). At least one additional earthquake occurred at 16.5 ± 1.9 ka (PD6) based on an erosional unconformity that separates deformed Lake Bonneville silt and flat-lying Provo-phase shoreline gravel. Earthquakes PD5–PD1 yield latest Pleistocene (post-Provo) and Holocene mean recurrence intervals of ~ 1.6 kyr and $\sim 1.7-1.9$ kyr, respectively. Using 1.0–1.4 m of per-event vertical displacement for PD5–PD1, latest Pleistocene and Holocene vertical slip rates for the Penrose Drive site are 0.5–0.9 mm/yr. These data correspond well with the results of previous investigations: PD1–PD3b corroborate previously identified SLCS earthquakes at 4–10 ka, PD4 and PD5 occurred within an ~ 8 -kyr (17–9 ka) time interval on the SLCS previously interpreted as a period of seismic quiescence, and PD6 possibly corresponds with a previously identified earthquake at ~ 17 ka (although both events have large timing uncertainties).

The Penrose Drive data, when combined with previous paleoseismic results, improve the latest Pleistocene–Holocene earthquake chronology of the SLCS, and demonstrate that the SLCS has been a consistently active source of large-mag-

nitude earthquakes since the latest Pleistocene. At least nine surface-faulting earthquakes (S1–S9) have occurred since the highstand of Lake Bonneville (~ 18 ka). Where the SLCS earthquake record is most complete (since ~ 14 ka), per-site estimates of mean recurrence are similar for the latest Pleistocene (post-Provo) (~ 1.6 kyr), Holocene ($\sim 1.6-1.9$ kyr), and late Holocene ($\sim 1.2-1.4$ kyr). These SLCS paleoearthquake data indicate an essentially stable rate of earthquake recurrence since the latest Pleistocene and are important for understanding the earthquake potential of the SLCS, clarifying the seismogenic relation between the SLCS and WVFZ, and forecasting the probabilities of future large-magnitude earthquake in the Wasatch Front region.

INTRODUCTION

Purpose and Scope

The Salt Lake City segment (SLCS) of the Wasatch fault zone (WFZ) and the West Valley fault zone (WVFZ) comprise Holocene-active normal faults that together form a 3–12-km-wide intrabasin graben in the northern part of Salt Lake Valley (figures 1 and 2). These faults trend through the most densely populated part of Utah and have evidence of recurrent, large-magnitude ($M \sim 6-7$) surface-faulting earthquakes, but, because of urbanization, have received limited paleoseismic study. At the time of this investigation, significant questions remained regarding the paleoseismic histories of both faults, including (1) the timing of Holocene earthquakes on the northern SLCS (previous paleoseismic data were limited to the southern third of the segment), (2) the timing, recurrence, and displacement of mid-Holocene to latest Pleistocene earthquakes on both faults, and (3) whether the WVFZ is seismically independent of, or moves coseismically with, the SLCS. Understanding these fault characteristics is critical to accurately quantifying the seismic hazard of the central Wasatch Front.

To improve the quality and resolution of paleoseismic data for the SLCS and WVFZ, as well as our understanding of the seismic relation between them, we completed fault-trench investigations at two sites—one on the SLCS (Penrose Drive

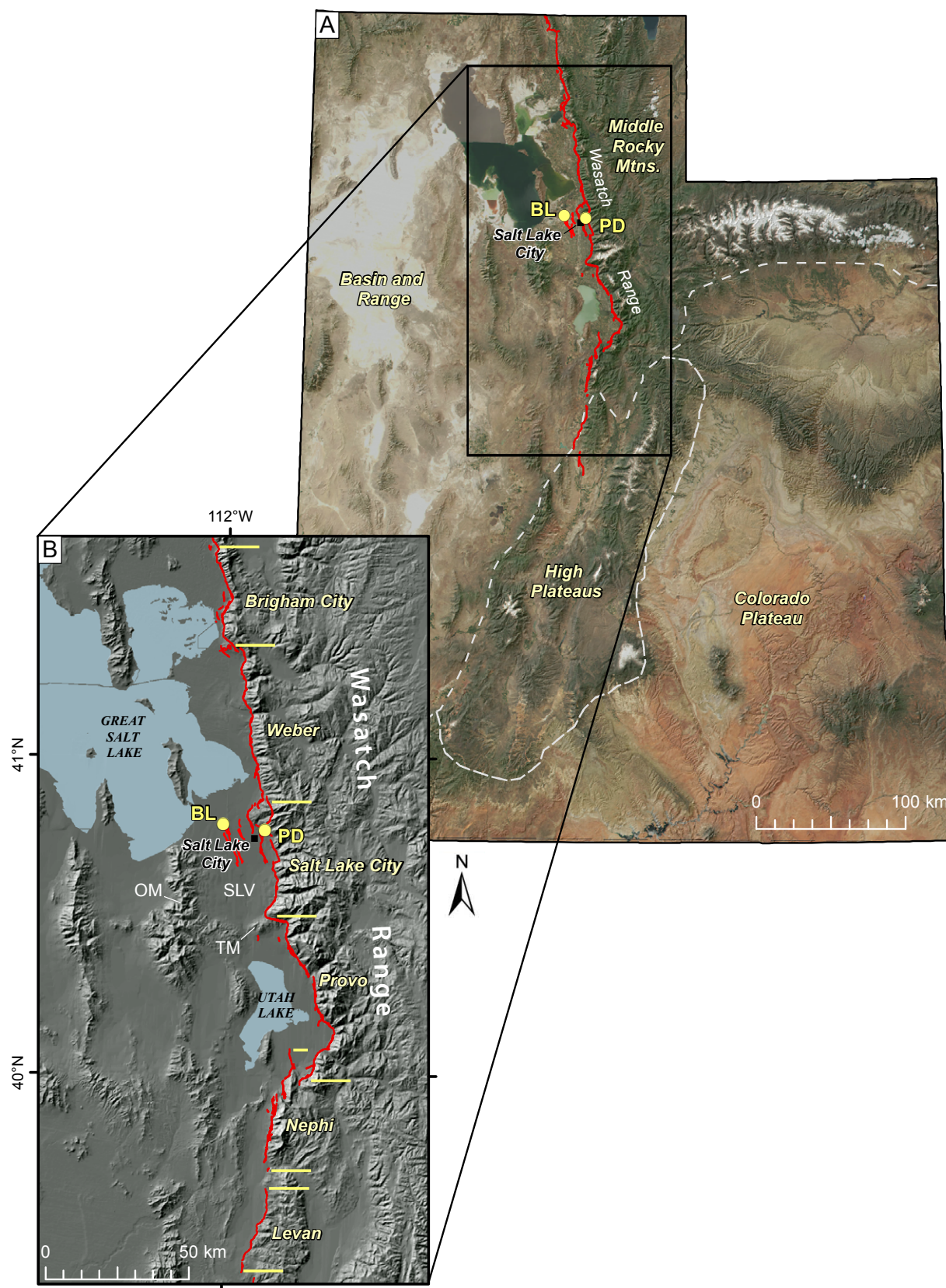


Figure 1. (A) Physiographic provinces of Utah (gray dashed lines; AGRC, 2012), showing the Wasatch fault (red) and the general location of the Penrose Drive (PD; this study) and Baileys Lake (BL; Hylland and others, 2014) trench sites. Base map: true-color satellite image from the National Aeronautics & Space Administration (NASA, 2006; taken May 31, 2001) overlain on a 90-m digital elevation model (DEM; AGRC, 2012). (B) Central segments of the Wasatch fault zone from Black and others (2003). Horizontal yellow lines indicate segment boundaries. Base map: 90-m DEM (AGRC, 2012). OM – Oquirrh Mountains, SLV – Salt Lake Valley, TM – Traverse Mountains.

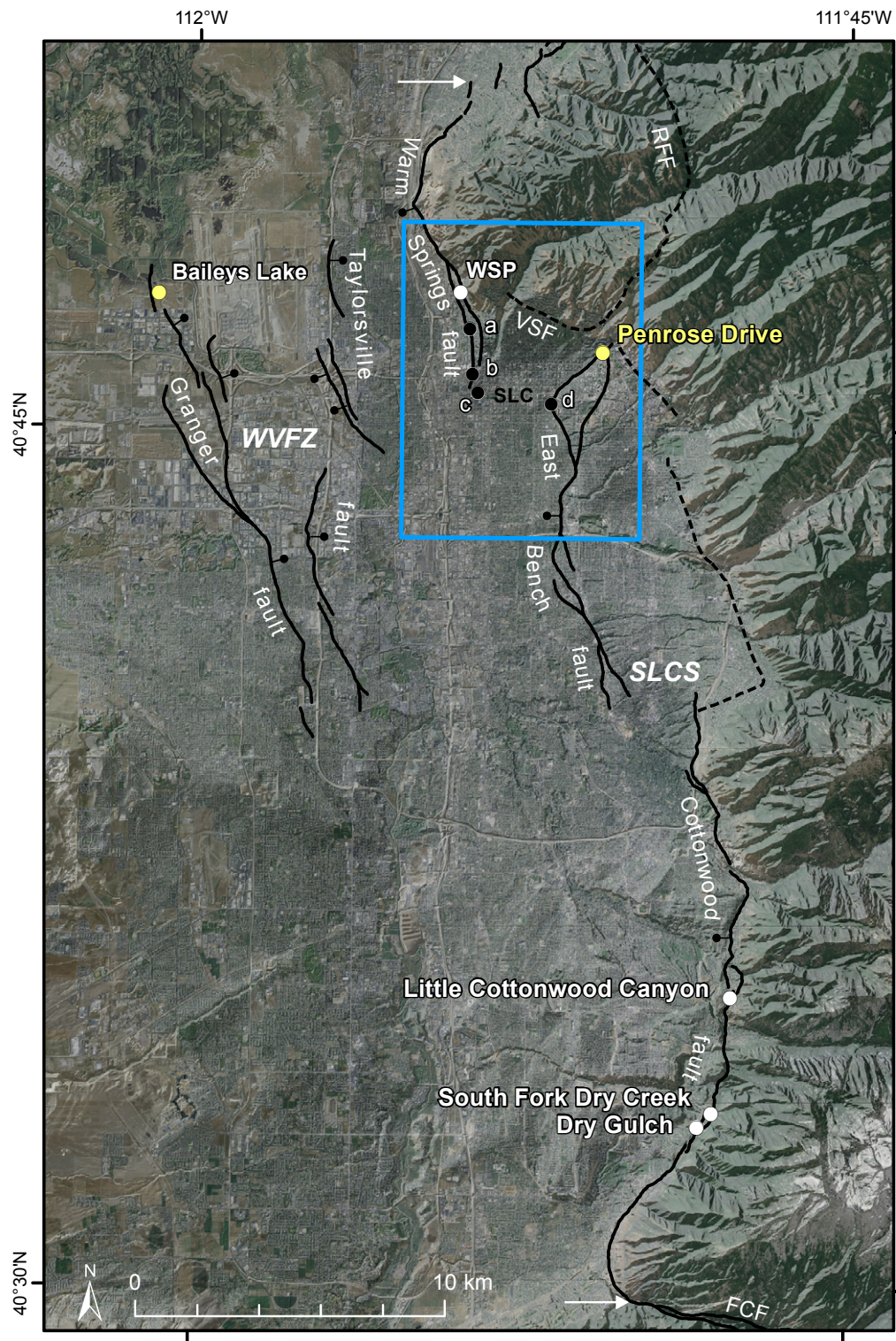


Figure 2. Holocene-active traces of the Salt Lake City segment (SLCS) of the Wasatch fault zone and the West Valley fault zone (WVFZ) (solid black lines; Black and others, 2003; dashed lines are pre-Holocene traces), showing the Penrose Drive (this study) and Baileys Lake (Hylland and others, 2014) trench sites (yellow circles). White circles denote the Warm Springs Park (WSP) trench site (this study) and previous SLCS trench studies. Black circles indicate paleoseismic investigations that provided fault-location information, but not individual earthquake-timing data: a. Washington Elementary School (Robison and Burr, 1991), b. Salt Palace expansion project (Kleinfelder, 1999; Simon-Bymaster, 1999), c. 400 South cone penetrometer study (Leeftang, 2008), d. Dresden Place (Machette and others, 1992). FCF – Fort Canyon fault, RFF – Rudys Flat fault, VSF – Virginia Street fault. White arrows indicate the northern and southern ends of the SLCS. Base map is 2011 color aerial photography (USDA, 2012) overlain on a 2-m DEM (AGRC, 2012). Box outlined in blue shows extent of figure 3.

site) and one on the WVFZ (Baileys Lake site). The trench investigation at Penrose Drive is the subject of this paper; for paleoseismic results from the Baileys Lake trench study, see the companion paper by Hylland and others (2014; this volume). These two reports supersede the initial release of the study results in a Final Technical Report to the USGS (DuRoss and Hylland, 2012). A separate paper (DuRoss and Hylland, in review) will integrate the results of these two investigations and include expanded discussions on the SLCS paleoearthquake history and the seismogenic relation between the SLCS and WVFZ.

Our Penrose Drive investigation included (1) detailed topographic and geologic mapping of the trench site, (2) scarp profiling, (3) excavating two trenches, (4) mapping the trench-wall exposures in detail, (5) sampling organic remains and fine-grained detrital sediment for radiocarbon and luminescence dating, respectively, (6) developing probabilistic models of earthquake times using OxCal software, and (7) determining earthquake chronologies, vertical displacement, recurrence, and fault slip rate. These data refine earthquake chronologies, mean-recurrence intervals, and slip-rate estimates for the SLCS, and, when combined with paleoseismic results from the Baileys Lake investigation, improve our understanding of how the SLCS and WVFZ interact seismogenically (Hylland and others, 2014).

Geologic Setting

Salt Lake Valley occupies one of several north-south-trending grabens at the eastern margin of the actively extending Basin and Range Province. The Wasatch Range and Oquirrh Mountains bound the valley on the east and west, respectively; Great Salt Lake lies to the north; and the east-west-trending Traverse Mountains separate Salt Lake Valley from Utah Valley to the south (figure 1). Two Quaternary geologic features that have been particularly important in producing the modern physiography of the region are the WFZ and late Pleistocene Lake Bonneville.

The WFZ, the longest active normal-slip fault in the western United States and the most active fault in Utah, forms a prominent structural boundary between the actively extending Basin and Range Province and the relatively more stable Middle Rocky Mountain and Colorado Plateau provinces to the east. Extending 350 km from southern Idaho to central Utah, the WFZ includes 10 segments, 5 of which have evidence of repeated Holocene earthquakes (Machette and others, 1992). Each segment is generally considered seismogenically independent on the basis of (1) fault structure and range-front morphology, (2) shallowly buried bedrock at fault salients, (3) geophysical data indicating separate hanging-wall basins, (4) late-Quaternary fault-trace geometries, and (5) for the central segments, unique Holocene surface-faulting earthquake chronologies (Swan and others, 1980; Schwartz and Coppersmith, 1984; Machette and others, 1992; Wheeler

and Krystinik, 1992). However, available paleoseismic data permit exceptions to the traditional model of individually rupturing segments (e.g., multi-segment ruptures considered by Chang and Smith, 2002; DuRoss, 2008; and DuRoss and others, 2011). Since the mid-Holocene (~6 ka), surface-faulting earthquakes have occurred on average every 1300–2500 years per segment (Lund, 2005), and average vertical slip rates range from about 0.5 to 2.2 mm/yr using paleoseismic and geomorphic data (Machette and others, 1992; Friedrich and others, 2003; Lund, 2005).

Lake Bonneville was the most recent and largest of several pluvial lakes to occupy the eastern Great Basin during the Pleistocene (Gilbert, 1890). Details of Lake Bonneville's history are the subjects of ongoing research, but the general record of the rise and fall of the lake is well established. As summarized by Currey (1990) and Oviatt and others (1992), and recently updated by Godsey and others (2005, 2011), Oviatt and others (2005), Benson and others (2011), and Miller and others (2013), the Bonneville lake cycle began around 30 ka. Over time, the lake rose and eventually reached its highest level at the Bonneville shoreline (~1550 m [5090 ft] above mean sea level [amsl]) around 18 ka. At the Bonneville highstand, lake water overflowed the Bonneville basin threshold at Zenda in southeastern Idaho, spilling into the Snake–Columbia River drainage basin. In Salt Lake Valley, the Bonneville highstand is generally expressed as a single, prominent shoreline.

Around 17.6 ka, the Zenda threshold failed catastrophically, resulting in a rapid drop in lake level of approximately 110 m during the Bonneville Flood. The lake level stabilized when erosional downcutting was stopped by a bedrock-controlled threshold near Red Rock Pass, about 2.5 km south of Zenda, or possibly about 9 km farther south near Swan Lake (Janecke and Oaks, 2011). The lake remained at or near this level until about 14–15 ka (Godsey and others, 2005, 2011), forming the Provo shoreline (~1450 m [4760 ft] amsl). In Salt Lake Valley, the Provo shoreline is less well expressed than the Bonneville shoreline.

A climatic change to warmer and drier conditions caused the lake to regress rapidly from the Provo shoreline to near desiccation levels by the end of the Pleistocene (Eardley, 1962; Currey and others, 1988b; Currey, 1990). A small rise in lake level to an elevation of 1295 m (4250 ft) amsl marked the Gilbert phase around 12 ka (Oviatt and others, 2005; Benson and others, 2011), after which the lake regressed to near modern Great Salt Lake levels (historical average elev. 1280 m [4200 ft] amsl) (Currey, 1988a). The remarkable stratigraphic and geomorphic records of Lake Bonneville have proven extremely valuable in reconstructing the paleoseismic history of the WFZ, particularly along the central segments of the fault.

Surface Faulting in Salt Lake Valley

Salt Lake City Segment of the Wasatch Fault Zone

The 40-km-long SLCS consists of three subsections separated by left steps: the Warm Springs, East Bench, and Cottonwood faults (Scott and Shroba, 1985; Personius and Scott, 1992) (figure 2). At the northern end of the SLCS, the Warm Springs fault marks the western edge of the Salt Lake salient, a fault-bounded block of Tertiary bedrock that defines the boundary between the SLCS and the Weber segment to the north. The Warm Springs fault is at least 7.5 km long (Personius and Scott, 1992) and may extend an additional 3 km southward (e.g., Scott and Shroba, 1985; Black and others, 2003) into downtown Salt Lake City, where possible evidence of surface faulting has been exposed in construction exposures (Simon-Bymaster, Inc., 1999). At the southern end of the Warm Springs fault, the SLCS steps east about 3–4 km to the East Bench fault (figure 3), where large, prominent scarps are about 3–5 km west of the range front. The East Bench fault bounds uplifted and incised alluvial-fan surfaces and Lake Bonneville sediments, and has multiple, anastomosing traces that continue southward for 12 km. At the southern end of the East Bench fault, the SLCS steps 2–3 km eastward to the Cottonwood fault—the longest subsection of the SLCS. The Cottonwood fault is a complex fault zone that follows the range front and has large scarps, which bound prominent, but relatively narrow (<500 m wide) grabens. The Cottonwood fault extends for about 20 km to the southern end of the SLCS, where the Traverse Mountains and east-west oriented Fort Canyon fault separate the SLCS from the Provo segment (Bruhn and others, 1992).

The earliest movement on the WFZ in the Salt Lake City area likely occurred about 17.6 ± 0.7 Ma based on a K-Ar age on sericite from fault rock exhumed from ~11 km depth (Parry and Bruhn, 1987). Continued fault movement uplifted and exhumed the range along the northern SLCS at a rate of about 0.2–0.4 mm/yr over the past 5 myr, compared to 0.6–1.0 mm/yr over 2.5 Ma for the southern SLCS (Armstrong and others, 2004). The faster exhumation rate to the south is consistent with the steep range-front morphology (Armstrong and others, 2004) and the location of the greatest structural throw on the SLCS (Parry and Bruhn, 1987).

Previous paleoseismic data for the SLCS are from fault-trench investigations at Little Cottonwood Canyon (LCC) and South Fork Dry Creek (SFDC) (table 1), both at the south end of Salt Lake Valley on the Cottonwood fault (figure 2). In an early study at LCC, Swan and others (1981) found evidence of two to three Holocene earthquakes, but they were only able to determine an early Holocene minimum limiting age for the second (penultimate) earthquake. In 1999, McCalpin (2002) reoccupied the LCC site and, with a “megatrench” investigation, extended the paleoseismic record for the southern SLCS into the latest Pleistocene. McCalpin (2002) interpreted seven post-Bonneville (<18 ka) earthquakes, including four

earthquakes younger than about 6 ka. Significantly, McCalpin (2002) interpreted a period of seismic quiescence on the SLCS between about 17 and 9 ka. Using the lower (western) fault zone exposed at LCC, which has colluvial-wedge evidence of the youngest four events, McCalpin (2002) estimated an average displacement of 1.8 m per event using the total displacement (~7.5 m) across the fault. This average displacement estimate does not account for possible displacement on the upper (eastern) fault and thus could be a minimum value.

At SFDC, about 5 km south of LCC, the WFZ forms a complex zone of faulting in Holocene alluvial-fan deposits. Schwartz and Lund (1988) excavated trenches across three of six scarps at SFDC, and reported maximum-limiting ages for two earthquakes. In a follow-up study at SFDC, Lund and Mayes (1995) excavated five trenches (resulting in all of the scarps at the site being trenched) and constrained the timing of four earthquakes. The SFDC data, combined with the results of a geotechnical trench excavation at Dry Gulch (Black and others, 1996), established the current chronology of four earthquakes younger than 5.3 ka on the Cottonwood fault (Black and others, 1996; Lund, 2005; table 1). Per-event displacements are about 1.5–2.5 m based on a debris-flow levee vertically offset by two and possibly three surface-faulting events (Black and others, 1996; DuRoss, 2008).

Two exploratory trenches excavated in 1986 across the East Bench fault at the Dresden Place site (Machette and others, 1992; figure 2), about 2 km southwest of Penrose Drive (figure 3), also provide paleoseismic data for the SLCS. The trenches exposed 3 m of plastic, monoclinical warping in Lake Bonneville (highstand?) laminated silt and clay. This deformation likely occurred during a single earthquake between the highstand of Lake Bonneville (about 18 ka) and dewatering of the site following the regression from the Provo shoreline (about 14 ka) (Machette and others, 1992). An additional 4 m or more of post-Bonneville (~Holocene) faulting occurred during one or more earthquakes; however, individual earthquake times were not constrained.

Table 1. Summary of previous late Holocene earthquake-timing data for the Salt Lake City segment.

Earthquake	South Fork Dry Creek ¹ (ka)	Little Cottonwood Canyon ² (ka)	UQFPWG Consensus ³ (ka)
Z	<i>shortly after</i> $1.3 +0.25/-0.2$	~1.3	1.3 ± 0.7
Y	<i>shortly after</i> 2.45 ± 0.35	~2.3	2.5 ± 0.6
X	<i>shortly after</i> $3.95 +0.55/-0.45$	~3.5	4.0 ± 0.6
W	<i>shortly after</i> $5.3 +0.45/-0.35$	~5.3	5.3 ± 0.8

¹ Black and others (1996); includes the Dry Gulch trench.

² McCalpin (2002).

³ SLCS consensus earthquake timing (and estimated 5th–95th percentile uncertainty) of the Utah Quaternary Fault Parameters Working Group (UQFPWG; Lund, 2005), rounded to the nearest century.

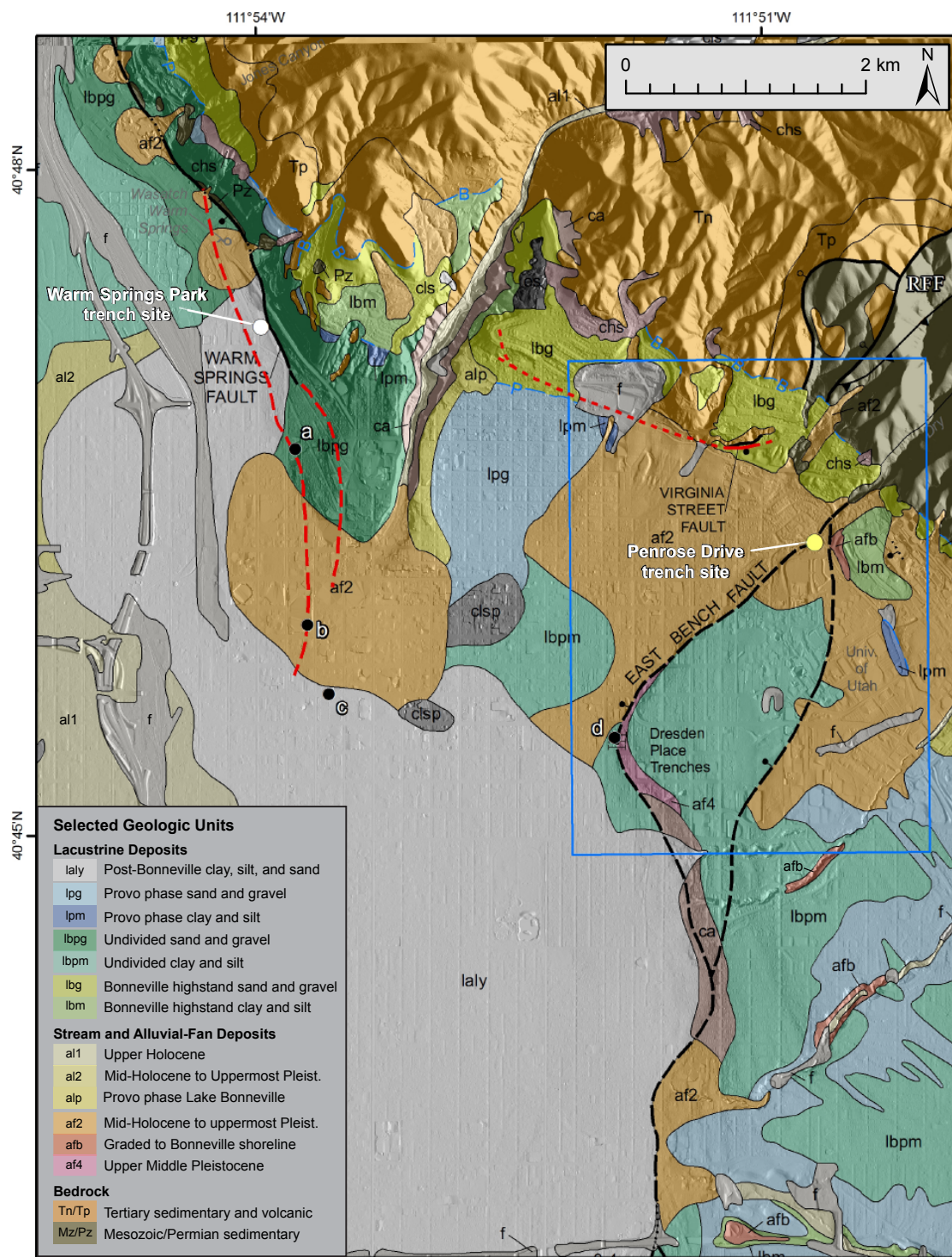


Figure 3. Surficial geologic map of the northern East Bench fault and southern Warm Springs fault modified from Personius and Scott (1992; GIS data from Personius and Scott, 2009). Heavy black lines are normal faults, dashed where inferred; ball and bar on down-thrown side; RFF – Rudys Flat fault. Red dashed lines show trace of the Warm Springs fault based on Scott and Shroba (1985; data from Black and others, 2003); red solid and dotted lines show trace of the Virginia Street fault from Van Horn and Crittenden (1987). Blue lines are Bonneville highstand (B) and Provo-phase (P) shorelines. For a complete description of map units, see Personius and Scott (1992). Black circles correspond with those on figure 2. Base map is 2-m DEM (AGRC, 2012) with hillshade illumination from the east. Box outlined in blue shows extent of figure 5.

Geotechnical studies of the Warm Springs fault offer valuable information on the location, style, and relative timing of faulting on the SLCS, but provide only limited earthquake-timing data. For example, trenches on the southern Warm Springs fault (Washington Elementary School site; figure 2) indicated 12 m of displacement since about 15 ka, but the timing of individual earthquakes is unknown (Robison and Burr, 1991). At the Salt Palace Convention Center in downtown Salt Lake City (figure 2), construction excavations and exploratory trenches revealed complex fault zones and grabens likely related to at least one surface-faulting earthquake (Simon-Bymaster, 1999; Simon and Shlemon, 1999). Two radiocarbon ages for bulk-soil sediment limit the timing of faulting in one of several trenches to a maximum of ~9.0 ka (no mean-residence-time correction applied). Charcoal from a different trench limited the timing of a presumably younger earthquake to before ~7.4 ka (Kleinfelder, 1999; Simon-Bymaster, 1999). The location of the Salt Palace faults coincides with the inferred southern extent of the Warm Springs fault mapped by Scott and Shroba (1985). However, Kleinfelder (1999) and Korbay and McCormick (1999a) interpreted the complex fault zone as a liquefaction-induced lateral spread in post-Bonneville sediments, relying on cone-penetrometer (CPT) data (contoured in Simon-Bymaster, 1999) that show minimal (less than ~1 m) vertical offset in Lake Bonneville sediments across the grabens. However, we note that the CPT data (1) were irregularly distributed across the Salt Palace site and that few points extended west, beyond the grabens; and (2) have poor vertical accuracies due to surveying errors (Korbay and McCormick, 1999b). Finally, the CPT data considered did not include ~3 m of vertical offset in Bonneville sediments measured in sounding CP-9 as the location was not surveyed (Simon-Bymaster, 1999). To address these fault versus lateral-spread interpretations, Leeftang (2008) completed a 1.7-km long, east-west CPT line along 400 South (about 0.5 km south of the Salt Palace) across the projected trace of the Warm Springs fault (figure 2). Leeftang (2008) interpreted tectonic displacement near the projected trace of the fault due to (1) 10.4–11.8 m of vertical offset in pre-Bonneville alluvium and transgressive (basal) Lake Bonneville sediments based on three CPT soundings over a horizontal distance of 460 m (soundings to the east and west show flat-lying Lake Bonneville sediments), (2) an increase in the thickness of the transgressive deposits on the down-thrown side of the inferred fault zone (from about 4–7 m to 12 m thick), (3) differential offset between transgressive (basal) and regressive (upper) Lake Bonneville sediments, which indicate multiple surface-faulting earthquakes at the site, and (4) liquefaction analysis using the CPT data that only supports minor settlement and lateral-spread displacements.

West Valley Fault Zone

The WVFZ consists of intrabasin normal faults that span an area 16 km long by 1–6 km wide in the northern part of Salt Lake Valley (figure 2). The two subparallel, northwest-trending main traces and their associated subsidiary traces are

known as the Granger fault (western traces) and Taylorsville fault (eastern traces). Both faults have scarps on post-Bonneville lake cycle (latest Pleistocene to Holocene) lacustrine and alluvial deposits, and previous paleoseismic studies (Keaton and others, 1987; Keaton and Currey, 1989) have documented multiple Holocene surface-faulting earthquakes. The scarps are typically about 0.5–1.5 m high, but have a maximum height of 6 m near the southern end of the Granger fault. Scarps on the Granger fault face east, and scarps on the Taylorsville fault face both east and west. As a whole, the WVFZ is considered an antithetic structure to the west-dipping SLCS master or controlling fault (e.g., Bruhn and Schultz, 1996).

Previous studies have produced a long-term (140 kyr) slip history for the WVFZ, but timing and displacement data for individual surface-faulting earthquakes have been lacking. For example, Keaton and others (1987) and Keaton and Currey (1989) mapped parts of the fault, excavated trenches, and drilled numerous boreholes. Boreholes on the Granger fault indicate 0.7–3 m of displacement in post-Bonneville sediments (<12 ka) and 5–7 m in Bonneville lake-cycle deposits (12–28 ka), but no evidence of individual surface-faulting events. Trenches excavated by consultants have yielded earthquake-timing information for the WVFZ where the Utah Geological Survey (UGS) was able to sample organic sediment for radiocarbon dating. Radiocarbon ages from these trenches indicate surface faulting earthquakes on the Granger fault at about 1.3–1.7 ka (unpublished UGS data) and Taylorsville fault at about 2.2 ka (Solomon, 1998), which correspond well with the timing of the youngest SLCS earthquakes (table 1). However, the context of the samples and their relation to earthquake timing is not well understood owing to brief site visits that precluded detailed logging and the nature of the bulk-soil (apparent mean residence time [AMRT]) ages, which are difficult to interpret (Machette and others, 1992).

Why Trench the Salt Lake City Segment?

Because of extensive development in Salt Lake Valley, limited paleoseismic data are available for the SLCS. Previous research trenches on the SLCS define several Holocene surface-rupturing events; however, these studies have been limited to the Cottonwood fault on the southern part of the SLCS, which is about 15 km southeast of the southernmost scarps on the WVFZ. In addition, important questions remain regarding the mid-Holocene to latest Pleistocene earthquake record for the SLCS, including whether earthquakes occurred between 17 and 9 ka. Finally, previous investigations of the SLCS relied on AMRT radiocarbon ages, which are problematic in that they are composite ages that reflect the total age distribution of carbon in the sampled soil and require a mean-residence-time (MRT) correction based on the assumed age of the soil at the time of burial (Machette and others, 1992). Because of these limitations, the previously available data are insufficient to understand the timing and rupture extent of earthquakes on both the northern and southern SLCS, as well as their relation to earthquakes on the WVFZ.

OVERVIEW AND METHODS

Trench Investigations

We identified trench sites on the SLCS using (1) fault-trace and surficial-geologic mapping by Scott and Shroba (1985) and Personius and Scott (1992); (2) our interpretation of 1937 (Agricultural Stabilization and Conservation Service, 1937) and 1970s (low-sun-angle) aerial photographs (Cluff and others, 1970; included in Bowman and others, 2009) and 2006–2009 orthophotography from the National Agricultural Imagery Program (NAIP) (U.S. Department of Agriculture [USDA], 2012; Utah Automated Geographic Reference Center [AGRC], 2012); (3) 2-m-posting LiDAR data for Salt Lake Valley (AGRC, 2012); and (4) field reconnaissance of prospective sites. We also considered the discussions and analyses of SLCS paleoseismic data by the Utah Quaternary Fault Parameters Working Group (UQFPWG; e.g., Lund, 2005, 2007) prior to selecting preferred sites. We found only three potential sites on the SLCS, and we excavated trenches at two of them: the Warm Springs Park site on the southern Warm Springs fault and the Penrose Drive site on the northern part of the East Bench fault (figures 2 and 3).

Warm Springs Park Site

Warm Springs Park is close to the southern end of the Warm Springs fault (figure 3) where Gilbert (1890) documented evidence of Holocene surface faulting. However, at the time of our study, virtually the entire Warm Springs fault had been modified by extensive development or aggregate mining. As a result, the Warm Springs Park site provided the only opportunity to conduct a paleoseismic trench investigation. We excavated three trenches at the site in May 2010 (figure 4), but only exposed cultural fill and extensively modified sediments. Two northern trenches, which were 8 and 21 m long, exposed cultural fill to a depth of about 4–5 m. About 0.4 km south, an 8-m-long and about 2-m-deep southern trench encountered rotated blocks of probable Tertiary Salt Lake Formation that are likely landslide deposits, but no evidence of faulting. Because we did not encounter in-place native deposits or expose the WFZ, we did not clean or map these trench exposures. Thus, we show the site and trench locations on figure 4, but do not discuss the Warm Springs site further.

Penrose Drive Site

The Penrose Drive site is near the northern end of the East Bench fault (figures 3 and 5), north of the University of Utah campus (near the intersection of Penrose Drive and Military Way in Salt Lake City), where a northwest-facing scarp crosses Lake Bonneville sediments and post-Bonneville alluvial-fan deposits (Personius and Scott, 1992). This site was one of only a few possible trench sites on the East Bench fault that had not been fully developed. We chose the site because of the simple geometry and moderately large height of the fault scarp, and because the site had minimal evidence of cultural

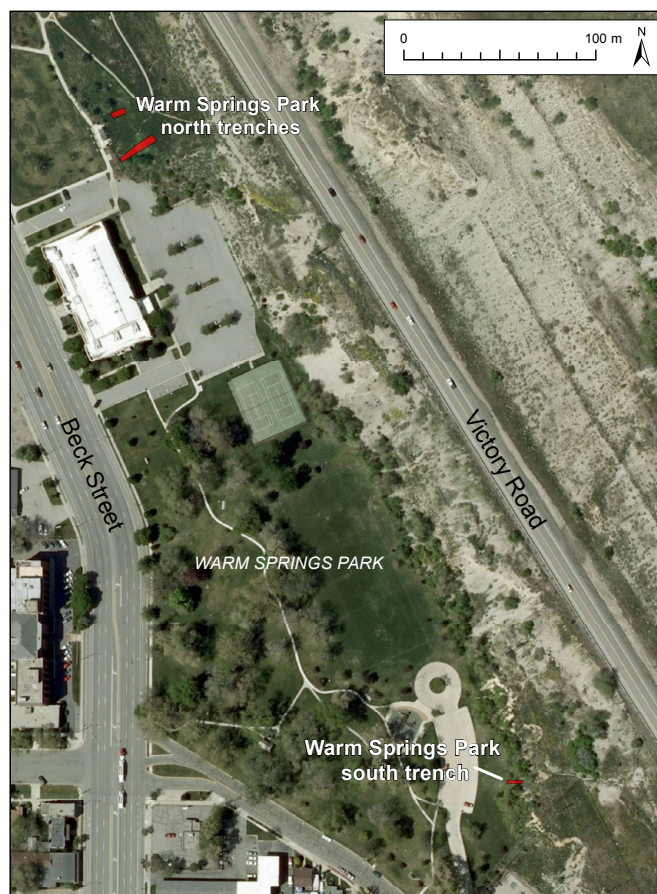


Figure 4. Warm Springs Park trench site on the southern Warm Springs fault. Because we exposed only manmade fill or landslide blocks of Tertiary Salt Lake Formation and did not expose the Wasatch fault, we did not clean or map these trenches. Base map is 2009 NAIP data (USDA, 2012; AGRC, 2012). Red shaded areas show excavated trenches.

disturbance based on examination of the 1937–2009 aerial photographs (figure 6).

We excavated two trenches at Penrose Drive in May 2010: a 36-m-long western trench and, 20 m to the northeast, a 14-m-long, parallel eastern trench (figure 7). The western trench was generally less than 4 m deep, whereas the eastern trench reached depths of about 5 m. To map the exposures, we used an electronic distance meter (Trimble TTS 500) to measure the positions of markers (e.g., nails and flagging) along stratigraphic contacts and structures and projected those points to a vertical plane that represented the average orientation of the trench wall. We then mapped the points for each wall at 1:20 scale on gridded drafting film and sketched in additional detail in the fault zones. The total station and averaged vertical plane were also used to set up a 1-m square grid on the trench walls, which we used as a reference grid to construct 1:20-scale photomosaics of the walls. We mapped the northeast-facing wall of the west trench, and the entire southwest-facing wall and uppermost northeast-facing wall of the east trench. Plate 1 includes maps and photomosaics of the exposures with a single

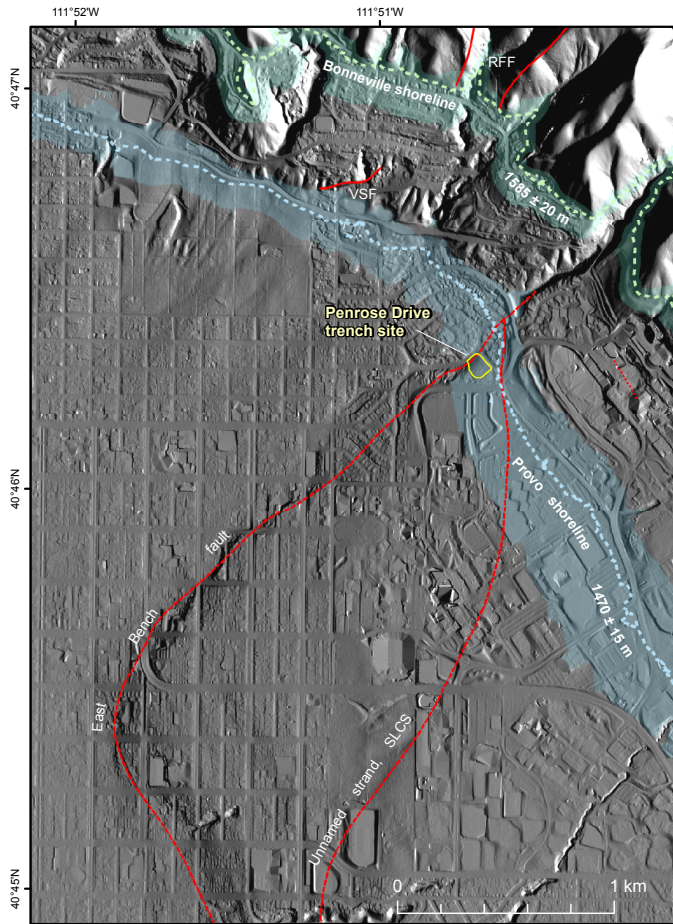


Figure 5. Northern part of the East Bench fault, showing the Penrose Drive trench site and the approximate elevations of the Bonneville-highstand and Provo-phase shorelines of Lake Bonneville (shoreline elevations based on Currey, 1990; see text for discussion). Wasatch fault traces, including the Virginia Street fault (VSF) and Rudys Flat fault (RFF), are from Personius and Scott (1992, 2009). Yellow outline shows the Penrose Drive trench site (figure 7). Base map is 1-m DEM (AGRC, 2012) with hillshade illumination from the east.

coordinate system for both trenches referenced using horizontal (h-) and vertical (v-) meter marks. For example, the fault zone exposed in the west trench is h-21.5 m, v-5.0 m, west trench; plate 1. Stratigraphic units are described in appendix A and summarized on plate 1.

Numerical Dating

Radiocarbon Dating

We sampled bulk soil A-horizon sediment (appendix B) and radiocarbon (^{14}C) dated discrete fragments of charcoal recovered from the horizons (appendix C) to estimate the ages of buried soil and to limit the timing of paleoearthquakes. For discussions of common sources of uncertainty in ^{14}C dating and paleoseismic studies, see Nelson and others (2006) and DuRoss and others (2011). To increase the likelihood of dating locally derived charcoal (e.g., sagebrush) rather than non-

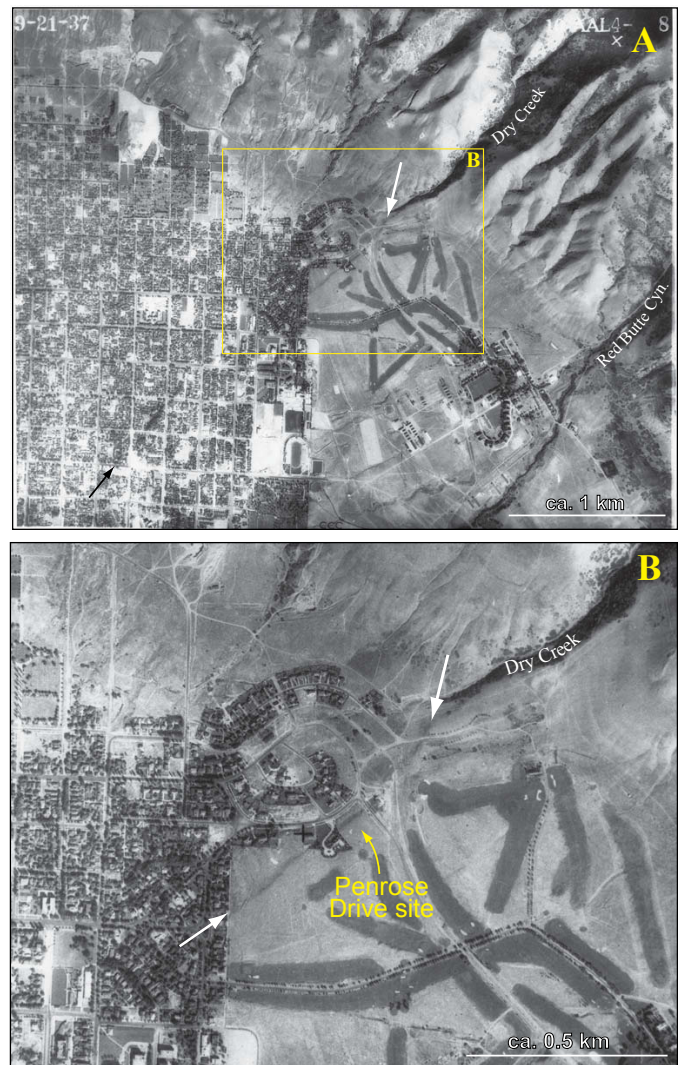


Figure 6. (A) 1937 aerial photograph (AAL 4-8; Agricultural Stabilization and Conservation Service, 1937) showing the Penrose Drive trench site and the prominent expression of the East Bench fault scarps (denoted by black and white arrows). Yellow box shows area of figure 6B. (B) Detail of 1937 aerial photograph, showing the northernmost East Bench fault scarps (white arrows) and location of the Penrose Drive site.

local (detrital) charcoal (e.g., conifer transported from higher elevations), PaleoResearch Institute (Boulder, Colorado) separated and identified by genus (if possible) charcoal fragments from bulk A-horizon sediment samples. Locally derived charcoal fragments are more likely burned in place or very close by, and therefore less likely to have an inherited, older age (Puseman and Cummings, 2005). Four of 20 individual charcoal samples from Penrose Drive could be identified (e.g., *Artemisia*—flowering plants such as sagebrush, and *Quercus*—oak; appendix B) and were likely locally derived. The remaining Penrose Drive samples only produced collections of small, unidentified charcoal fragments. For each sample, these unidentified fragments were recombined into samples of at least ~0.5 mg, which yielded composite charcoal ages.

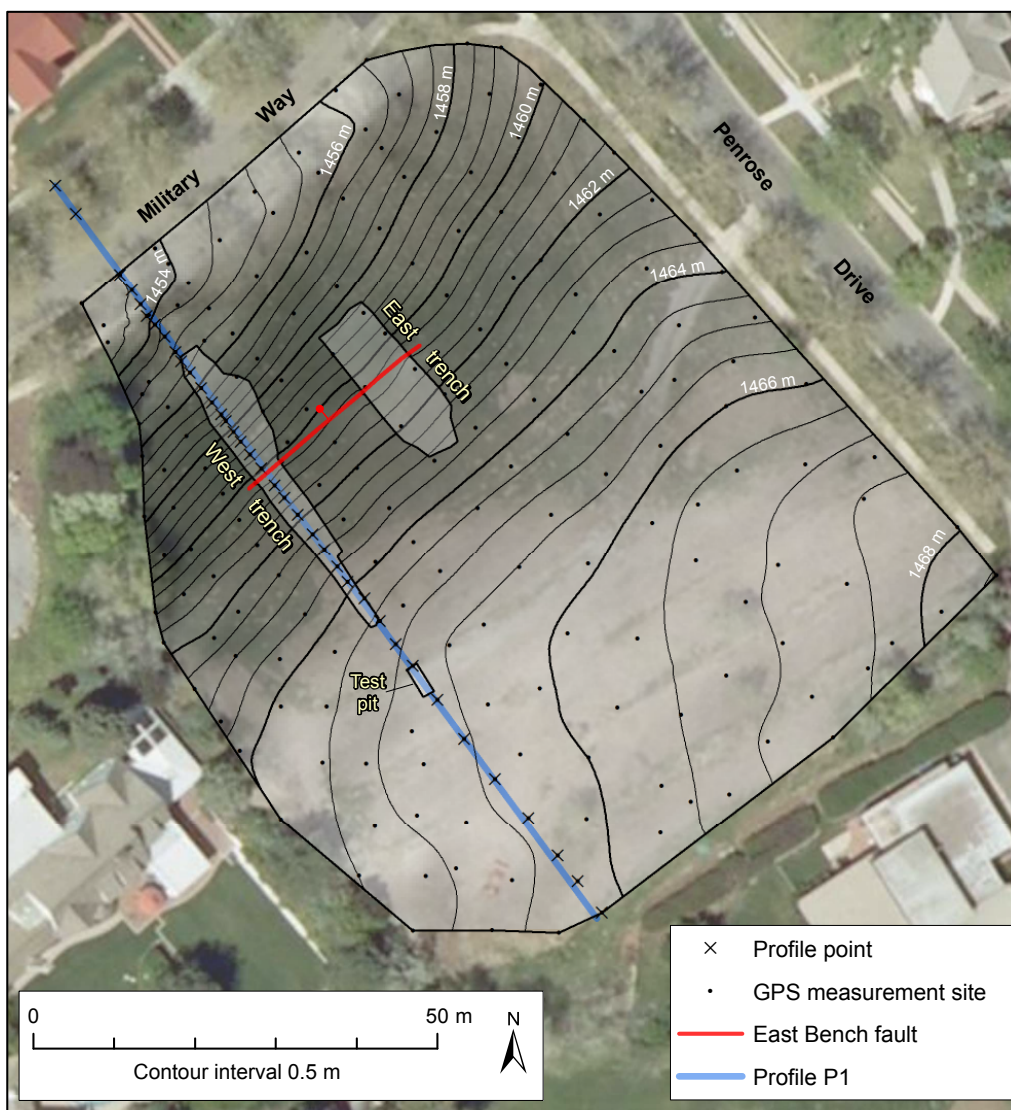


Figure 7. Topographic map (0.5-m contours) of the Penrose Drive site based on survey-grade GPS data measured May 5–25, 2010. Traces of the East Bench fault exposed in the west and east trenches (and projected between them) are shown in red; ball and bar on down-thrown side. Blue line indicates scarp profile (figure 8). Contours interpolated using kriging method; hillshade illumination from the east. Base map is 2009 high resolution (25-cm) orthophotography (AGRC, 2012).

Although detrital charcoal could have been present in either the unidentified or identified samples, the stratigraphic consistency of the ages and the similar ages between the unidentified and identified charcoal fragments (from the same A horizons) indicate minimal age uncertainty related to a detrital signal or post-depositional modification of the dated material.

We submitted the charcoal samples to the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) Facility of the Woods Hole Oceanographic Institution (Woods Hole, Massachusetts) for accelerator mass spectrometry (AMS) ^{14}C dating. We report the radiocarbon ages as the mean and two-sigma (2σ) uncertainty rounded to the nearest century in thousands of calendar years before 1950 (ka) using the Reimer and others (2009) terrestrial calibration curve applied in OxCal (Bronk Ramsey, 1995, 2001).

Luminescence Dating

We used optically stimulated luminescence (OSL) dating to estimate burial ages of lacustrine and colluvial-wedge sediments at Penrose Drive (appendix D). OSL dating relies on the cumulative dose of in situ natural radiation in sediment (e.g., quartz grains) to estimate the time when the sediment was last exposed to sunlight prior to final deposition (Huntley and others, 1985). Ideally, the sunlight exposure was sufficiently long (about 10 minutes) during erosion and transport to fully reset or “zero” any preexisting luminescence signal in the grains, and thus the luminescence age should represent the time when the sediment was deposited (Aitken, 1994). If the sediment’s exposure to sunlight was not long enough (e.g., because of rapid deposition, a short travel path, or filtered light in turbid water) to fully zero the sediment, then the sediment may re-

tain an inherited luminescence signal (Duller, 2008), which results in an overestimated (maximum) age for the deposit. In contrast, underestimated (minimum) ages result if the luminescence signal becomes saturated, where the signal does not increase despite continued exposure of the sediment to radiation (Duller, 2008). Saturation results in a maximum age limit for OSL dating of ~75–300 ka, depending on the radiation dose rate and mineral dated (Duller, 2008; Rhodes, 2011).

Luminescence ages for the Penrose Drive site (appendix D) include OSL ages on quartz grains (quartz-OSL) and in some cases, infrared-stimulated luminescence (IRSL) ages on feldspar grains measured as a complement to the OSL ages. We generally prefer the quartz-OSL ages because the IRSL signal takes longer to zero than the OSL signal—after sunlight exposure durations of about tens of seconds to minutes, there is a 1–2 order-of-magnitude difference in the remaining OSL and IRSL signals (Duller, 2008). However, OSL and IRSL ages that overlap within error provide an additional degree of confidence that partial bleaching (insufficient sunlight exposure) is not a problem in the sediments.

Our luminescence samples were processed at the U.S. Geological Survey Luminescence Dating Laboratory (Denver, Colorado). Background radiation from potassium, uranium, and thorium was measured in the field using a portable gamma-ray spectrometer; however, field moisture was measured in the laboratory. We report OSL ages (appendix D) as the mean and one-sigma uncertainty rounded to the nearest decade. However, where discussed in the text, the error is doubled (2σ rounded to the nearest century) for continuity with the calendar-calibrated ^{14}C ages and the modeling of earthquake times in OxCal. In discussing the OSL ages, we report the ages in thousands of years before the sample processing date (2010) (ka) and do not account for the 60-year difference in the OSL sample date (2010) versus the reference standard for ^{14}C (1950). This difference is minor compared to the large OSL age uncertainties (generally ~1–3 kyr at 2σ), and is accounted for in later modeling of earthquake times in OxCal (discussed below).

OxCal Modeling Methods

To evaluate earthquake timing and associated uncertainties, we used OxCal ^{14}C calibration and analysis software (version 4.1; Bronk Ramsey, 1995, 2001; using the IntCal09 calibration curve of Reimer and others, 2009). OxCal probabilistical models the timing of undated events (e.g., earthquakes) by weighting the time distributions of chronological constraints (e.g., radiocarbon and OSL ages and historical constraints) included in a stratigraphic model (Bronk Ramsey, 2008). The program generates a probability density function (PDF) for each event in the model, or the likelihood that an earthquake occurred at a particular time, using the chronologic and stratigraphic constraints and a Markov Chain Monte Carlo (MCMC) sampling method (Bronk Ramsey, 2008, 2009). For more detailed discussions of the application of OxCal model-

ing to paleoseismic data, see discussions by Lienkaemper and Bronk Ramsey (2009) and DuRoss and others (2011).

OxCal depositional models for the Penrose Drive site (appendix E) use stratigraphic ordering information, radiocarbon and OSL ages, and a historical constraint that no large surface-faulting earthquakes ($M \sim 6.5+$) have occurred since about 1847 to define the time distributions of earthquakes identified at the site. We correlated depositional units between the west and east trenches and constructed a single OxCal model for the site. Where necessary, we removed numerical-age outliers using geologic judgment (knowledge of sediments, soils, and sample contexts), the degree of inconsistency with other ages in the model for comparable deposits (e.g., stratigraphically inverted ages), and an agreement index between the original (unmodeled) and modeled numerical ages (Bronk Ramsey, 1995, 2008). For the SLCS, we also constructed OxCal models for the previously studied paleoseismic sites using available data. Because these previous investigations used bulk-soil-sediment (AMRT) ages, we used the Delta_R command to correct for the estimated residence time of the soil at the time of burial (see DuRoss and others [2011] for discussion). We report earthquake time ranges for each site as the mean and 2σ uncertainty in thousands of calendar years B.P. (ka) rounded to the nearest century.

PENROSE DRIVE TRENCH SITE, SALT LAKE CITY SEGMENT

Surface Faulting and Geology

The Penrose Drive site is at the northern end of the East Bench fault, where the Holocene trace of the SLCS trends 230° (N. 50° E.) for about 3 km before terminating at the mouth of Dry Creek (Personius and Scott, 1992; figures 3 and 6). The northern East Bench fault is separated from the Warm Springs fault to the west by a 3–4-km-wide overlapping left step (figure 2). No known Holocene faults span the step-over zone between these faults; however, a short, less than 0.5-km-long (Personius and Scott, 1992) to ~2.5-km-long (Van Horn and Crittenden, 1987), west-northwest trending normal fault (Virginia Street fault [VSF]; figures 2 and 3) with a pre-Holocene time of most-recent movement partly bounds the southern extent of Tertiary bedrock in the northern part of the step-over zone. Although the Holocene trace of the SLCS steps west, the pre-Holocene Rudys Flat fault (RFF; figures 2 and 3) continues north, juxtaposing Paleozoic and Tertiary bedrock and forming the eastern boundary of the Salt Lake salient (Personius and Scott, 1992). The RFF has no evidence of late Quaternary movement; however, surficial deposits are limited (Personius and Scott, 1992). Although we cannot preclude a subsurface connection between the East Bench and Rudys Flat faults, it is more likely that the Warm Springs fault, which bounds the western edge of the Salt Lake salient and has clear evidence of Holocene surface faulting (Gilbert, 1890; Personius and Scott, 1992), is the active trace of the WFZ to the north of the East Bench fault.

Surficial geology near Penrose Drive is dominated by Lake Bonneville lacustrine sediments and geomorphic features, and both pre- and post-Bonneville alluvial-fan deposits (figure 3). Deposits associated with the Lake Bonneville highstand generally include laminated silt and fine sand below the shoreline and sand to coarse gravel forming wave-built terraces in the shorezone. Close to the site (within about 5 km), the highstand shoreline is mapped at about 1570–1585 m elevation (Personius and Scott, 1992), which compares well with a measurement of 1586 ± 1 m made by Currey (1982) (shoreline elevations in this discussion are not corrected for isostatic rebound; e.g., Oviatt and others, 1992). Similar deposits are associated with the Provo-phase shoreline, which spans an elevation range of about 1465–1475 m (Personius and Scott, 1992) and is less well expressed than the Bonneville shoreline. The Penrose Drive site spans an elevation of 1454–1466 m, which is well below the elevation of the Bonneville highstand (~1585 m), but very close to the elevation of the Provo shoreline (~1470 m). Alluvial-fan deposits in the area consist of overland (sheet) and debris flows emanating from Dry Creek and Red Butte Canyon, which are cut into Paleozoic to Mesozoic bedrock east of the SLCS. Post-Bonneville alluvial-fan sediments are most prevalent; however, southwest of Penrose Drive, pre-Bonneville alluvial-fan remnants are exposed in the footwall of the East Bench fault (Personius and Scott, 1992).

Wasatch Fault Scarp and Surface Offset

At the Penrose Drive site, the East Bench fault is expressed as a single 11-m-high, northwest-facing scarp at about 1455–1465 m elevation (figures 7 and 8). Above the elevation of the scarp (1465–1468 m), the upper surface slopes downward gently to the west to northwest and has likely been modified by Provo-phase shorezone processes and possibly cultural disturbance related to the historical use of the site as an orchard. Below the scarp, the lower surface has been partly developed, but based on the trench exposures (discussed below), may be underlain by Provo-phase shorezone sediments. We estimate 11.0 m of vertical surface offset using projections of the upper and lower surfaces along a northwest-oriented profile (figures 7 and 8).

Trench Stratigraphy and Structure

Our two Penrose Drive trenches served to (1) locate the East Bench fault and expose fault-related sediments (west trench; figure 9), and (2) maximize the exposure in the fault zone (east trench). We exposed four distinct packages of sediment in both trenches: (1) pre-Bonneville alluvial-fan deposits, (2) Lake Bonneville sediments, (3) scarp-derived colluvium (colluvial wedges), and (4) cultural (manmade) fill (figures 9, 10, and 11). We also exposed the pre-Bonneville sediments in a test pit about 9 m southeast of the west trench (figure 12). Because we exposed very similar fault geometries and packages of sediment in both trench exposures, including nearly identical individual colluvial-wedge deposits, and given the close (about 20 m) horizontal distance between the trenches,

we describe a single set of sedimentary units for the entire site in appendix A.

Pre-Bonneville Alluvial-Fan Deposits

We exposed pre-Bonneville alluvial-fan gravel (unit 1, plate 1) in the eroded footwall of the East Bench fault. The gravel consists of vertically aggraded stream- and debris-flow deposits likely derived from Dry Creek and (or) Red Butte Canyon to the east. The texture of the gravel within individual (intra-unit) subunits varies laterally along the exposures, but generally unit 1 includes massive to well-bedded, clast-supported, fine to coarse gravels in an oxidized red-orange sand matrix. The red-orange color is likely related to post-depositional oxidation of the alluvial-fan gravel, rather than being primary in origin (e.g., derived from a single iron-stained bedrock unit exposed in the Wasatch Range). Individual subunits are less than about 1.5–1.9 m thick, together reach a thickness of at least 6–7 m in the east trench, and have bedding contacts with apparent dips of zero to about 5–8° NW.

A soil consisting of an A horizon and a well-developed calcic Bkt horizon has formed on the pre-Bonneville alluvial-fan gravels (soil S6; h-1.0–4.0 m, v-11.1–11.2 m; west trench; plate 1). In the southeast part of the west trench, the carbonate in this soil is generally diffuse (only locally weakly laminated), but it cements gravel clasts in a 0.2–0.7-m-thick B horizon (soils 2Bk and 2Btk; plate 1). We exposed similar Bk and Btk horizons on pre-Bonneville alluvial-fan deposits in the test pit (figure 12). Soil S6 also includes a 0.2–0.3-m-thick A horizon, which overlies and locally overprints the soil carbonate. The A horizon is best expressed at the end of the west trench and in the test pit and is less developed on the slope of the scarp face.

Unit-1 fan gravels are best exposed in the footwall of the west trench, where we mapped several individual stream or debris-flow deposits and found lenses of fine sand, which we sampled for quartz-OSL dating. Samples PD-L1 to -L3, from a sandy upper part of a debris-flow deposit near the top of the package of fan gravels, yielded mean ages of 64.4 ± 8.0 ka (sample PD-L3; all ages are $\pm 2\sigma$), 69.3 ± 8.1 ka (PD-L2), and ~ 77 ka (PD-L1). Another OSL sample from the base of the flow yielded a mean age of 58.8 ± 3.4 ka (PD-L4). IRSL ages on feldspar grains yielded ages of 134.7 ± 13.7 ka (PD-L1) and 220.8 ± 19.8 ka (PD-L4) (appendix D). The significantly older IRSL ages could indicate that the quartz-OSL ages are saturated, and are thus minimum ages. Alternatively, the IRSL ages could be too old (maximum ages for unit 1) if the feldspars were only partially bleached, which is likely the case for PD-L4. We favor the quartz-OSL ages as representing the age of the fan gravel because the OSL samples have consistent mean ages and relatively small (6–12%) uncertainties. Only one sample (PD-L1) yielded a poorly defined age, which could be a function of poor sample luminescence or a saturated age. The PDF of the sum of the four OSL ages (PD-L1–L4) indicates a mean age of 67.3 ± 14.4 ka (2σ) for the pre-Bonneville fan gravels.

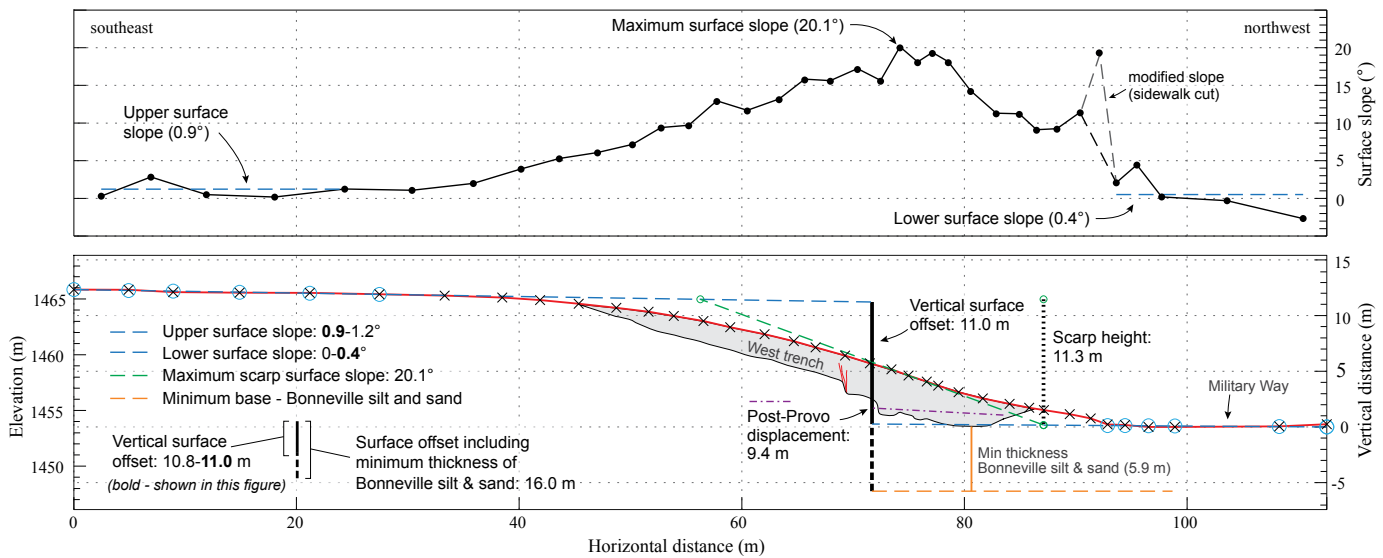


Figure 8. Scarp profile P1 (red line) measured across the Penrose Drive site (May 5, 2010). Profile points (X's) measured using high-precision GPS; elevation is relative to mean sea level; vertical distance is relative to minimum surface elevation (1453.5 m). Black dots show surface slope at midpoint distances between profile points. Blue circles indicate profile points selected for upper and lower surface-slope measurements (horizontal blue dashed lines in upper figure). The ranges of surface slopes and vertical offsets reflect the selection of alternate profile points; bold values correspond with this figure. Scarp height is the vertical distance between the intersections of the maximum scarp slope with the upper and lower surface-slope projections (green circles). Orange dashed line is horizontal projection of the minimum base of Bonneville highstand silt and sand (unit 2) from a hand-auger hole at 33.1 m horiz., 1.0 m vert. (west trench), which met refusal in unit 2 at 5.9 m below the bottom of the west trench (vertical orange line). Gray shaded area shows extent of the west trench; red lines are faults corresponding with plate 1.



Figure 9. East Bench fault of the Wasatch fault zone (red lines) and scarp-derived colluvium (units 4–8) exposed in the northeast-facing wall of the west trench at the Penrose Drive site. S1 and S5 (buried by cultural fill) indicate prominent soil A horizons formed in Provo-phase boulder gravel and scarp-derived colluvium, respectively. See plate 1 for additional stratigraphic contacts and soils mapped in the west trench. Pink level lines form 1-m squares.

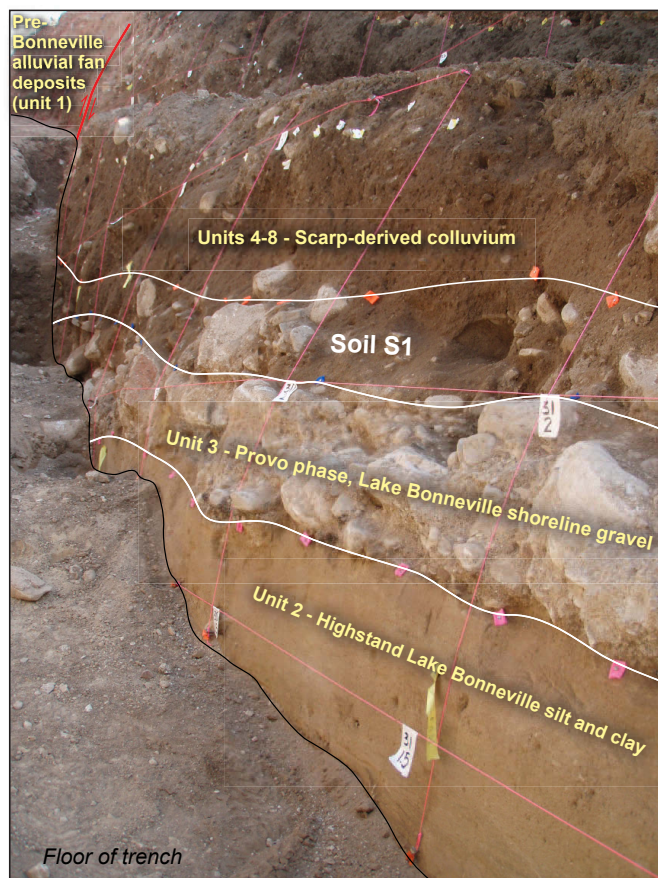


Figure 10. Lake Bonneville highstand sediments (unit 2), Provo-phase boulder gravel (unit 3), and scarp-derived colluvium (units 4–8) exposed on the hanging wall of the East Bench fault (red line) in the northeast-facing wall of the west trench at the Penrose Drive site. S1 is prominent soil A horizon developed within the Provo-phase boulder gravel. Pre-Bonneville alluvial-fan deposits (unit 1) in the footwall of the East Bench fault are in the upper-left part of the figure. See plate 1 for additional stratigraphic contacts and soils mapped in the west trench. Lowest two horizontal level lines are 0.5 m apart, all other level lines (horizontal and vertical) form 1-m squares.

Lake Bonneville Sediments

Lacustrine sediments related to Lake Bonneville are the oldest units exposed on the hanging wall of the East Bench fault at this site and include fine silt and sand deposited during the Bonneville highstand (unit 2; plate 1). The silt and sand are overlain by coarse boulder-cobble gravel (unit 3; plate 1) that was likely deposited during formation of the Provo-phase shoreline. A well-developed soil A horizon is present on unit 3 (soil S1; plate 1; figure 10). Units 2 and 3 are not present in the footwall of the fault in the trenches.

In the west trench, unit 2 consists of massive to thinly and subhorizontally bedded silt with little variability in its texture over an 8-m-long exposure (figure 10). Two OSL samples of fine silt from the uppermost part of unit 2 yielded ages of 17.0 ± 1.4 ka (PD-L5) and 17.8 ± 0.7 ka (PD-L6). These ages correspond well with the age of the latest highstand occupation

(Bonneville flood) of 14,500 ^{14}C yr B.P. (Oviatt, 1997), which we calendar calibrated to 17.6 ± 0.3 ka (2σ) using OxCal.

We also exposed Lake Bonneville sediments in the 2-m-wide lowermost exposure of the east trench (figure 11) immediately adjacent to the fault plane. In this exposure, unit 2 is slightly coarser than in the west trench and contains abrupt, linear contacts that separate silt and fine sand laminae. The bedding in unit 2 dips steeply to the northwest. We measured apparent dips of 30–45° NW on several contacts and a true dip of 53° N (275° strike, using right-hand rule and 12° declination) for one contact based on a three-dimensional exposure. We attribute the dip of these beds to monoclinal folding associated with movement on the East Bench fault (at least one surface-faulting earthquake), rather than to primary depositional dip (e.g., foreset beds of a delta or onlap of beds onto a preexisting scarp). In addition, we do not consider subaqueously deposited colluvium as a likely origin for the inclined beds because of the fine, well-sorted sediment and planar interbed contacts. This pattern of deformation is similar to the monoclinal, fault-related warping of Lake Bonneville silt and clay described at the Dresden Place site (2 km to the south) on the East Bench fault by Machette and others (1992). However, at Penrose Drive, the folded Lake Bonneville sediments are eroded and unconformably overlain by flat-lying Provo-phase shoreline gravel (h-7.5 m, v-1 m, east trench; plate 1). We interpret the folded Bonneville highstand beds and angular unconformity with the overlying Provo gravel as evidence of at least one surface-faulting earthquake that occurred after deposition of Bonneville highstand silt at the site (~17–18 ka based on OSL ages for unit 2; appendix D), but before the regression from the Provo shoreline (~14.5 ka) (figure 13).

We drilled an 8-cm-diameter hand-auger hole in the bottom of the west trench in an attempt to locate the pre-Bonneville fan gravel on the fault hanging wall (h-33; plate 1). The borehole penetrated 5.9 m of silt and sand prior to refusal; however, no pre-Bonneville fan gravels were encountered. Based on this hole, we conclude that deposits from the Lake Bonneville transgression and highstand (unit 2) have a minimum thickness of 6.5 m at the base of the scarp at the Penrose Drive site. In contrast, correlative Bonneville sediments were not observed on the fault footwall, including in the test pit 9 m south of the west trench.

We offer several possible explanations for the thick Bonneville highstand deposits on the hanging wall but no highstand deposits on the footwall. One explanation is that Bonneville sediments were deposited on the footwall but later eroded in the Provo-phase shorezone. However, we find it unlikely that at least 6.5 m of fine-grained Bonneville sediment has been completely eroded from the footwall since the lake dropped to the Provo level at about 18 ka. A second explanation is that pre-Bonneville topography, either from a north- to west-sloping alluvial-fan surface or a sublacustrine fault scarp (greater than a few meters high), enhanced deposition of highstand fine sediment on the hanging wall. Finally, fault movement

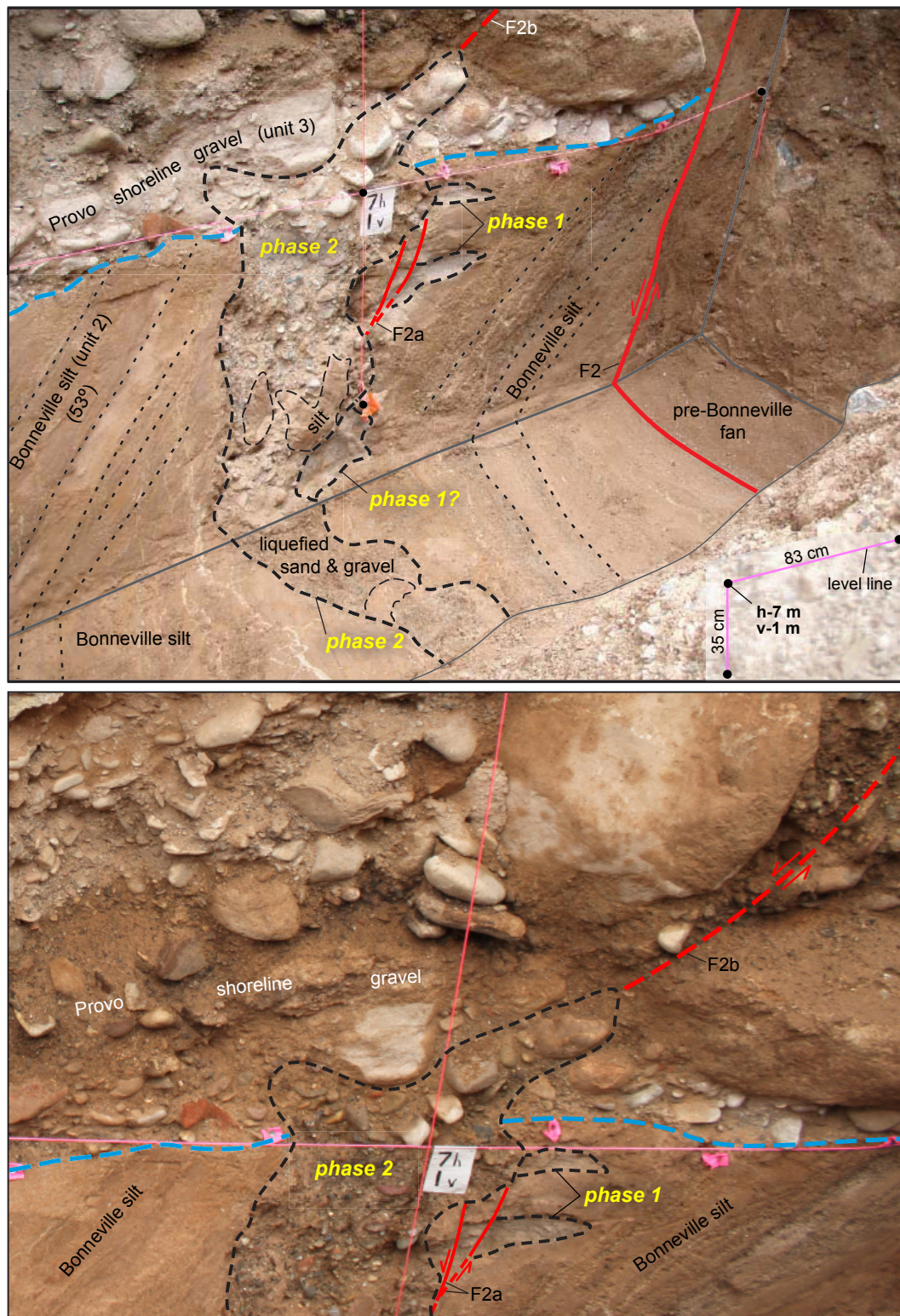


Figure 11. Upper photo shows monoclinical folding in Lake Bonneville silt (unit 2) in the base of the east trench that predates an angular unconformity formed during the Provo-shoreline occupation (flat-lying Provo shoreline gravel) and provides evidence of at least one surface-faulting earthquake (PD6). Red lines show traces of the East Bench fault, including subsidiary traces (short solid and dashed lines) that are partly obscured by liquefied sand and gravel. Phase-1 liquefaction denotes sand horizontally injected into Bonneville highstand silt (possibly during earthquake PD6); however, later-phase liquefaction has obscured this possible cross-cutting relation. Phase-2 liquefaction marks liquefied sand and pebble gravel extending into the lower Provo shoreline gravel that occurred during PD5 or possibly a later earthquake. See figure 13 for conceptual models of the faulting and liquefaction observed in the East Trench. View is to the southeast. Lower photo shows detail near grid intersection 7 m horizontal and 1 m vertical.

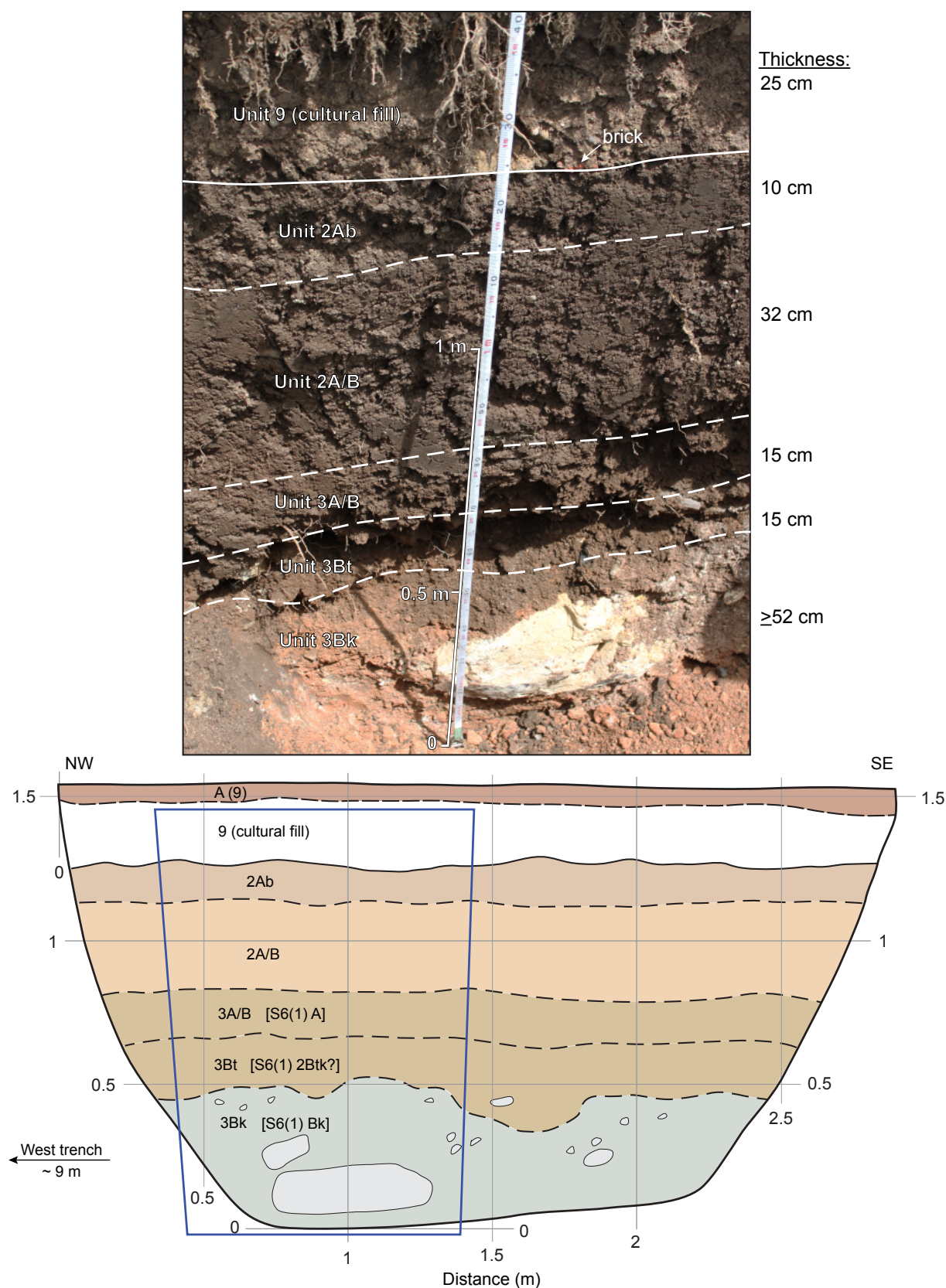


Figure 12. Soil profile exposed in the test pit excavated on the footwall of the East Bench fault, about 9 m southeast of the south end of the west trench at the Penrose Drive site. Soil description on annotated image and map is for this exposure only; a possible correlation of soil horizons with those exposed in the west trench is shown in brackets. Photograph taken May 12, 2010; box outlined in blue shows location of photograph relative to map of exposure.

could have played a role in the preservation and erosion of the highstand sediments. For example, vertical fault movement during the highstand and Provo-phase occupations would have dropped and preserved sediments on the hanging wall and uplifted and exposed sediments on the footwall (figure 13). If strike-slip motion occurred (discussed below), then local variations in sediment thickness could be juxtaposed at the site. We favor a combination of these explanations to explain our observations: preexisting topography and fault movement likely enhanced deposition and preservation of fine-grained Bonneville highstand sediment on the fault hanging wall, whereas erosion of these (relatively thinner) sediments on the footwall likely occurred as they were uplifted and exposed in the Provo shoreline.

Unit 3 consists of carbonate-cemented coarse sand and boulder gravel unconformably (east trench; figure 11) to conformably (west trench; figure 10) overlying the highstand silt and sand of unit 2. The boulder gravel is 0.5 m thick in the east trench (where undisturbed by liquefaction) and about 0.6–1.1 m thick in the west trench, and includes numerous gastropod shells (and fragments), which we sampled but did not date. At a distance greater than about 3 m from the East Bench fault, a well-developed, 0.2–0.5-m-thick soil A horizon is present in unit 3 (soil S1; west trench; plate 1). Within about 3 m of the fault, soil S1 is formed on scarp colluvium that postdates the boulder gravel (east trench; plate 1).

We sampled macrocharcoal from the A horizon of soil S1 and also collected a bulk sample of the A-horizon for ^{14}C dating. Two unidentifiable macrocharcoal fragments from the east trench yielded ages of 11.4 ± 0.3 ka (PD-R1) and 10.9 ± 0.2 ka (PD-R3), compared to an age of 10.6 ± 0.1 ka (PD-R2) for *Rosaceae* (flowering plant) charcoal from the west trench. The slightly younger age from the west trench could be related to the location of PD-R3, which sampled the uppermost part of soil S1. However, it is also possible that PD-R3 sampled distal colluvial-wedge sediment (and organics) which directly overlies soil S1 in the sample area. Unidentified charcoal fragments separated from the S1 soil (sample PD-R13; west trench) yielded an age of 11.5 ± 0.3 ka, which agrees well with the 10.9–11.4-ka age for PD-R1 and -R3.

Liquefied Sand and Gravel

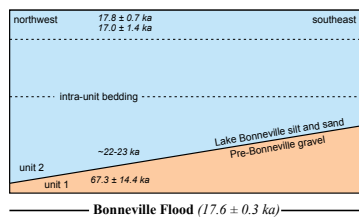
In the basal exposure of the eastern trench, a prominent liquefaction vent (h-7 m, v-1 m; plate 1; figure 11) injected sand and gravel into the silty Bonneville sediments (unit 2) and the overlying Provo shoreline deposits (unit 3) along lower (F2a) and upper (F2b) splay faults that parallel the main trace of the East Bench fault. The feature records at least two phases of liquefaction: an initial event that injected fine sand vertically and horizontally into unit 2 (phase 1; figure 13), and a later event that injected a much larger volume of sandy pebble gravel vertically into unit 2 and the lower part of unit 3 (phase 2; figure 13). Liquefied sand and gravel in both phases likely

correspond with the splay faults; however, the later event has obscured the expression of discrete faulting in much of the exposure. Evidence of shearing and unit displacement and truncation includes (1) displacement of phase-1 fine-sand injection features in unit 2 by fault F2a (h-7.1 m, v-0.8 m, east trench; plate 1), (2) shearing and clast rotation in the upper part of unit 3 along fault F2b (h-7.4 m, v-1.5 m, east trench; plate 1), (3) a ~10-cm step in the unit 3/unit 4 contact coincident with upward termination of fault F2b (h-7.4 m, v-1.7 m; plate 1), and (4) apparent offset (~4–5 cm) of the base of unit 3 across the later-phase liquefaction event (inferred location of splay fault F2b). Although it is possible that fault F2a, which cuts the initial-phase injection features, terminates at the unit 2–3 contact; the later-phase liquefaction has obscured this possible cross-cutting relation (figure 11) (h-7.1 m, v-0.9 m; east trench; plate 1).

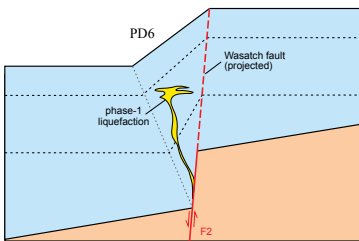
The spatial association of liquefaction features with the splay faults indicates that these features are likely the result of seismic shaking from at least two surface-faulting earthquakes on the East Bench fault, rather than from earthquakes elsewhere in the region. The timing of these “liquefaction” earthquakes can be roughly estimated by stratigraphic relations with the lacustrine sediments: the earlier liquefaction event postdates the deposition of Bonneville transgressive and highstand silts and may be related to the earthquake that resulted in the monoclinical folding of these sediments, and the later event postdates the Provo shoreline. Termination of the lower splay faults (F2a)—which displace the initial-phase injection features—at the unit 2–3 contact would be evidence of a third earthquake in the later stages of the Bonneville transgression; however, this possible upward termination is obscured by later-phase liquefaction (figure 11) and we cannot preclude the possibility that faults F2a and F2b in units 2 and 3, respectively, moved contemporaneously (models A and B; figure 13). We observed another liquefaction feature in the west wall of the east trench, where a deposit of fine sand is injected into scarp colluvium (unit 6) subparallel to the main fault zone (h-8.2 m, v-3.1 m; plate 1). Given its height in the stratigraphic section and the relations described above, this feature likely was formed during a younger, separate earthquake that postdated the deposition of unit 6.

Scarp-Derived Colluvium

We identified five and possibly six deposits of scarp-derived colluvium (units 4, 5, 6a, 6b, 7, and 8; plate 1), each providing evidence of an individual surface-faulting earthquake on the SLCS. The colluvial units have similar wedge-shaped geometries, and with the exception of unit 6a, have soil A horizons developed on them. The youngest scarp-colluvial wedge (unit 8) is not faulted, whereas units 4–7 have been faulted down to the northwest along the East Bench fault. In general, the colluvial deposits reflect an evolving depositional environment in which the oldest wedges have a limited lateral extent of 3–6 m away from the fault compared to the younger wedges, which extend about 11 m from the

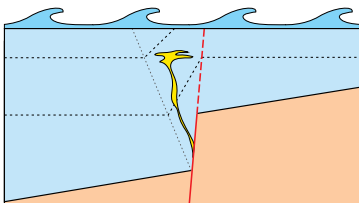
Model A: One Lake Bonneville Highstand to Provo Phase Earthquake**Initial Condition**

Transgressive and highstand silt and fine sand (unit 2) deposited between about 22-23 ka and 18 ka (Bonneville Flood) on possibly west-to north-sloping pre-Bonneville alluvial fan surface (unit 2).

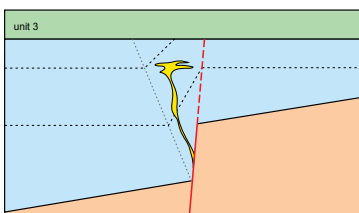
**Earthquake PD6**

Earthquake PD6 occurs during Provo-phase (14-18 ka) occupation, resulting in subaqueous scarp and folding in cohesive highstand sediments (unit 2).

Liquefied fine sand injected vertically and horizontally into folded unit 2 (phase 1).

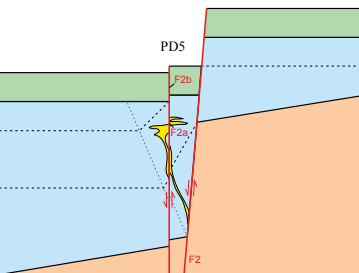
**Erosion During Provo Shoreline**

Bonneville sediments in footwall and near fault zone eroded during Provo-phase of Lake Bonneville (~18-14 ka).

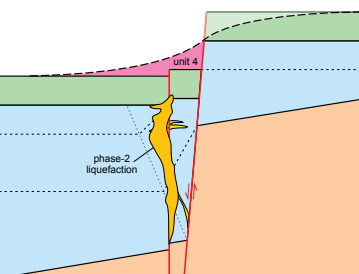
**Deposition of Provo Shoreline Gravel**

Provo-phase boulder gravel (unit 3) deposited on folded and eroded Bonneville highstand sediments (unit 2).

Lake Bonneville regresses from site by about 14 ka.

**Earthquake PD5**

Provo shoreline boulder gravel (unit 3), folded Bonneville highstand sediments (unit 2), and phase-1 liquefied sand faulted in earthquake PD5.

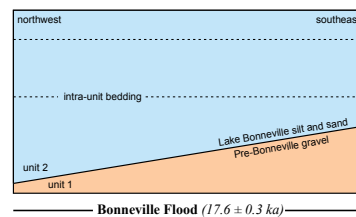
**Scarp-Colluvium Deposition and Liquefaction**

Colluvial-wedge (unit 4) deposited following earthquake PD5.

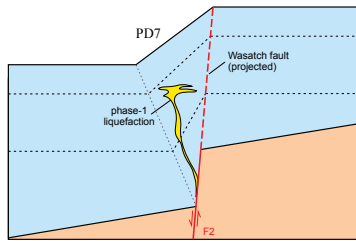
During a later earthquake (PD4-PD1), liquefied sand and gravel (phase 2) injected into units 2 and 3, overprinting synthetic faulting and phase-1 liquefaction.

EXPLANATION

- Erosion related to Provo-shoreline occupation of site
- Unit 4. Scarp-derived colluvium eroded from fault scarp formed in earthquake PD5.
- Phase-2 liquefaction. More extensive sand and gravel (compared to phase-1) vertically injected into Bonneville highstand and Provo-phase sediments along synthetic fault.
- Phase-1 liquefaction. Fine sand vertically and horizontally injected into Bonneville highstand sediments (unit 2); limited extent.
- Unit 3. Lake Bonneville Provo-phase boulder gravel. Carbonate-cemented coarse sand and boulders about 0.5-1.1 m thick deposited in near-shore environment.
- Unit 2. Lake Bonneville highstand silt and sand. Massive to subhorizontally bedded silt with fine sand interbeds deposited during Lake Bonneville highstand occupation.
- Unit 1. Pre-Bonneville alluvial-fan gravel. Massive to well-bedded, clast supported, fine to coarse gravels in an oxidized red-orange sand matrix

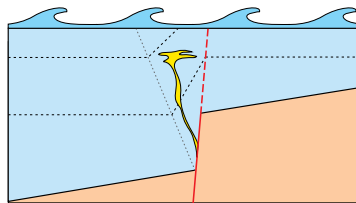
Model B: Two Lake Bonneville Highstand to Provo Phase Earthquakes**Initial Condition**

Transgressive and highstand silt and fine sand (unit 2) deposited between about 22-23 ka and 18 ka (Bonneville Flood) on possibly west- to north-sloping pre-Bonneville alluvial fan surface (unit 2).

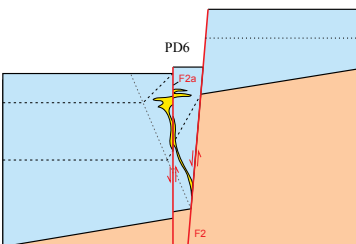
**Earthquake PD7**

Earthquake PD7 occurs during Provo-phase (14-18 ka) occupation, resulting in subaqueous scarp and folding in cohesive highstand sediments (unit 2).

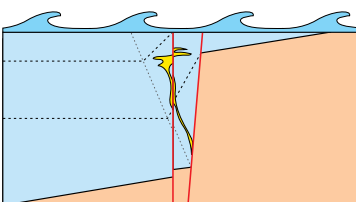
Liquefied fine sand injected vertically and horizontally into folded unit 2 (phase 1).

**Erosion During Provo Shoreline**

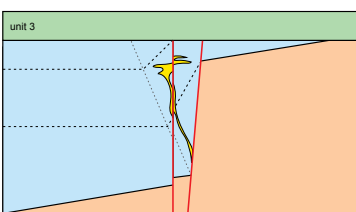
Bonneville sediments in footwall and near fault zone eroded during Provo-phase of Lake Bonneville (~18-14 ka).

**Earthquake PD6**

Folded and Bonneville fine sand and silt and phase-1 liquefied sand faulted by earthquake PD6.

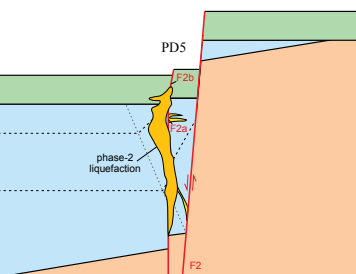
**Erosion During Provo Shoreline**

Bonneville sediments in footwall and near fault zone eroded during Provo-phase of Lake Bonneville (~18-14 ka).

**Deposition of Provo Shoreline Gravel**

Provo-phase boulder gravel (unit 3) deposited on folded and eroded Bonneville highstand sediments (unit 2).

Lake Bonneville regresses from site by about 14 ka.

**Earthquake PD5**

Provo shoreline boulder gravel and folded Bonneville fine sand and silt faulted in earthquake PD5.

Liquefied sand and gravel (phase 2) obscures overprints phase-1 liquefaction.

Colluvial-wedge (unit 4) deposited following earthquake PD5 (not shown).

fault, equal to the horizontal length of the scarp. In addition, the basal contacts of the wedges steepen as they become younger, reflecting a growing scarp that has progressively influenced scarp-colluvium deposition. In the west trench, the basal contacts steepen upward from 13° to 25°, in increments of 2°–4° over distances of 1–6 m from the trace of the East Bench fault. In the east trench, the basal contacts steepen upward from 6° to 25°, in more irregular 0°–11° increments over distances of 0–4 m from the fault.

Unit 4—the oldest scarp-colluvial wedge—contains a distinct mixture of subrounded boulders that were likely derived from unit 3 and orange-red sand and gravel of unit 1 (h-7.4 m, v-1.8 m; east trench; plate 1). Unit 4 tapers from 1.0 to 0.7 m thick over a distance of about 3 m and, adjacent to the East Bench fault, has slope-parallel clast fabric. Because soil S1 is developed on unit 4 and no soil is present on the Provo boulder gravel, we suspect that this earthquake occurred shortly after the Provo shoreline regressed from the site. Calibrated ¹⁴C ages from charcoal in soil S1 indicate that unit 4 was deposited before about 10.9–11.5 ka (PD-R1, -R3, -R13; appendix C; plate 1). We did not expose unit 4 in the west trench, which did not extend deep enough adjacent to the fault zone.

Unit 5 consists of a mixture of silt, sand, and gravel clasts, and soil organics that is about 0.8 m thick adjacent to the fault (in both trenches) and pinches out over a horizontal distance of about 6 m. Although locally massive, unit 5 includes fine gravel that defines slope-parallel lenses and stone lines. The A horizon of soil S2 is developed on unit 5 and is 0.2–0.3 m thick. We could not clearly identify soil S2 within about 1 m of the fault, possibly because of fault-related disturbance, or because the deposition of scarp colluvium continued close to the fault at the time of soil S2 development. OSL sample PD-L7 constrains the age of the uppermost part of unit 5 (below soil S2) to 11.0 ± 1.2 ka. This age agrees well with two radiocarbon ages of 10.6 ± 0.1 ka (PD-R6a) and 10.1 ± 0.2 ka (PD-R6b) on unidentified charcoal fragments from a bulk sample of soil S2.

Two distinct packages of scarp colluvium, separated by a prominent stone line, compose unit 6 (6a-lower, 6b-upper; plate 1). Units 6a and 6b consist of a mixture of mainly fine sand, silt, and soil organics with interspersed pebble to small cobble clasts that form slope-parallel lenses and stone lines. Unit 6 is locally massive and, in the east trench, fines to the northwest. Unit 6a tapers from about 0.8 m thick to zero over a horizontal distance of about 5 m, and unit 6b tapers from about 0.7–0.8 m thick to zero over a distance of 4–5 m. The maximum (combined) thickness of units 6a and 6b is 1.6 m. A

prominent pebble and cobble stone line marks the boundary between units 6a and 6b, but no soil is present at the contact. This stone line is best expressed in both walls of the east trench (h-7.0 m, v-3.6 m; plate 1) and is visible (but more subtle) in the west trench (h-22.5 m, v-4.8 m; plate 1). Two OSL samples of unit 6 yielded ages of 7.4 ± 0.9 ka (unit 6a; PD-L8) and 8.4 ± 1.3 ka (unit 6b; PD-L9). Although PD-L9 is stratigraphically inverted with PD-L8, the two ages have about 67% overlap at one sigma (appendix B) and PD-L9 likely represents a maximum constraint for unit 6b. We also sampled a moderately well-developed, 0.2–0.4-m-thick soil A horizon (soil S3) developed on unit 6b. Two microcharcoal samples and a charred *Prunus*-type (similar to Cherry) seed fragment yielded ages of 6.3 ± 0.1 ka (PD-R8), 6.3 ± 0.1 ka (PD-R10b), and 6.6 ± 0.2 ka (PD-R10a), respectively. An additional sample of unidentified charcoal from soil S3 yielded an age of 3.8 ± 0.1 ka (PD-R5); however, we dismiss this age because it differs greatly from the concordant PD-R8 and PD-R10 ages. The anomalously young age for S3 is likely related to mixing of organic-rich sediment from the overlying younger soil S4 (well dated to ~4 ka; discussed below) with S3 through burrowing.

Our favored interpretation is that units 6a and 6b are evidence of two separate surface-faulting earthquakes based on the prominent stone line and their individual maximum thicknesses of 0.8 m, which are nearly identical to those for units 4, 5, 7, and 8. Because no soil is present between units 6a and 6b, we cannot dismiss the possibility that units 6a and 6b represent two pulses of scarp colluvium following a single large-displacement earthquake. We address both of these alternative interpretations in two separate OxCal models (appendix E).

Unit 7 consists of silt and sand mixed with soil organics and interspersed pebble and cobble clasts, which form slope-parallel lenses within about 4 m of the East Bench fault. At greater distances from the fault, unit 7 is finer grained and massive. Unit 7 tapers from 0.7 m thick adjacent to the fault to zero over a distance of about 11 m. Soil S4 is an A horizon soil developed on unit 7 that reaches a maximum thickness of about 0.2 m, but is locally only weakly developed. Beyond about 2–3 m from the fault, unit 7 and soil S4 are locally overprinted by soil S5. Soil S4 is locally burrowed, but it is best expressed in the west trench, where we collected two samples of the A horizon. Unidentified charcoal fragments from soil S4 (PD-R14a) and two microcharcoal samples (PD-R14b and -R9b) yielded ages of 4.2 ± 0.2 ka, 4.4 ± 0.1 ka, and 4.4 ± 0.2 ka, respectively. An additional charcoal sample (PD-R9a) was too small to date. As discussed previously, sample PD-R5 (~3.8 ka) likely dates charcoal derived from soil S4.

Figure 13. (opposite page) Conceptual models of faulting in Lake Bonneville sediments. Model A shows monoclinial folding related to at least one earthquake (PD6) between the Bonneville flood and the regression from the Provo shoreline, and younger splay faulting (contemporaneous movement of faults F2a and F2b) in earthquake PD5. Model B includes at least two earthquakes (PD7 and PD6) between the Bonneville flood and Provo regression that predate earthquake PD5. In this model, fault F2a is active in PD6 and F2b in PD5. In both models, phase-1 liquefaction occurs during monoclinial folding of unit 2 and phase-2 liquefaction occurs after deposition of unit 3.

Scarp colluvium in unit 8 includes a poorly sorted mixture of silt, sand, soil organics, and gravel that bury an eroded scarp free face and the faulted soil A horizon S4. The unit is mostly massive, but locally the clasts define a weak slope-parallel fabric. Unit 8 has a maximum thickness of 1.0 m, and thins to about 0.7 m within 2–3 m from the East Bench fault before being completely overprinted by soil S5. Soil S5 varies in thickness from about 0.3 to 0.6 m where developed on unit 8 in the center of the fault scarp to about 0.7–0.8 m in the northwestern part of the west trench. S5 is extensively burrowed, but locally very well developed. We separated charcoal fragments from two samples of the S5 A-horizon sediment. A fragment of *Quercus* (oak) charcoal yielded an age of 0.5 ± 0.05 ka (PD-R11) and *Artemisia* (herbs and shrubs of the daisy family Asteraceae) charcoal provided an age of 0.5 ± 0.04 ka (PD-R12).

Cultural Fill

A deposit of cultural (manmade) fill (unit 9; plate 1; figure 9) overlies soil S5 on the hanging wall of the East Bench fault. Unit 9 is distinctive as it includes fragments of brick and metal. The cultural fill has a maximum thickness of 1.6 m, which coincides with the base of the East Bench fault scarp (h-30 m; plate 1) in the west trench. At the northwest end of the west trench, unit 9 is at most 0.5 m thick where it overlies colluvial unit 8. Unit 9 may be the result of site excavation and grading (above the elevation of the west trench) for a fruit orchard. We found no evidence of cultural disturbance or manmade fill below soil S5.

East Bench Fault of the Wasatch Fault Zone

The East Bench fault (fault F2; plate 1) is characterized by a sharp, steeply dipping zone of sheared sediment consisting of carbonate-rich silt, sand, and gravel in which clasts are rotated parallel to one of several fault planes. In the west trench, two faults dipping 79° – 90° NW bound a 0.3–0.7-m-wide zone of sheared sediment. In the east trench, a narrow, ~0.1-m-wide shear zone is bounded by two subparallel, linear faults dipping 83° – 85° NW. In a three-dimensional exposure of fault gouge at the base of the east trench, we measured a fault striking 229° and dipping 88° NW; in the same location, a flat, ~0.1-m-wide rotated clast was striking 227° and dipping 79° NW. In the base of the west trench, the southeastern fault bounding the sheared sediment has an orientation of $229^{\circ}/90^{\circ}$. Where projected to the surface and shown on our site topographic map (figure 7), the fault strike is 229° . Based on these measurements, we prefer a strike of 229° and dip of $85 \pm 5^{\circ}$ NW for the East Bench fault.

Partly because of the planar and steeply dipping character of the East Bench fault, the contacts of stratigraphic units have only been slightly rotated (flattened) or dragged (steepened) adjacent to the fault zone. The progressive decrease in the dips of the bases of the colluvial wedges could be interpreted-

ed as evidence of fault rotation; however, we interpret these decreasing dips to be depositional and the result of colluvial wedges being deposited on the sloping surface of a progressively growing scarp. In the west trench, a slight upward inflection in the contact between units 2 and 3 within about 7.5 m of the fault (from subhorizontal to dipping 4° NW at h-29.5 m; plate 1) could be related to fault drag, but not rotation. Averaged over several earthquakes, the 4° change in dip indicates that only a very small amount of fault drag has occurred since the time of the Provo shoreline. One exception is unit-2 interbeds that dip 30° – 50° adjacent to the fault in the base of the east trench. We interpret these inclined beds as related to monoclinical folding of saturated highstand sediments during at least one surface-faulting earthquake that occurred between the Bonneville highstand and Provo-shoreline occupation (figure 13).

We measured vertical displacement on the East Bench fault using the minimum offset of the pre-Bonneville fan gravel, surface-slope information from the scarp profile, the inferred stratigraphic offset of the Provo-phase shoreline, and the maximum thicknesses of colluvial wedges. Because Lake Bonneville highstand sediments were not exposed in the footwall, we cannot measure the cumulative displacement that has occurred since the Bonneville highstand. To estimate the minimum displacement on the East Bench fault since deposition of the pre-Bonneville fan gravel, we used the thickness of augered Lake Bonneville highstand sediments (unit 2) on the hanging wall. Using the 6.5-m thickness of unit 2, and a 0.9° sloping upper surface from the scarp profile, the minimum vertical displacement of the pre-Bonneville fan gravel is 16 m (figure 8).

Our estimates of post-Provo-phase displacement assume that the upper surface from the scarp profile (~1466 m amsl; figure 8) corresponds with the Provo shoreline elevation and thus the Provo shoreline boulder gravel (unit 3) exposed in the trenches. The basis for this assumption is the absence of Lake Bonneville highstand sediments on the footwall (likely eroded while in the Provo shorezone) and the Provo shoreline elevation near the site (~1470 m amsl; figure 5). Using a 0.9° sloping upper-surface projection, a 3° slope for the top of the Provo-phase boulder gravel (top of soil S1 where best expressed from h-29–33 m; plate 1), and an 85° fault dip, the displacement is 9.4 m (figure 8). We consider this to be a maximum displacement because (1) it is possible that the top of unit 3 is not correlative with the upper surface (~1466 m amsl) and could be a shoreline from a lower, later Provo phase (e.g., P9 of Godsey and others, 2005), and (2) there may have been a preexisting scarp at the site, as discussed above.

To estimate total post-Provo displacement as well as displacement per event, we use maximum colluvial-wedge thickness as a proxy for fault displacement (DuRoss, 2008). As described above, the maximum thicknesses of colluvial wedges are as follows: unit 4–1.0 m, unit 5–0.8 m, unit

6a–0.8 m, unit 6b–0.8 m, unit 7–0.7 m, and unit 8–1.0 m. The sum of these is 5.1 m, which represents the minimum vertical displacement that occurred after deposition of the Provo gravel. Using this estimate, and the vertical displacement from the scarp profile, our preferred post-Provo-phase displacement is 5.1–9.4 m. The maximum thicknesses of individual wedges have only minor variations and indicate a mean per-event displacement of 0.9 m (0.7–1.0-m range). Increasing the per-event displacements by 84% to account for a total upper-bound displacement of 9.4 m, suggests that the mean per-event displacement could be 1.6 m (1.3–1.8-m range). Our preferred per-event displacement is 1.2 m (the midpoint between the 0.9 and 1.6 m mean displacements), with a possible range of 0.7–1.8 m.

We mapped three minor-displacement subsidiary faults in the west trench. Two down-to-the-northwest faults about 1–3 m southeast of the main East Bench fault trace (F2; plate 1) dip 74–78° NW (faults F1a and F1b; plate 1). Fault F1a has less than 0.1 m of vertical displacement; we were unable to correlate intra-unit gravel beds in unit 1 to determine F1b displacement. We also identified a poorly expressed (possibly reverse) fault about 1.5 m northwest of the main fault trace that dips 81° SE (fault F3; plate 1). F3 corresponds with a minor down-to-the-northwest inflection in the top of soil S3; however, the contact between units 6a and 6b suggests little to no displacement.

Subsidiary faults in the east trench consist of down-to-the-northwest splay faults in Lake Bonneville highstand silt and Provo-phase shoreline gravel (figure 11). Fault F2a (h-7.1 m, v-0.9 m; plate 1) displaces liquefied sand injected into folded Lake Bonneville highstand silt (unit 3). Because F2a has been disturbed by a later liquefaction event (figure 11), we were unable to measure the total displacement in unit 2. F2a may terminate at (predate) the unit 2–3 contact; however, this relation has been obscured by liquefaction. Fault F2b (h-7.4 m, v-1.5 m; plate 1) displaces Provo-phase shoreline gravel (unit 3) down to the northwest about 5–10 cm based on the apparent offset of the unit 2–3 contact (about 4–5 cm) and a northwest-down step in the unit 3–4 contact (about 10 cm). Because liquefaction has removed evidence of faulting near the base of unit 3, the geometry of fault F2b in unit 2 is poorly constrained.

The steeply dipping, planar, and simple fault zone exposed at Penrose Drive is unusual compared to other trenches that have exposed the Wasatch fault (e.g., see Machette and others, 1992; DuRoss and others 2009, 2012). The near-vertical planar fault may indicate that a component of strike-slip motion occurs on this part of the fault. The Penrose Drive site is on a part of the East Bench fault where the fault's strike is subparallel to the general extension direction for the Salt Lake City segment as a whole. The northern 3 km of the East Bench fault strikes about 230° (N. 50° E.), which is essentially identical to the 229° strike of the fault exposed at Penrose Drive. Bruhn and others (1992) show that the gen-

eral direction of slip for all sections of the SLCS is 230–250° based on slickenlines measured on bedrock fault planes, or 240° based on a paleostress analysis for the Salt Lake City–Provo segment boundary. Comparably, the geodetic extension direction for the Wasatch Front is 266°, using data in a 65-km-wide zone across the Wasatch fault (Chang and others, 2006). Given this geometry, it is possible that both normal and strike-slip faulting occurs on the northernmost East Bench fault. Thus, while normal faulting is likely the main slip direction at the Penrose Drive site (based on the significant vertical surface offset), a component of strike-slip motion may help explain the unusual subsurface fault geometry.

Paleoseismology of the Penrose Drive Site

Chronology of Surface-Faulting Earthquakes

We interpret at least six and possibly seven surface-faulting earthquakes at the Penrose Drive site (PD1–PD6; table 2) after deposition of Lake Bonneville highstand silt (unit 2) at about 17.0–17.8 ka (figures 13 and 14). Monoclinical folding in unit 2 that predates an angular unconformity formed during the Provo-shoreline occupation provides evidence of at least one surface-faulting earthquake (PD6), whereas earthquakes PD5–PD1 are based on distinct scarp-colluvial deposits and soil A horizons. The timing of these earthquakes is based on two OxCal models: a preferred model that includes seven earthquakes (accounting for units 6a and 6b; OxCal model 4b; appendix E; figure 14), and an alternative model that includes six earthquakes (a single earthquake for unit 6; OxCal model 4c; appendix E). We report earthquake times from the seven-earthquake OxCal model as the mean and 2 σ uncertainty; however, for earthquakes having asymmetrically distributed timing PDFs (i.e., where the mean and modal times differ by several hundred years or more), the modal times and 5th–95th percentile ranges (table 2; appendix F) may better approximate the earthquake times. Per-event vertical displacements for PD1–PD5 range from about 0.7 to 1.8 m based on colluvial-wedge thickness and the total post-Provo displacement at the site (tables 2 and 3).

Earthquake PD6 occurred at 16.5 ± 1.9 ka based on an angular unconformity between folded Bonneville highstand silt beds (unit 2) and relatively flat-lying Provo-phase boulder gravel (unit 3). Considering the ductile deformation and elevation of the site close to the Provo-shoreline elevation, earthquake PD6 likely produced a subaqueous scarp that was later modified and eroded by Provo-phase shorezone processes. Liquefied sand injected into the steeply dipping highstand silt beds along a fault splay synthetic to the East Bench fault may be evidence of PD6 or an earlier earthquake (figure 13). Two OSL ages (PD-L5 and -L6) provide maximum-limiting times of 17.0–17.8 ka, whereas ¹⁴C ages from Provo-shoreline environments at similar elevations in the Bonneville basin provide a minimum time constraint for this earthquake. Using a Provo-shoreline elevation range of 1430–1450 m (adjusted for isostatic rebound) for Penrose Drive, 13 ¹⁴C ages compiled by Godsey and others

Table 2. Timing and displacement of surface-faulting earthquakes at the Penrose Drive site.

Event ¹	Mean ² (cal yr)	$\pm 2\sigma^2$ (yr)	5 th 2 (cal yr)	50 th 2 (cal yr)	95 th 2 (cal yr)	Mode ² (cal yr)	Displacement ³ (m)	Unit ⁴
PD1	4000	500	3530	4070	4250	4100	1.0–1.8	8
PD2	5890	700	5140	6010	6250	6210	0.7–1.3	7
PD3a	7510	760	6890	7520	8150	7520	0.8–1.5	6b
PD3b	9700	1110	8390	9910	10,190	10,160	0.8–1.5	6a
(PD3)	(9370)	(1540)	(7820)	(9680)	(10,170)	(10,150)	(1.6–2.9)	(6)
PD4	10,870	240	10,680	10,870	11,060	10,920	0.8–1.5	5
PD5	12,080	1590	11,400	11,810	13,830	11,620	1.0–1.8	4
PD6	16,470	1910	14,580	16,680	17,660	17,140	unknown	-

¹ Earthquakes identified at Penrose Drive and modeled in OxCal (figure 14; appendices E and F). Events in bold are included in our preferred seven-event OxCal model 4b, including PD3a and PD3b. An alternative 6-event OxCal model (4c) includes a single earthquake PD3 in place of PD3a and PD3b.

² Mean earthquake times, 2σ ranges, and 5th–50th–95th percentile ranges, and modal times are based on OxCal models 1 and 2 (appendix E; see text for discussion).

³ Per-event vertical displacement. Ranges are based on the maximum colluvial wedge thickness and an upper-bound displacement using the wedge thickness adjusted for a maximum post-Provo displacement (see text for discussion).

⁴ Map unit for scarp-derived colluvium associated with the event (plate 1, appendix A).

Table 3. Vertical slip rates at the Penrose Drive site.

Event ¹	Mean ² (ka)	Disp. ³ (m)	Total Displacement ⁴ (m)	Elapsed Time ⁵ (kyr)	Slip Rate ⁶ (mm/yr)
PD1	4.0	1.0–1.8	-	-	-
PD2	5.9	0.7–1.3	1.0–1.8 (PD1)	1.9 (PD2–PD1)	0.5–0.9
PD3a	7.5	0.8–1.5	1.7–3.1 (PD2–PD1)	3.5 (PD3a–PD1)	0.5–0.9
PD3b	9.7	0.8–1.5	2.5–4.6 (PD3a–PD1)	5.7 (PD3b–PD1)	0.4–0.8
PD4	10.9	0.8–1.5	3.3–6.1 (PD3b–PD1)	6.9 (PD4–PD1)	0.5–0.9
PD5	12.1	1.0–1.8	4.1–7.6 (PD4–PD1)	8.1 (PD5–PD1)	0.5–0.9
PD6	16.5	unknown	5.1–9.4 (PD5–PD1)	12.5 (PD6–PD1)	0.4–0.8

¹ Earthquakes identified at Penrose Drive and modeled in OxCal model 4b (figure 14; appendix E).

² Mean earthquake times from OxCal model 4b (table 2; appendix E).

³ Per-event vertical displacement (see table 2 and text for description).

⁴ Total displacement equal to sum of per-event displacements for earthquakes in parentheses.

⁵ Elapsed time between events in parentheses, using the mean earthquake times.

⁶ Vertical slip rate, based on total displacement divided by elapsed time.

(2005)—ranging from 17.4 ka (~14,300 ¹⁴C yr B.P.) to 13.8 ka (~11,900 ¹⁴C yr B.P.)—fall within this elevation range. We determined the minimum elevation range of the Provo shoreline at the site by (1) taking the elevation of the Provo boulder gravel where it is projected into the fault (1455 m; figure 8), (2) accounting for a (minimum) fault displacement of 5 m (1460 m), (3) correcting for isostatic rebound using the methods of Oviatt and others (1992) (1440 m adjusted elevation), and (4) adding an uncertainty of ± 10 m as recommended by Oviatt and others (1992) (1430–1450 m elevation). When summed, the age ranges of Godsey and others (2005) have a midpoint of 15.6 ka, 2σ uncertainty of 2.7 kyr, and a 5th to 95th percentile (5–95%) range of 13.7–17.5 ka. To model the minimum constraint in OxCal, we include a single “calendar date” (“C_Date” in model) of 15.6 ± 2.7 ka. Although this results in a peak probability at 15.6 ka (compared to peaks in the summed PDF at 13.8 and 16.8 ka) for the age of the Provo shoreline, PD6 has a 5–95% range of 14.4–18.0 ka, which is consistent with our

interpretation that the earthquake occurred after the Bonneville flood (~17.6 ka) but before regression of the Provo shoreline from the site (~14.5 ka).

Earthquake PD5 occurred at 12.1 ± 1.6 ka, during a time of very low lake level following regression from the Provo shoreline. Evidence for this event includes scarp-derived colluvium (unit 4) derived from both lacustrine and alluvial-fan sediments (units 1–3). A splay fault that displaces Provo-shoreline gravel (unit 3), but not the scarp colluvium (unit 4), also provides evidence of PD5. A prominent sand- and gravel-filled liquefaction vent that extends through unit 2 and into unit 3 and coincides with the splay fault (figure 11) is likely related to PD5. However, it is also possible that this liquefaction occurred during a later earthquake (possibly PD3a) based on fine sand injected into younger scarp-colluvium (unit 6) (h-8.1 m, v-3.2 m; west wall of east trench; plate 1). The Provo-shoreline age of 15.6 ± 2.7 ka described above provides a maximum constraint for the

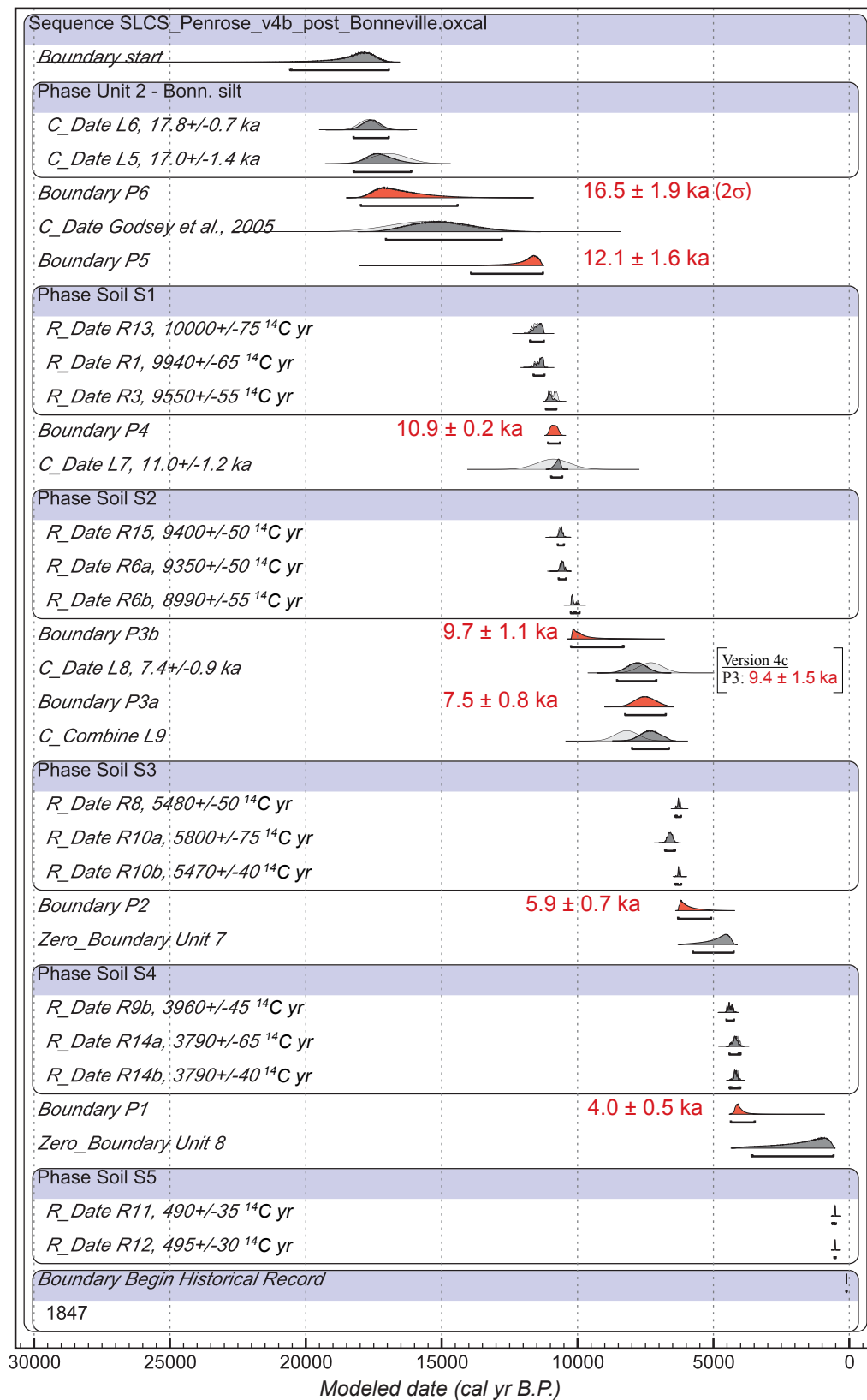


Figure 14. OxCal model 4b for the Penrose Drive site, showing stratigraphic ordering of numerical data (appendices C and D) and probability density functions (PDFs) for earthquakes PD1–PD6. The models include **C_Date** for luminescence ages, **R_Date** for radiocarbon ages, **Phases** for groups of ages where the relative stratigraphic ordering is unknown, and **Boundary** for undated events (e.g., earthquake PD1) (see appendix E and DuRoss and others [2011] for discussion). Our preferred model of seven earthquakes is shown; an alternate, six-event model 4c is included in appendix E. Model constructed using OxCal version 4.1 (Bronk Ramsey, 1995, 2001) and the IntCal09 radiocarbon calibration curve (Reimer and others, 2009). Brackets below PDFs indicate 2 σ time ranges.

time of PD5. Soil S1 on unit 4 contains a well-developed A horizon and provides minimum time constraints of 10.9–11.5 ka (PD-R1, -R3, and -R13). An additional age (PD-R2) constrains soil S1 to 10.6 ka; however, this age is likely a poor minimum constraint on the timing of PD5 as the dated soil is developed on Provo boulder gravel (unit 2) away from the main scarp colluvium (several meters southwest of fault F2), where soils S1, S2, and S3 coalesce. Therefore, PD-R2 could potentially postdate earthquake PD4 (be contemporaneous with soil S2) as well as PD5. PD-R2 (10.6 ka) agrees better with the age of soil S2 (10.1–10.6 ka) than soil S1 (10.9–11.5 ka), and thus we do not use PD-R2 to constrain the time of earthquake PD5. We estimate 1.0–1.8 m of vertical displacement in PD5 (table 2).

The time of earthquake PD4 is well constrained to 10.9 ± 0.2 ka. Evidence for PD4 includes scarp colluvium (unit 5) that postdates soil S1 and predates soil S2. Soil S1 ages of 10.9–11.5 ka provide a maximum constraint on PD4 timing, whereas ages from soil S2 of 10.1–10.6 ka (PD-R6; east trench) and 10.6 ka (PD-R15; west trench) provide minimum constraints. An OSL age for unit 5 of 11.0 ± 1.2 ka (L7) is also a minimum timing constraint, and within its 1σ uncertainty, is consistent with the soil S2 ages. We estimate that earthquake PD4 had a vertical displacement of about 0.8–1.5 m (table 2).

The lower (unit 6a) and upper (unit 6b) colluvial wedges of unit 6 can be interpreted as either evidence of two earthquakes at 9.7 ± 1.1 ka (6a–PD3b) and 7.5 ± 0.8 ka (6b–PD3a), or a single earthquake at 9.4 ± 1.5 ka (PD3) (table 2). We prefer the two-earthquake interpretation, PD3a and PD3b, based on the distinct stone line between units 6a and 6b and because, individually, the two earthquakes have per-event displacements of 0.8–1.5 m, which is similar to the 0.7–1.8 m displacements estimated for PD1, PD2, PD4, and PD5. However, the absence of a soil between units 6a and 6b prevents us from dismissing the possibility of a single earthquake (PD3) having 1.6–2.9 m of vertical displacement. PD3b (and PD3) timing is based on maximum constraints of 10.1–10.6 ka for soil S2 and a minimum constraint of 7.4 ka (PD-L8) for unit 6a. PD3a occurred after deposition of unit 6a at about 7.4 ka, but before unit 6b and the formation of soil S3 within it. Unit 6b has OSL and IRSL mean ages of 8.4 and 8.1 ka (PD-L9), respectively, that are stratigraphically inverted with PD-L8 (7.4 ka); however, all three ages agree within their 1-kyr 2σ uncertainties. Because the IRSL age (8.1 ka) for PD-L9 is younger than the OSL age (8.4 ka), we combined both in the OxCal model. Radiocarbon ages for soil S3 provide a minimum constraint of 6.3–6.6 ka (PD-R8 and -R10) on the timing of PD3a. We disregard an additional age for soil S3 of 3.8 ka (PD-R5), which likely dated burrowed sediment.

Earthquake PD2 occurred at 5.9 ± 0.7 ka, after formation of soil S3 within unit 6b and before deposition of scarp colluvium from this earthquake (unit 7). A possible fault termination at the soil S3–unit 7 contact (h-23.3 m, v-5.1 m, west trench; plate 1) is also evidence of this earthquake. The ages from soil S3 of 6.3–6.6 ka provide a maximum constraint on the time of PD2, whereas ages of 4.2 ka (PD-R14a and -R14b) and 4.4 ka

(PD-R9) from soil S4 developed on unit 7 provide minimum constraints. Earthquake PD2 had a vertical displacement of 0.7–1.3 m (table 2).

Earthquake PD1—the most recent earthquake—occurred at 4.0 ± 0.5 ka and had a vertical displacement of about 1.0–1.8 m. Evidence for PD1 includes unfaulted scarp colluvium (unit 8) that unconformably overlies sheared sediment and an eroded fault-scarp free face. Unit 8 also buries soil S4, which we estimate to have an age of 4.2–4.4 ka. Because unit 8 is extensively burrowed, we could not find a suitable place to sample it for dating. Soil S5 is developed on unit 8, and our two ages (PD-R11 and -R12) from S5 are both about 0.5 ka, which provides a poor minimum constraint on the time of PD1. We prefer a time for earthquake PD1 that is close to the ~4-ka maximum ages from soil S4, given the thick, strongly developed A horizon (several times thicker than soils S2–S4) on unit 8; this well-developed A horizon likely indicates a relatively long elapsed time since earthquake PD1. Furthermore, PD-R9 and PD-R14 sampled soil S4 less than 2 m from the fault zone; because of the preexisting scarp and easily erodible scarp colluvium and alluvial-fan soil, soil S4 in this area was likely buried by colluvium shortly after surface faulting during earthquake PD1.

Earthquake Recurrence and Fault Slip Rate

We calculated inter-event and mean recurrence intervals between individual Penrose Drive earthquakes using the mean earthquake times (table 2). Inter-event recurrence is the elapsed time between two successive earthquakes (e.g., S9–S8); mean recurrence is the mean over several seismic cycles based on the elapsed time between the oldest and youngest earthquakes (e.g., S9–S1) divided by the number of closed inter-event intervals.

Inter-event recurrence intervals vary from 1.2 kyr for PD5–PD4 and PD4–PD3b to 4.4 kyr between PD6 and PD5. However, additional earthquakes may have occurred in the ~4-kyr time between PD6 and PD5, which roughly corresponds with the time window during which the Provo shoreline could have occupied the site (~18–14 ka). If these earthquakes occurred during the Provo-phase occupation, such is likely the case for PD6, the sublacustrine colluvial wedges may have been removed by erosion. For example, 53° dipping Bonneville silt beds that we describe as evidence of PD6 could have been deformed by two events if the splay fault F2a, which displaces older, phase-1 liquefied sand (likely generated in PD6), is truncated at the angular unconformity between Bonneville silt and Provo gravel (unit 2–3 contact) (figure 11). Thus, we consider the PD6–PD5 recurrence interval poorly constrained.

Mean recurrence intervals for Penrose Drive earthquakes range from about 1.6 to 2.1 kyr, depending on the time interval (table 4). Including all events (PD6–PD1), the

Table 4. Mean recurrence intervals for Salt Lake City-segment paleoseismic sites.

Time Period (To Present) ¹	Penrose Drive ²			Little Cottonwood Canyon ³			South Fork Dry Creek ³		
	Events	Time (kyr)/ int.	Mean RI (kyr)	Events	Time (kyr)/ int.	Mean RI (kyr)	Events	Time (kyr)/ int.	Mean RI (kyr)
Post-Bonneville Highstand	PD6–PD1 (S9–S3)	12.5/6	2.1	T–Z (S9–S1)	15.2/6 15.2/8	2.5 1.9	-	-	-
Post-Provo phase	PD5–PD1 (S8–S3)	8.1/5	1.6	-	-	-	-	-	-
Holocene	PD4–PD1 (S7–S3)	6.9/4	1.7	-	-	-	-	-	-
Holocene	PD3b–PD1 (S6–S3)	5.7/3	1.9	U–Z (S6–S1)	8.2/5	1.6	-	-	-
Late Holocene	-	-	-	W–Z (S4–S1)	4.2/3	1.4	A–D (S4–S1)	3.7/3	1.2

¹ Latest Pleistocene time periods are based on the Bonneville highstand (~18 ka) and Provo shoreline (~14 ka) datums. Holocene and mid-Holocene indicate time periods younger than ~10–11 ka and 5–6 ka, respectively.

² Penrose Drive mean recurrence intervals are based on the mean times shown in tables 2 and 5.

³ Little Cottonwood Canyon and South Fork Dry Creek mean recurrence intervals are based on the mean times shown in table 5.

mean recurrence since the Bonneville highstand is 2.1 kyr; however, this estimate includes the long (~4-kyr), and possibly incomplete record between PD6 and PD5, and is thus poorly constrained. Considering the more complete post-Provo-shoreline record, the mean recurrence between earthquakes PD5 and PD1 is 1.6 kyr. Holocene mean recurrence estimates vary from about 1.7 to 1.9 kyr based on earthquakes PD4–PD1 and PD3b–PD1, respectively. Because the most recent Penrose Drive earthquake occurred at about 4.0 ka, there is insufficient data to calculate a late Holocene mean recurrence interval.

The post-Provo vertical slip rate for the East Bench fault at Penrose Drive ranges from 0.3 to 0.9 mm/yr; however, we prefer an estimate of 0.5–0.9 mm/yr based on 4.1–7.6 m of displacement in the 8.1-kyr span between PD5 and PD1 (table 3). This slip rate is nearly identical to those calculated using shorter time periods, such as PD4–PD1 (table 3). If we include the poorly constrained PD6–PD5 recurrence (and PD5 displacement), then 5.1–9.4 m of displacement occurred in the 12.5 kyr between PD6 and PD1, yielding a rate of 0.4–0.8 mm/yr. Alternatively, an open-ended post-Provo slip rate, which accounts for the 4-kyr elapsed time since PD1, is 0.3–0.7 mm/yr using 5.1–9.4 m of displacement and a Provo-shoreline age of 15.6 ± 2.8 ka. Because Lake Bonneville highstand sediments have likely been eroded from the footwall of the fault, we have insufficient data to calculate a post-Bonneville highstand slip rate.

A poorly constrained, long-term vertical slip rate is based on the minimum displacement of the pre-Bonneville alluvial-fan gravel. A minimum of 16 m of vertical displacement divided by the mean age of unit 1 (67.3 ± 14.4 ka) yields a slip rate of greater than 0.2–0.3 mm/yr.

PALEOSEISMOLOGY OF THE SALT LAKE CITY SEGMENT

Correlation of Earthquakes

Surface-faulting earthquake histories for the East Bench and Cottonwood faults indicate that at least nine earthquakes (S1–S9; table 5) have occurred on the SLCS since the latest Pleistocene. At Penrose Drive, at least seven earthquakes occurred between about 16.5 ka and 4.0 ka, postdating the highstand of Lake Bonneville (~18 ka) (figure 15; table 2). Similarly, seven post-Bonneville earthquakes occurred at LCC (events T–Z; McCalpin, 2002; figure 16); however, of these, we only correlate five earthquakes between the sites (figure 17). Black and others (1996) identified four late Holocene earthquakes at SFDC (W–Z; Black and others, 1996; renamed earthquakes A–D for clarity), two of which likely correlate with the youngest two Penrose Drive events (figure 17). Because each site only exposed a subset of the nine SLCS earthquakes, important questions remain regarding the extent of individual fault ruptures during these earthquakes.

We constructed OxCal models for the LCC and SFDC sites (appendix E) to compare with our Penrose Drive results. Our OxCal models use previously published data, rely heavily on the original interpretations of the authors, treat the AMRT ages consistently, calendar calibrate the radiocarbon ages, and yield internally consistent models of the earthquake times (see DuRoss and others, 2011, for further discussion). Our OxCal results (figure 16 and appendix F) are similar to the previously published earthquake times, with minor differences related to AMRT corrections and the treatment of numerical-age and earthquake-timing uncertainties.

Table 5. Correlation of surface-faulting earthquakes on the Salt Lake City segment.

Earthquake	Penrose Drive ¹ (ka)	Little Cottonwood Canyon ² (ka)	South Fork Dry Creek ³ (ka)
S1	no evidence	1.3 ± 0.04 (Z-1.3)	1.3 ± 0.2 (D)
S2	no evidence	2.1 ± 0.3 (Y-2.3)	2.2 ± 0.4 (C)
S3	4.0 ± 0.5 (PD1)	4.4 ± 0.5 (X-3.5)	3.8 ± 0.6 (B)
S4	5.9 ± 0.7 (PD2)	5.5 ± 0.8 (W-5.3)	5.0 ± 0.5 (A)
S5	7.5 ± 0.8 (PD3a)	7.8 ± 0.7 (V-7.5)	not exposed
S6	9.7 ± 1.1 (PD3b)	9.5 ± 0.2 (U-9)	“
S7	10.9 ± 0.2 (PD4)	no evidence	“
S8	12.1 ± 1.6 (PD5)	no evidence	“
S9	16.5 ± 1.9 (PD6)	16.5 ± 2.7 (T-17)	“

¹ Penrose Drive earthquake timing (mean ± 2σ) based on OxCal model 4b.

² Little Cottonwood Canyon (LCC) earthquake timing (mean ± 2σ) based on OxCal model (appendix E) using paleoseismic data from McCalpin (2002). The earthquake times as published by McCalpin (2002) are included in parentheses. The timing uncertainty for LCC event T is based on the minimum-maximum possible range rather than 2σ standard deviation (see text for discussion).

³ South Fork Dry Creek (and Dry Gulch) earthquake timing (mean ± 2σ) based on OxCal model (appendix E) constructed using paleoseismic data from Black and others (1996).

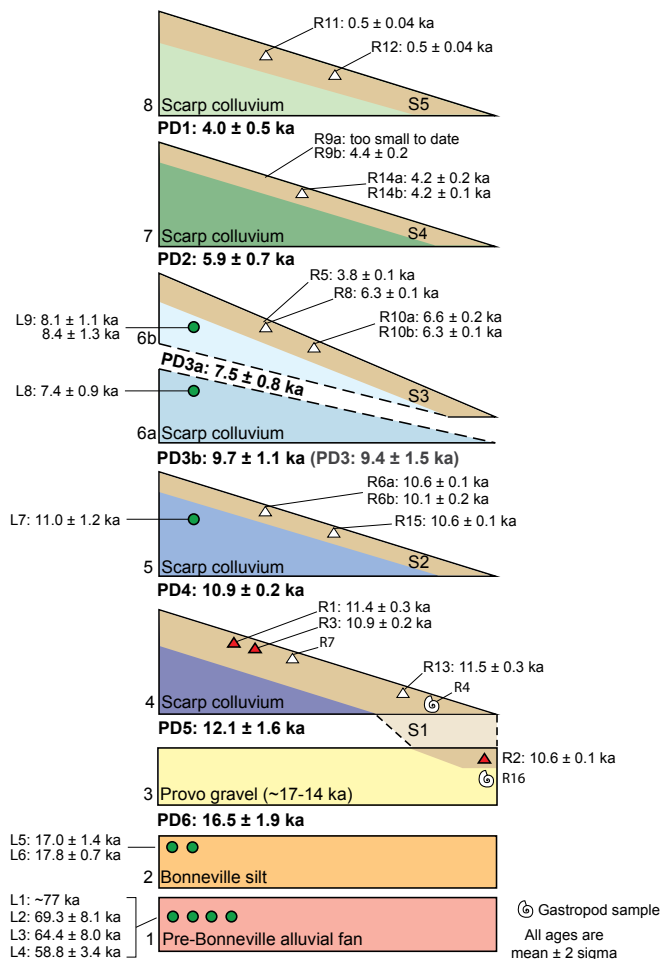


Figure 15. Surface-faulting earthquake chronology of the Penrose Drive site, showing stratigraphic units, soils, and numerical age controls (appendices C and D). White triangles indicate bulk soil-sediment samples; red triangles indicate macrocharcoal samples. Green circles indicate samples dated using optically stimulated luminescence. Earthquake mean ages and 2σ uncertainties based on OxCal models 4b (including earthquakes PD3a and PD3b) and 4c (including earthquake PD3) (appendix E; figure 14).

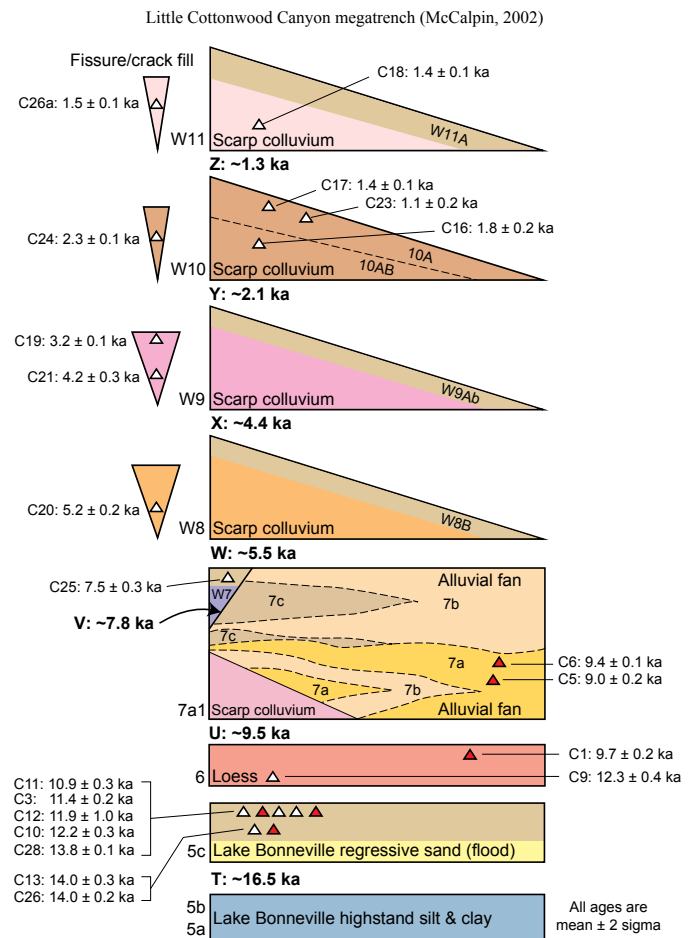


Figure 16. Chronology of surface-faulting earthquakes at the Little Cottonwood Canyon site, based on stratigraphic units and evidence of surface-faulting earthquakes from McCalpin (2002). White triangles indicate bulk soil-sediment samples; red triangles indicate macrocharcoal samples. Earthquake mean ages and 2σ uncertainties based on OxCal model constructed for the site (this study; appendix E).

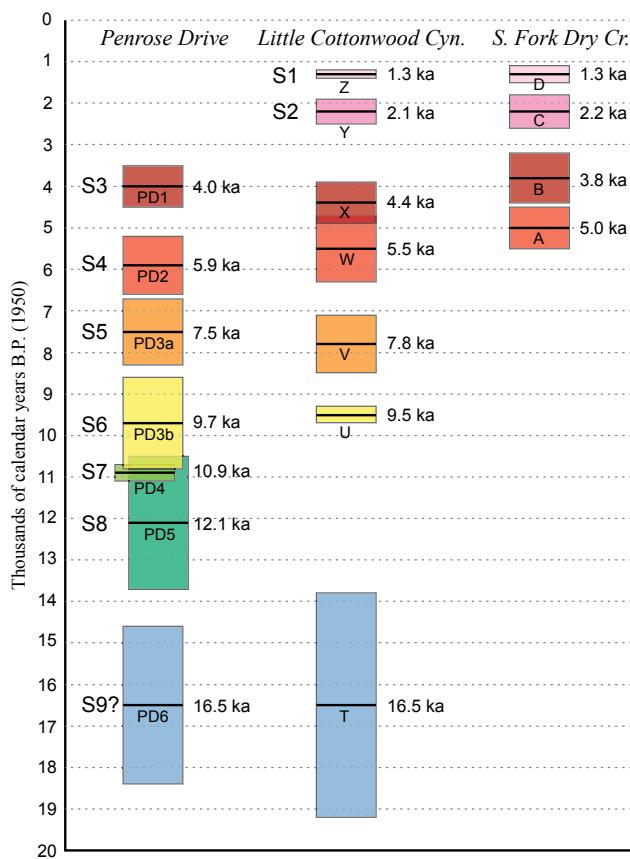


Figure 17. Correlation of SLCS earthquakes identified at the Penrose Drive, Little Cottonwood Canyon, and South Fork Dry Creek trench sites. Mean earthquake times (black horizontal lines) and 2σ uncertainties (boxes) are derived from our OxCal models (appendix E).

Penrose Drive earthquake PD6 (~16.5 ka) possibly correlates with the oldest LCC earthquake (T, ~16.5 ka) as SLCS earthquake S9. At LCC, event T postdates Lake Bonneville highstand silt, but possibly predates a regressive sand that McCalpin (2002) interpreted to be contemporaneous with the Bonneville Flood (thus deposited ~17–18 ka) on the basis of its increased thickness within a large graben. However, the regressive sand was only exposed in and along the flanks of the graben, where it could have been eroded during scarp degradation; thus, the thickness outside of the graben is uncertain. In addition, whereas at least one minor fault is truncated at the highstand silt and regressive sand contact, three additional faults terminate at various soil horizons (Ab, AC, C1 and C2; McCalpin, 2002) formed on the regressive sand. Finally, the regressive sand was not dated, and thus uncertainty remains in its age in relation to the flood. Considering these uncertainties, we include two alternative OxCal models for LCC (versions 4 and 4b; appendix E), with event T occurring (1) before deposition of the regressive sand (i.e., before the flood), and (2) after the flood, but before an A horizon developed on the sand over about 10.9–14.0 ka. These models yield earthquake times of 17.9 ± 0.7 ka (event T predates the flood) and 15.2

± 2.0 ka (event T postdates the flood). To account for both models, we summed the PDFs, yielding a single, broadly constrained earthquake PDF for event T with a mean of 16.5 ka and a possible range of 13.8–19.2 ka (because of the resulting bimodal distribution, we prefer the uncertainty based on the range, ± 2.7 kyr, over the 2σ uncertainty of ± 3.0 kyr). Although we include an alternate model, our mean time of 16.5 ka corresponds well with the 17 ka age interpreted for event T by McCalpin (2002). We correlate LCC earthquake T with Penrose Drive earthquake PD6 considering the striking similarity in faulted highstand silt and unfaulted post-highstand sand or gravel at both sites. However, we recognize that the LCC earthquake T could be a separate, slightly older event than PD6 (which postdates the Bonneville highstand and predates the Provo shoreline) if the earthquake predates the Bonneville flood as interpreted by McCalpin (2002).

The timing of PD6 and LCC event T (SLCS earthquake S9) corresponds well with evidence of surface warping in Lake Bonneville (highstand?) silt and clay at the Dresden Place site (about 2 km southwest of Penrose Drive) on the East Bench fault (Machette and others, 1992). The earthquake at Dresden Place likely occurred between the Lake Bonneville highstand and latest Provo-phase shoreline, about 18–14 ka.

SLCS earthquakes S8 and S7 are based solely on Penrose Drive earthquakes PD5 (12.1 ka) and PD4 (10.9 ka). At LCC, McCalpin (2002) used the absence of earthquakes in the ~8-kyr-long period between earthquakes T (~17 ka) and U (9.5 ka) as evidence of a period of seismic quiescence on the SLCS. This time period is represented by the Lake Bonneville regressive sand (and 11–14-ka soil) and a post-Bonneville loess (and ~10–12-ka soil). McCalpin (2002) discussed the possibility that stratigraphic evidence of events in this time period was removed by alluvial-fan erosion at about 9–10 ka, but considered the scenario unlikely. However, we note that the loess (his unit 6) appears to fill a fault-related depression (graben?), which is possibly evidence of earthquakes postdating the regressive sand and predating the ~9–10 ka alluvial-fan deposits. Evidence of these earthquakes could also have been obscured by the extensive deposition of pedogenic carbonate, which complicated the interpretation of depositional environment (McCalpin, 2002). Considering these uncertainties, we consider it plausible but not certain that PD5 and PD4 ruptured the LCC site (possibly with small displacements?), but were not recognized.

SLCS earthquake S6 is based on the correlation of Penrose Drive earthquake PD3b (9.7 ka) with LCC event U (9.5 ka). Although earthquake PD3b has a larger uncertainty (± 1.1 kyr) than event U (± 0.2 kyr), both earthquakes postdate soils formed at about 10–11 ka. The larger uncertainty for PD3b stems from the minimum ages of 7–8 ka, whereas charcoal from alluvial-fan deposits postdating event U tightly constrain this event to a minimum of about 9.0–9.4 ka (appendix E). The time of event U is slightly older (~9.8 ka) if the youngest maximum limiting age—C1 at ~9.7 ka (appendix E)—is

excluded due to its position outside the area of burial from event-U colluvium; however, we agree with McCalpin (2002) that the ~9.7-ka age likely represents a reasonable time for event U and thus include it in the OxCal model. Event PD3b had 0.8–1.5 m of vertical displacement, whereas McCalpin (2002) did not estimate displacement for event U.

Penrose Drive earthquake PD3a (7.5 ka) and LCC event V (7.8 ka) define the occurrence of SLCS earthquake S5. PD3a and event V have similar mean times and uncertainties despite differences in the type and quality of their limiting ages. Event V is best constrained (to a minimum) by a soil developed on a fissure-fill deposit and dated at 7.5 ka; charcoal ages of 9.0–9.4 ka for a thick alluvial-fan package provide a poor maximum limit for event V. In contrast, PD3a postdates colluvium deposited about 7.4–8.4 ka, and predates soil ages of 6.3–6.6 ka. Earthquake PD3a produced about 0.8–1.5 m of vertical displacement, whereas the displacement for V is unknown because the colluvial wedge resulting from this event was not exposed.

The timing of SLCS earthquakes S5 and S6 corresponds well with the general timing of surface faulting on the Warm Springs fault, as documented in excavations for an expansion of the Salt Palace Convention Center in downtown Salt Lake City. At the Salt Palace expansion project site, one and possibly two earthquakes occurred between about 7.4 and 9.0 ka (Kleinfelder, 1999; Simon-Bymaster, 1999). However, questions regarding the number of events at the site and the context of the samples reduce our confidence in analyzing potential earthquakes on the Warm Springs fault. Displacements at the Salt Palace are not well constrained because of complex faulting and extensive graben formation.

We correlate Penrose Drive earthquake PD2 (5.9 ka) with LCC event W (5.5 ka) and SFDC earthquake A (5.0 ka) to define earthquake S4 for the SLCS. Earthquake S4 has similar uncertainties (± 0.5 –0.8 kyr) at the three sites, but slightly different mean ages because of their limiting ages. Event PD2 has maximum ages of 6.3–6.6 ka and minimum ages of 4.2–4.4 ka from soils developed on scarp colluvium. Event W has a presumably poor maximum age from the post-event V soil (7.5 ka), but a better minimum age from event-W fissure fill dated to 5.2 ka. At SFDC, earthquake A occurred after 5.1–5.8 ka, but before ~4 ka based on ages from soils developed on alluvial-fan deposits. Given these limiting ages, S4 likely occurred between 4 and 6 ka. Excluding graben-fill sediments, the colluvial wedge from event W has a maximum thickness of about 0.8 m; however, McCalpin (2002) estimated an average displacement of 1.8 m as discussed above. Black and others (1996) did not report per-event displacement for SFDC events because of an unknown amount of antithetic faulting to the west. Black and Lund (1995) did estimate displacement using colluvial-wedge thickness; however, we do not include these values because of significant back-rotation (tilting) observed in several trenches (e.g., trench DC-1; Black and others, 1996) and because of uncertainties in correlating colluvial

wedges exposed in multiple trenches. Our displacement range for Penrose Drive earthquake PD2 is 0.7–1.3 m.

The most recent earthquake at Penrose Drive (PD1, 4.0 ka) likely correlates with LCC event X (4.4 ka) and SFDC earthquake B (3.8 ka) to define SLCS earthquake S3. SFDC event B has close limiting ages of 4.0 ka (maximum) and 3.8–4.0 ka (minimum), which is consistent with the maximum ages of 4.2–4.4-ka for earthquake PD1. An age from fissure fill constrains LCC event X to a minimum of 4.2 ka; however, McCalpin (2002) reported a slightly younger event-X age of 3.5 ka. These limiting ages support a time for earthquake S3 of about 4 ka. Using maximum colluvial-wedge thickness, we estimate 1.0–1.8 m of displacement in event PD1, compared to the average displacement of 1.8 m for event X.

SLCS earthquakes S2 (~2.1–2.2 ka) and S1 (~1.3 ka) did not rupture the Penrose Drive site. Although we cannot rule out the possibility that event PD1 at Penrose Drive—which only has a maximum limiting age of ~4 ka—correlates with one of these events, we consider it unlikely. As discussed above, the ~4-ka soil faulted in PD1 was likely buried by scarp colluvium shortly after the earthquake, whereas a long period of time elapsed after PD1 based on the well-developed soil A horizon formed on scarp colluvium that resulted from the event. Per-event vertical displacements for both S2 and S1 are based on the average displacement of 1.8 m from LCC (McCalpin, 2002) and an average displacement of 2.0 ± 0.5 m at the SFDC site, based on a debris-flow levee that has been faulted during two and possibly three earthquakes (Black and others, 1996).

Earthquake Recurrence

Nine earthquakes (S9–S1) occurred on the SLCS since the latest Pleistocene based on paleoseismic records from Penrose Drive, LCC, and SFDC (table 5; figure 17). Because each site exposed an incomplete SLCS earthquake record, we compare mean recurrence intervals for the individual sites that are based on the number of events that occurred since the (1) latest Pleistocene, using the Bonneville-highstand (~18 ka) and Provo-shoreline (~14 ka) datums, (2) early Holocene (~10–11 ka), and (3) mid-Holocene (~5–6 ka) (table 4). Mean recurrence estimates reported here are simplified, including only the mean earthquake timing results; see DuRoss and Hylland (in review) for a more detailed probabilistic analysis of recurrence (including two-sigma recurrence estimates) that accounts for the full individual earthquake-timing distributions (e.g., DuRoss and others, 2011).

The Penrose Drive and LCC data yield recurrence intervals for the time periods since the Bonneville highstand and Provo shoreline (Provo phase). At Penrose Drive, the post-Bonneville-highstand mean recurrence between earthquakes S9 and S3 is 2.1 kyr, which excludes the long elapsed time (~4 kyr) since the youngest earthquake S3. A comparable mean recurrence for LCC is 2.5 kyr (earthquakes S9–S1); however, this

interval does not account for earthquakes S8 and S7, which were identified at Penrose Drive and possibly could have ruptured the LCC site. Including S8 and S7 reduces the LCC latest Pleistocene recurrence interval to 1.9 kyr. We have relatively low confidence in these recurrence values given the long (~4 kyr) elapsed time between earthquakes S9 and S8 observed at Penrose Drive, and thus, uncertainty regarding the completeness of the SLCS earthquake record prior to about 14 ka. The absence of earthquakes in the 4-kyr period between S9 and S8 could be related to (1) a period of seismic quiescence on the SLCS, (2) difficulty recognizing evidence of earthquakes owing to Provo-phase shoreline erosion and deposition, or (3) the possibility of Penrose Drive earthquake PD6 and LCC event T being two separate earthquakes. Because we cannot fully rule out any of these explanations, we consider the SLCS record poorly constrained (and possibly incomplete) prior to about 14 ka.

A post-Provo-phase mean recurrence estimate for the SLCS is 1.6 kyr based on earthquakes S8–S3 that postdate the Provo shoreline (~14 ka) at Penrose Drive. We have more confidence in this mean recurrence than in the post-Bonneville-highstand mean recurrence because it is similar to Holocene recurrence intervals calculated for both Penrose Drive (1.7–1.9 kyr) and LCC (1.6 kyr) (discussed below). Although the LCC record extends to ~18 ka, SLCS earthquakes S8 and S7, which occurred after abandonment of the Provo shoreline, were not identified at the site, and thus, we do not calculate a post-Provo-shoreline mean recurrence using the LCC data.

Holocene mean recurrence intervals for the SLCS are based on the number of inter-event intervals that occurred after S7 (~10.9 ka at Penrose Drive) and S6 (~9.5–9.7 ka based on Penrose Drive and LCC), whereas late Holocene mean recurrence is based on the intervals postdating S4 (~5.0–5.5 ka based on data from LCC and SFDC). The Holocene mean recurrence is 1.7–1.9 kyr at Penrose Drive and 1.6 kyr at LCC. In contrast, late Holocene mean recurrence intervals are 1.2 kyr at SFDC and 1.4 kyr at LCC; minor differences in these mean estimates relate to the 0.5-kyr difference in the S4 time at LCC (5.5 ka) and SFDC (5.0 ka). We have the most confidence in the ~1.2–1.4-kyr late Holocene mean recurrence estimates as they stem from the best-constrained events, S4–S1, which have been identified at two to three trench sites. Importantly, these late Holocene estimates are reasonably similar to the Penrose Drive post-Provo-phase mean recurrence estimate of 1.6 kyr, possibly indicating that the SLCS earthquake record is complete after ~14 ka. Slightly longer mean recurrence rates for the Holocene (1.7–1.9-kyr at Penrose Drive) likely stem from variability in the inter-event recurrence times (aperiodicity). For example, the longer mean recurrence intervals for the Holocene include relatively long (~2-kyr) inter-event recurrence times for earthquake pairs S6–S5 and S5–S4.

Vertical Slip Rate

Of the three SLCS trench investigations, only the Penrose Drive site yielded vertical-slip-rate information. We have the most confidence in closed-interval slip rates of 0.5–0.9 mm/yr for the Penrose Drive site calculated using various post-Provo time periods (e.g., PD5–PD1; table 3). However, these rates are possibly minima considering the position of the Penrose Drive site on the northernmost East Bench fault. If the along-strike displacement on the East Bench fault and the SLCS follow that for historical normal-faulting earthquakes in the Basin and Range Province (and elsewhere) (Hemphill-Haley and Weldon, 1999; Wesnousky, 2008; Biasi and Weldon, 2009), per-event displacements likely increase south of Penrose Drive, toward the center of the East Bench fault and the center of the SLCS.

We also consider a long-term slip rate calculated using a vertically offset glacial moraine at the mouth of Bells Canyon, south of LCC. Swan and others (1981) profiled the crest of the Bells Canyon moraine and found 14.5 m (11.5–24.5 m range) of vertical surface offset. Using an age of 15.9 ± 0.7 ka derived from two ^{10}Be exposure ages for boulders on the youngest parts of the moraine (Lips, 2005; Lund, 2007), the vertical slip rate is 0.9 mm/yr (0.7–1.6 mm/yr range). However, the UQFPWG (Lund, 2005) preferred a Holocene rate for the SLCS of 1.2 mm/yr (0.6–4.0 mm/yr approximate 5th–95th percentile range) because of the long-term nature of the Bells Canyon rate (and the possible post-Bonneville seismic quiescence) and higher Holocene rates measured for the adjacent Weber and Provo segments.

Rupture Extent

Surface-fault-rupture length (straight-line distance between rupture end points) is important for understanding fault segmentation, such as the persistence of mapped segment boundaries and the relative frequency of single-, partial-, and multi-segment ruptures on a long structure such as the WFZ. Rupture length is also important for estimating and understanding earthquake magnitudes (using magnitude-length empirical regressions), how displacement scales with length, and rupture-propagation direction effects. In essence, do ruptures on WFZ segments have consistent lengths and displacement profiles through time? Or is rupture variability influenced by partial- or multi-segment ruptures or propagation direction?

SLCS earthquake rupture lengths are difficult to assess because the segment consists of the three separate strands, only two of which have robust paleoseismic data (Cottonwood and East Bench faults). In addition, the Penrose Drive site is close to the northern end of the East Bench fault, and thus, it is possible that ruptures could have extended to the East Bench fault, but not ruptured the Penrose Drive site. Thus, we recognize that our length estimates are minimum estimates, and that additional paleoseismic data are necessary to resolve the rupture behavior of the SLCS in more detail.

Of the nine SLCS earthquakes (table 5), four and possibly five have been identified on both the East Bench and Cottonwood faults, with minimum rupture lengths of 25 km for S3 and S4 (Penrose Drive to SFDC) and 21 km for S5 and S6 (Penrose Drive to LCC). Earthquake S5 or S6 may have also ruptured the Warm Springs fault at the Salt Palace site, which would not affect the minimum rupture lengths for these events, but could indicate a full rupture of the SLCS. If LCC event T and Penrose Drive earthquake PD6 correlate in SLCS earthquake S9, surface faulting during this earthquake would have a minimum rupture length of 21 km.

Earthquakes S1 and S2 ruptured the Cottonwood fault (at both LCC and SFDC), but were not identified at Penrose Drive. We consider it unlikely that evidence of these earthquakes was misinterpreted, unrecognized, or disturbed at Penrose Drive because of the length of the west trench and the clear evidence of the most recent earthquake at the site (unfaulted unit 8). However, it is possible that surface ruptures from S1 and S2 extended north of the site on an unidentified strand of the fault, near the active channel of Dry Creek and were later modified by stream processes or obscured during development of the area. Although possible, we do not consider this scenario very likely as the seven previous SLCS earthquakes ruptured the Penrose Drive site (and in fact, the same fault) and had a moderate amount of displacement (~1 m per event), which would likely be evident at the surface if that displacement had occurred on a different fault strand. Alternatively, surface ruptures from these Cottonwood fault earthquakes could have continued on to the East Bench fault, but not as far north as Penrose Drive. The minimum rupture length for S1 and S2 is poorly constrained because of the short distance between the LCC and SFDC sites (3.5 km), but is possibly ~20 km, equal to the length of the Cottonwood fault. Longer rupture lengths are possible if S1 and S2 ruptured part of the East Bench fault south of Penrose Drive. Additional paleoseismic data (particularly for the East Bench fault) are necessary to refine the rupture lengths of earthquakes S1 and S2.

The Penrose Drive data provide new evidence of two earthquakes (S7 and S8) that may have ruptured the East Bench fault, but not the Cottonwood fault. However, as discussed above, the timing of these events corresponds with a part of the LCC stratigraphic record that is difficult to interpret due to complicated faulting from later earthquakes and extensive carbonate soil development. Thus, while S7 and S8 may have been limited to only the East Bench (and Warm Springs?) fault, we cannot completely rule out the possibility that they also ruptured the Cottonwood fault. Separate paleoseismic data confirming that these earthquakes are missing from the Cottonwood fault record are needed. Because earthquakes S7 and S8 have only been identified at one site, their rupture lengths are unknown.

DISCUSSION

Our investigation at Penrose Drive improves the latest Pleistocene to present earthquake history of the SLCS (figure 17). Using our preferred correlation of events, we identify nine earthquakes (S9–S1) on the SLCS that postdate the highstand of Lake Bonneville (~18 ka). Earthquakes PD1 (~4.0 ka) to PD3b (~9.7 ka) provide independent evidence of SLCS earthquakes S3 to S6, which were previously identified at LCC and SFDC, and thus, improve estimates of the event times, displacements, and rupture extents. We identify two additional earthquakes at Penrose Drive that occurred between about 11 and 14 ka (PD4 and PD5), within a previously inferred period of seismic quiescence between ~17 and 9 ka based on the LCC earthquake chronology (McCalpin, 2002). PD4 and PD5 reduce the recurrence time between the earliest two SLCS earthquakes from ~8 kyr to ~4 kyr and show that the apparent lack of earthquakes in this period is likely related to an incomplete geological record rather than a significant change in fault behavior. The earliest earthquake at Penrose Drive (PD6; ~16.5 ka) possibly correlates with the earliest earthquake at LCC (event T; ~16.5 ka); however, these earthquakes have 2–3-kyr timing uncertainties, so we have less confidence in this correlation.

Latest Pleistocene and Holocene mean recurrence intervals for the Penrose Drive, LCC, and SFDC sites range from 1.2 to 2.5 kyr. We have the most confidence in late Holocene mean recurrence estimates of 1.2–1.4 kyr for SFDC and LCC, a post-Provo-phase estimate of 1.6 kyr for Penrose Drive, and a Holocene recurrence estimate of 1.6 kyr for LCC. Penrose Drive data indicate slightly longer Holocene mean recurrence estimates of 1.7–1.9 kyr; however, the two most recent SLCS earthquakes (S1 and S2) did not rupture the site and thus the data are skewed by the ~2-kyr recurrence times for S6–S5 and S5–S4. In contrast, the Holocene mean recurrence interval for LCC, which includes the six most recent SLCS earthquakes, is 1.6 kyr. The similarity in these late Holocene, Holocene, and post-Provo-phase recurrence intervals may indicate that the rate of surface-faulting earthquakes on the SLCS has been fairly constant since the regression of Lake Bonneville from the Provo shoreline (~14 ka). This is similar to paleoseismic results for the Provo segment (Mapleton site), which indicate a fairly constant rate of earthquake recurrence over the Holocene (Olig and others, 2011). The mean recurrence intervals for the SLCS also compare well with the 1.3-kyr (0.5–2.4 kyr approximate 5th–95th percentile range) late Holocene mean recurrence interval estimated for the SLCS (using the LCC and SFDC data) by the UQFPWG (Lund, 2005). We have less confidence in post-Bonneville-highstand mean recurrence estimates of 1.9–2.5 kyr, which include the long (~4-kyr) interval between earthquakes S9 and S8 (18–14 ka). The record of earthquakes in this time interval could be incomplete because of nondeposition or erosion related to the Provo shoreline.

The long-term (since latest Pleistocene) vertical slip rate for the SLCS is about 0.5–0.9 mm/yr based on a Provo-phase closed-seismic-interval slip rate of 0.5–0.9 mm/yr for Penrose Drive and the vertical offset of the Bells Canyon glacial moraine, which yields a slip rate of ~0.9 mm/yr since about ~16 ka. However, we consider this long-term rate only moderately well constrained because of questions regarding the position of the Penrose Drive site in the along-strike displacement profile of the SLCS, and the open-ended nature of the surface-offset-based rate for Bells Canyon. The Holocene rate of slip for the SLCS remains unconstrained.

Although we have refined the latest Pleistocene earthquake record of the SLCS, several questions remain. For example, the extent of individual ruptures along the segment remains uncertain, with minimum distances equal to the actual distance between sites where a specific rupture has been identified. An important question is why did SLCS earthquakes S1 (~1.3 ka) and S2 (~2.2 ka) fail to rupture the Penrose Drive site. Did these earthquakes rupture part of the East Bench fault south of Penrose Drive? Did they rupture the Warm Springs fault? One possibility is that S1 and S2 originated as earthquakes on the Provo segment at 1.5 ± 0.4 ka (earthquake P2 based on the Mapleton trench site; Olig and others, 2011) and 2.2 ± 0.4 ka (earthquake P3 based on the American Fork site; Machette and others, 1992) (S. Olig, written communication, 2013), and thus were spill-over ruptures (across the Provo–Salt Lake City segment boundary) that extended only along the southern part of the SLCS. This would be a similar scenario to that described by DuRoss and others (2012) and Personius and others (2012) where a late Holocene rupture on the Weber segment extended across the Weber–Brigham City segment boundary and onto the southern part of the Brigham City segment. We also note that SLCS earthquakes S7 (~10.9 ka) and S8 (~12.1 ka) ruptured the East Bench fault, but were not identified at LCC. Did S7 and S8 rupture the Cottonwood fault, or only the East Bench fault? If the latter, how do they relate to earthquakes on the Weber segment? Unfortunately, only limited earthquake-timing data are available for the Weber segment prior to about 6 ka (DuRoss and others, 2009).

The correlation of surface-faulting earthquakes at Penrose Drive with earthquakes previously identified at LCC and SFDC highlights important spatial and temporal gaps in paleoseismic data for the SLCS. To improve the resolution of SLCS earthquake rupture extent, additional paleoseismic data are required. Specifically, confirmation of the late Holocene earthquake record of the East Bench fault and the latest Pleistocene record for the Cottonwood fault is needed to determine whether these faults have ruptured independently. Paleoseismic data near the northern and southern boundaries of the SLCS (e.g., on the southern Weber segment or northern Provo segment) would also improve estimates of SLCS rupture lengths and shed light on the possibility of spill-over rupture across mapped segment boundaries. Finally, the earthquake history of the Warm Springs fault and the post-Bonneville highstand (~18–14 ka) earthquake record of the SLCS remain poorly constrained.

SUMMARY AND CONCLUSIONS

The Penrose Drive site provides important information on the timing, displacement, and recurrence of surface-faulting earthquakes on the East Bench fault of the SLCS. At least seven post-Bonneville highstand earthquakes occurred at ~4.0 ka (PD1), ~5.9 ka (PD2), ~7.5 ka (PD3a), ~9.7 ka (PD3b), ~10.9 ka (PD4), ~12.1 ka (PD5), and ~16.5 ka (PD6); earthquakes PD1 to PD5 each had about 1.0–1.4 m of vertical displacement. Where the record is most complete (since ~14 ka), earthquakes PD5–PD1 yield a latest Pleistocene mean recurrence interval of ~1.6 kyr that is similar to Holocene estimates for the site (1.7–1.9 kyr) and late Holocene estimates for the Cottonwood fault (1.2–1.4 kyr). Latest Pleistocene and Holocene vertical slip rates for the Penrose Drive site are 0.5–0.9 mm/yr.

Paleoseismic data from Penrose Drive—when combined with previous results from LCC and SFDC—demonstrate that the SLCS has been a consistently active source of large-magnitude earthquakes since the latest Pleistocene. At least nine surface-faulting earthquakes (S1–S9) have occurred on the SLCS since the Bonneville highstand, including two earthquakes (S7 and S8) that occurred within a previously interpreted ~8-kyr gap in the SLCS paleoseismic record. These data indicate an essentially stable rate of earthquake recurrence since the latest Pleistocene, corroborating similar results for the Provo segment. Refined paleoseismic data for the SLCS demonstrate the difficulty in obtaining a complete latest Pleistocene earthquake record on the WFZ and underscore the importance of having multiple lines of paleoseismic evidence when interpreting a segment-wide earthquake chronology. Although additional paleoseismic data for the SLCS are necessary to address questions of rupture extent and segmentation, our paleoearthquake data are important to understanding the earthquake potential of the SLCS, clarifying the seismogenic relation between the SLCS and WVFZ, and forecasting the probabilities of future large-magnitude earthquakes in the Wasatch Front region.

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APPENDIX A

DESCRIPTION OF STRATIGRAPHIC UNITS IN TRENCHES AT THE PENROSE DRIVE TRENCH SITE

Unit, genesis ¹	Station no. (trench) ²	Textural name ³	Texture (%) ⁴				Clasts		Plast- icity	Density/ consistency	Cemen- tation	HCL reaction	Clast ang.	Bedding	Structure	Sorting	Lower bound. ⁵	Color ⁶ dry (moist)	Notes
			F	S	G	C/B	Largest (cm)	Average (cm)											
Stratigraphic Units																			
1, S & DF	10.8, 8.9 (W)	silty gravel with sand & cobbles	15	15	60	10	46	1-5	low	med-high	weak- mod	mod- strong	ang.- subang.	mod. well strat.	variable	variable	not exp.	7.5YR6/4 (7.5YR4/6)	Pre-Bonneville alluvial-fan deposits
2, L	32.7, 1.4 (W)	slightly sandy silt with minor clay and rare pebbles	95	4	<1	0	2	0.5	med	firm	none	mod	subang- subround	mottled & bioturbated	matrix	well	not exp.	10YR6/6 (10YR5/6)	Lake Bonneville highstand silt; slightly sticky when wet
3, L	29.6, 1.8 (W)	boulder gravel with minor sand	1	6	18	75	40-50	20-25	none	med	mod- strong	strong	subround- round	massive	clast	variable	abrupt, smooth	10YR5/4 (10YR4/5)	Provo-phase shorezone deposits
4, C	7.6, 2.1 (E)	boulder gravel with silt and sand	25	15	20	40	65	5-15	low	low-high	none- weak	mod- strong	subround- round	variable	variable	poor	clear	10YR6/4 (10YR4/5)	Scarp-derived colluvium
5, C	22.3, 4.4 (W)	sandy silty gravel with cobbles	32	8	40	20	25-30	3-5	med	med	none	mod	subang- subround	variable	maxtrix	poor	clear	7.5YR6/4 (7.5YR4/6)	Scarp-derived colluvium; clast- supported near fault zone
6, C	22.6, 4.8 (W)	sandy silty gravel with cobbles	30	10	35	25	10-15	5-8	med	med	none	mod	subang- subround	variable	matrix	poor	gradual	7.5YR6/3 (7.5YR4/6)	Scarp-derived colluvium. Near fault zone: clast supported with aligned cobbles
7, C	22.9, 5.5 (W)	sandy silt with gravel	40	15	35	10	10-15	4-6	med	low-med	none	mod	ang- subround	variable	matrix	poor	gradual	7.5YR6/3 (7.5YR4.5/4)	Scarp-derived colluvium
8, C	21.9, 6.2 (W)	sandy silt with gravel and rare cobbles	45	10	35	10	24	2-5	med	low-med	none	mod	ang- subround	variable	matrix	poor	gradual	7.5YR7/3 (7.5YR5/4)	Scarp-derived colluvium
9, F	25.3, 5.8 (W)	gravelly silt with sand and cobbles	40	15	40	5	40	2-6	med	loose-low	none	mod- strong	subang- subround	nonstrat-poorly strat.	matrix	poor	clear, smooth	7.5YR5/4 (7.5YR4/3.5)	Cultural fill with metal fragments
Soils																			
S1(3)	27.6, 2.5 (W)	sand with gravel and silt	5	65	20	10	25	5	low	med	none- weak	mod	subang- round	nonstrat	matrix	poor	clear- gradual	(7.5YR3/2- 3)*	A horizon with weak granular structure; local carbonate filaments; minor bioturbation; developed in Provo shoreline gravel (unit 3)
S1(4)	6.75, 2.25 (E)	sand with gravel and fines	10	45	35	10	16	4-5	none- low	med	none	strong	subang	nonstrat	matrix	poor	clear- gradual	(7.5YR3/3)*	A horizon developed on unit 4 (scarp colluvium); locally contains carbonate filaments
S2	6.5, 2.7 (E)	sand with gravel and silt	10	50	30	10	13	3	low	med-high	none	mod- strong	subang- subround	nonstrat	matrix	poor	gradual	(7.5YR3/4)*	A horizon with granular structure developed on unit 5; minor carbonate filaments; locally very fine grained.
S3	23.9, 4.7 (W)	silty sand with gravel	15	55	20	10	15	5	med	low	none	mod	ang- subang	nonstrat	matrix	poor	gradual- diffuse	(7.5YR3/4)*	A horizon with weak granular structure developed on unit 6; abundant carbonate filaments.
S4	7.5, 5.05 (E)	gravel with sand and silt	25	30	40	5	8	2	med	low-med	none	mod- strong	ang- subang	nonstrat	matrix	poor	diffuse	(7.5YR3/4)*	Weak A horizon (no soil structure) developed on unit 8; locally bioturbated and overprinted by S5

S5	26.15, 4.6 (W)	gravel with fines and sand	25	25	45	5	17	1-2	med	low	none	none-weak	ang-subang	nonstrat	matrix	poor	clear-diffuse	(7.5YR2/2)*	A horizon with granular structure developed on several units; carbonate accumulation at 10-20 cm; locally very organic
S6(9)	26.85, 5.75 (W)	gravel with sand and silt	10	40	45	5	10	1-2	med	loose	none	mod	ang	nonstrat	variable	poor	gradual-diffuse	(7.5YR3/4)*	A horizon with granular structure developed on unit 9 (hanging wall); bioturbated
S6(1)	5.9, 10.95 (W)	silty sand with gravel and organic debris	18	50	30	2	7	2	low	loose	none	weak	ang-subround	nonstrat	matrix	poor	abrupt	(7.5YR2/2)*	A horizon with granular structure developed on unit 1 (footwall); biotrubated
S6(1) 2Bk	5.9, 10.75 (W)	sand with gravel and silt	5	55	30	10	15	2-3	low	med-high	mod	strong	subang-subround	nonstrat	matrix	poor	clear-diffuse	(7.5YR4/4)*	Carbonate soil horizon (stage II-III?) developed on unit 1; carbonate throughout matrix--though variable; locally well cemented with weak horizonatal laminations; most clasts completely coated; rinds <2 mm thick and diffuse (poorly laminated)

¹ Units correspond with plate 1. Genesis: S - stream, DF - debris flow, L - lacustrine, C - colluvium, F - fill. For soils (S1-S6), number in parentheses is unit soil is developed on (where described).

² Horizontal and vertical meters correspond to plate 1; (W) - west trench, (E) - east trench.

³ Texture terms based on the Unified Soil Classification System (density/consistency after Birkeland and others [1991]). Textural information may not be representative of entire unit due to vertical and horizontal heterogeneity in units.

⁴ Percentages of clast-size fractions (based on area) are field estimates. We used a U.S. Standard #10 (2 mm) sieve to separate matrix from gravel.

⁵ Lower boundary modified from Birkeland and others (1991). Distinctness: abrupt (1mm-2.5 cm), clear (2.5-6 cm), gradual (6-12.5 cm). Not exp. - base of unit not exposed.

⁶ Munsell color of matrix (year 2000 revised version). * indicates dry color not recorded.

Appendix B

Examination of Bulk Soil for Radiocarbon Datable Material and Extraction of Microcharcoal
from the Penrose Drive Trench Site, East Bench Fault, Salt Lake City, Utah

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INTRODUCTION

A total of eleven bulk soil samples, three charcoal samples, and two shell samples were examined for the presence of organic material suitable for radiocarbon analysis. These samples were recovered from two trenches at the Penrose Drive site in Salt Lake City, Utah. Botanic components and detrital charcoal were identified, and potentially radiocarbon datable material was separated. Dating of material from the trenches will be used to help develop detailed information on the timing and recurrence of paleoearthquakes on the Salt Lake City segment of the Wasatch Fault zone. Samples for AMS radiocarbon dating will be submitted to Woods Hole Institute.

METHODS

Flotation and Identification

The macrofloral samples were floated using a modification of the procedures outlined by Matthews (1979). Each sample was added to approximately 3 gallons of water, then stirred until a strong vortex formed. The floating material (light fraction) was poured through a 150 micron mesh sieve. Additional water was added and the process repeated until all floating material was removed from the sample (a minimum of five times). The material that remained in the bottom (heavy fraction) was poured through a 0.5-mm mesh screen. The floated portions were allowed to dry.

The light fractions were weighed, then passed through a series of graduated screens (US Standard Sieves with 2-mm, 1-mm, 0.5-mm and 0.25-mm openings) to separate charcoal debris and to initially sort the remains. The contents of each screen then were examined. Charcoal pieces larger than 2-mm, 1-mm, or 0.5-mm in diameter were separated from the rest of the light fraction and the total charcoal weighed. A representative sample of charcoal pieces was broken to expose fresh cross, radial, and tangential sections. Charcoal fragments were examined under a binocular microscope at a magnification of 70x and under a Nikon Optiphot 66 microscope at magnifications of 320-800x. The weights of each charcoal type within the representative sample also were recorded. The material that remained in the 2-mm, 1-mm, 0.5-mm, and 0.25-mm sieves was scanned under a binocular stereo microscope at a magnification of 10x, with some identifications requiring magnifications of up to 70x. The material that passed through the 0.25-mm screen was not examined. The heavy fractions were scanned at a magnification of 2x for the presence of botanic remains. Remains from the light and heavy fractions were recorded as charred and/or uncharred, whole and/or fragments. The term "seed" is used to represent seeds, achenes, caryopses, and other disseminules.

Charcoal fragments in the three charcoal samples were broken to expose fresh cross, radial, and tangential sections, then examined under a binocular microscope at a magnification of 70x and under a Nikon Optiphot 66 microscope at magnifications of 320-800x. The weights of each charcoal type were recorded. The two shell samples were water-screened through a 250 micron mesh and allowed to dry. Shell fragments were separated from the rest of the sample matrix and weighed. Macrofloral remains, including charcoal, are identified using manuals (Carlquist 2001; Hoadley 1990; Martin and Barkley 1961; Musil 1963; Panshin and de Zeeuw 1980; Schopmeyer 1974) and by comparison with modern and archaeological

references. Because charcoal and possibly other botanic remains were to be submitted for radiocarbon dating, clean laboratory conditions were used during flotation and identification to avoid contamination. All instruments were washed between samples, and samples were protected from contact with modern charcoal.

Microcharcoal Recovery

Now it is possible to recover microscopic charcoal (microcharcoal) from sediments for the purpose of obtaining an AMS radiocarbon age. Microscopic charcoal fragments are far superior to humates because they provide dates with the same precision as those obtained from larger pieces of charcoal, with the single exception that the individual pieces of microscopic charcoal are not identified to taxon.

A chemical extraction technique based on that used for pollen, and relying upon heavy liquid extraction, has been modified to recover microcharcoal for the purpose of obtaining an AMS radiocarbon age. After removing calcium carbonates and iron with hydrochloric acid (10%), the samples were screened through 150 micron mesh. The material remaining in the screen was examined for the presence of macroscopic charcoal. Since the amount of macroscopic charcoal was insufficient for obtaining a radiocarbon date, the screened samples then were rinsed until neutral, and a small quantity of sodium hexametaphosphate was added. Samples then were filled with reverse osmosis, deionized (RODI) water and allowed to settle according to Stoke's Law. After two hours the supernatant, containing clay, was poured off and the sample was rinsed with RODI water three more times, being allowed to settle according to Stoke's Law after each rinse to remove more clays. Once the clays had been removed, the samples were freeze-dried using a vacuum system, freezing out all moisture at -98 °C. Sodium polytungstate (SPT), with a density of 1.8, was used for the flotation process. The samples were mixed with SPT and centrifuged at 1500 rpm for 10 minutes to separate organic from inorganic remains. The supernatant containing pollen, organic remains, and microcharcoal was decanted. Sodium polytungstate again was added to the inorganic fraction to repeat the separation process until all visible microcharcoal had been recovered. The microcharcoal was recovered from the sodium polytungstate and rinsed thoroughly with RODI water. Following this step, the samples were examined using a binocular microscope at a magnification of up to 30x to check the matrix for microscopic charcoal and other debris. Each sample received a treatment with hot nitric acid (30%) for 30 minutes to remove extraneous debris. RODI water rinses followed, with another examination with the binocular microscope. The nitric acid treatments continued until examination of the samples using the binocular microscope indicated that all that remained was microcharcoal and feldspar. Feldspar and other microminerals cannot be removed from microcharcoal samples, however, the presence of these minerals will not affect the date that is obtained.

DISCUSSION

The two trenches at the Penrose Drive trench site crossed the East Bench fault of the Salt Lake City segment of the Wasatch fault zone. The trench site is noted to lie below the highest shoreline of Lake Bonneville and at the approximate elevation of the of the Provo shoreline. The trenches exposed pre-Bonneville alluvial-fan deposits, fine-grained Lake

Bonneville sediments related to the Bonneville highstand, a boulder gravel at the Provo shoreline, and fault-scarp-derived colluvium (Christopher DuRoss, personal communication, June 3, 2010). Excavation of the trenches yielded evidence for five (P1-P5) and possibly six surface-faulting earthquakes that occurred after abandonment of the Provo shoreline at around 14,000 B.P. The bulk soil samples and two of the charcoal samples were recovered from soils (S1-S5) developed between earthquakes on the fault-scarp-derived colluvium. One of the charcoal samples and the two shell samples were recovered from soils developed on the Provo boulder gravel.

Bulk samples PD-R12 and PD-R11 were recovered from soil S5 developed on distal P2 and P1 colluvium (Table 1). Sample PD-R12 contained three small fragments of *Artemisia* charcoal weighing 0.0010 g, three small fragments of hardwood charcoal too small for further identification weighing 0.0006 g, and unidentified charcoal weighing 0.0033 g (Table 2, Table 3). A few charred Poaceae C caryopses and unidentified seeds also were noted. Poaceae C caryopses reflect grasses with small seeds, such as *Agrostis* (bentgrass), *Muhlenbergia* (muhly grass), *Poa* (bluegrass), etc. Four pieces of charred, vitrified tissue weighing 0.0002 g may represent charcoal or other charred plant tissue with a shiny, glassy appearance due to fusion by heat. A few uncharred seeds and an uncharred hardwood wood fragment represent modern plants in the area. In addition, the sample contained several insect chitin fragments and a single snail shell with a depressed (flat) shape where the width is much bigger than the height.

A single piece of *Quercus* charcoal weighing 0.0010 g was present in sample PD-R11, as well as several fragments of hardwood charcoal too small for further identification weighing 0.0005 g. Components of the local vegetation are represented by a single uncharred *Descurainia* seed, a few root fragments, and several rootlets. Non-floral remains include an uncharred bone fragment, a few insect chitin fragments, and a few insect puparium fragments.

Samples PD-R14 and PD-R9 were collected from soil S4 developed on P2 colluvium in Unit 7. Seven fragments of hardwood charcoal too small for identification and weighing 0.0004 g were present in sample PD-R14. The sample also contained a single piece of charred vitrified tissue weighing 0.0001 g. In addition, the sample contained a few depressed snail shells and several snail shell fragments. Due to the small weight of charred material recovered in the sample, additional sediment was processed to recover microscopic charcoal for dating. Examination of the microcharcoal screen contents yielded an additional 0.0002 g of unidentified hardwood charcoal. A total of 0.0102 g of microcharcoal with about 30% feldspar was extracted (Table 4).

Sample PD-R9 yielded four fragments of hardwood charcoal too small for further identification weighing 0.0003 g. Additional sediment was processed to recover microcharcoal, resulting in 0.0022 g of microscopic charcoal (with about 60% feldspar) for dating. The sample also yielded a few uncharred rootlets from modern plants, an insect chitin fragment, an insect egg fragment, and a few depressed snail shells.

Samples PD-R10, PD-R8, and PD-R5 were taken from soil S3 developed on P3 colluvium in Unit 6. Sample PD-R10 contained a charred *Prunus*-type seed fragment weighing 0.0005 g suggesting the presence of a wild cherry in the area. In addition, the sample contained three fragments of charred parenchymous tissue weighing 0.0006 g and eight pieces of hardwood charcoal too small for further identification weighing 0.0002 g. Parenchyma is the botanical term for relatively undifferentiated tissue, composed of many similar thin-walled cells.

Parenchyma occurs in many different plant organs in varying amounts, especially large fleshy organs such as roots and stems. The vegetative storage parenchyma in roots and stems stores starch and other carbohydrates and sugars (Hather 2000:1). Recovery of charred parenchymous tissue might reflect burned root or stem tissue. Non-floral remains include an uncharred bone fragment, a moderate amount of insect eggs, a few depressed snail shells, and several snail shell fragments. Additional sediment also was processed to recover microcharcoal, and a total of 0.0029 g of microcharcoal (containing about 30% feldspar) was recovered.

A total of six pieces of hardwood charcoal too small for further identification weighing 0.0002 g were present in sample PD-R8, as well as a few uncharred rootlets from modern plants and a snail shell fragment. Additional soil was processed to recover microscopic charcoal, and an additional 0.0017 g of microcharcoal was obtained. Of this amount, about 30% was feldspar.

Sample PD-R5 contained several fragments of hardwood charcoal too small for further identification weighing 0.0005 g, as well as three small pieces of charred parenchymous tissue weighing 0.0001 g. A few uncharred rootlets from modern plants, an insect chitin fragment, a moderate amount of insect eggs, several snail shells with a depressed shape, and a moderate amount of snail shell fragments also were noted. Additional soil processed to recover microscopic charcoal yielded only 0.0003 g of microcharcoal, 50% of which was feldspar.

Samples PD-R15 and PD-R6 represent soil S2 developed on P4 colluvium in Unit 5. Pieces of hardwood charcoal too small for further identification and weighing 0.0012 g were present in sample PD-R15. A piece of charred parenchymous tissue weighing 0.0003 g and three fragments of charred vitrified tissue weighing 0.0002 g also were recovered. In addition, the sample contained several snail shells with a depressed shape and a moderate amount of snail shell fragments.

Sample PD-R6 yielded several fragments of unidentified hardwood charcoal weighing 0.0029 g and six pieces of small, vitrified charcoal from a twig fragment weighing 0.0031 g. The sample also yielded a few charred seeds and several uncharred *Celtis* seed fragments. Uncharred seeds normally are interpreted to represent components of modern or historic vegetation. However, *Celtis* seeds undergo natural mineralization (biomineralization) over time and contain large quantities of calcium carbonate, which makes them resilient to decomposition. As a result, uncharred *Celtis* seeds can survive in old deposits without other means of outside preservation, such as charring (Zohary and Hopf 2000). Non-floral remains in this sample include two uncharred bone fragments, fifteen depressed snail shells, a moderate amount of snail shell fragments, and an oblong snail shell where the height is much bigger than the width.

A charcoal sample and two snail shell samples were collected from soil S1 developed on the Provo boulder gravel. Charcoal sample PD-R2 yielded two fragments of probable Rosaceae charcoal weighing 0.0037 g and eight pieces of unidentified hardwood charcoal weighing 0.0012 g. Numerous snail shell fragments weighing 0.076 g were present in sample PD-R4. Sample PD-R16 contained several oblong snail shells and shell fragments weighing 0.757 g.

Bulk sample PD-R7 and charcoal samples PD-R1 and PD-R3 were recovered from soil S1 developed on P5 colluvium in Unit 4. Sample PD-R7 contained several fragments of hardwood charcoal too small for further identification weighing 0.0012 g, a vitrified piece of hardwood root charcoal weighing 0.0010 g, two fragments of vitrified hardwood twig fragments weighing 0.0007 g, and a small fragment of charcoal too vitrified for identification weighing less than 0.0001 g. In addition, the sample yielded two charred fragments of parenchymous tissue weighing 0.0005 g, a small charred and vitrified monocot/herbaceous dicot stem fragment weighing less than 0.0001 g, and a charred unidentified seed endosperm fragment. The sample also contained two uncharred bone fragments, an insect puparium, two depressed snail shells, and numerous snail shell fragments.

Eight fragments of hardwood charcoal too small and friable for further identification and weighing 0.0040 g were present in sample PD-R1. Pieces of hardwood charcoal weighing 0.0035 g also were noted in sample PD-R3.

Bulk sample PD-R13 from soil S1 possibly was developed on distal P5 colluvium in Unit 4. This sample contained seven fragments of hardwood charcoal too small for further identification weighing 0.0002 g and several fragments of charred parenchymous tissue weighing 0.0111 g. Non-floral remains include an insect chitin fragment, a depressed snail shell, and a moderate amount of snail shell fragments.

SUMMARY AND CONCLUSIONS

Flotation of sediment samples and identification of charcoal samples from two trenches at the Penrose Drive site in the Salt Lake City segment of the Wasatch Fault zone, Utah, resulted in recovery of charcoal and other charred botanic remains that can be submitted for radiocarbon analysis. Several samples contained charcoal or charred botanic remains in sufficient quantities for AMS radiocarbon dating. Five samples did not contain sufficient macroscopic charcoal for dating; therefore, the samples were processed to recover microscopic charcoal. Four of these samples yielded sufficient microcharcoal for dating. The majority of the charcoal fragments recovered from these samples consisted of hardwood charcoal too small for further identification. Fragments of identifiable *Artemisia* and *Quercus* charcoal in samples from the youngest S5 soil reflect sagebrush and oak in the area. A charred *Prunus*-type seed fragment in sample PD-R10 from soil S3 and pieces of probable Rosaceae charcoal in sample PD-R2 from the oldest S1 soil suggest the presence of a woody member of the rose family, such as chokecherry. Several samples contained pieces of charred parenchymous tissue, likely from burned root or stem tissue.

TABLE 1
PROVENIENCE DATA FOR SAMPLES FROM THE PENROSE DRIVE TRENCH SITE,
SALT LAKE CITY, UTAH

Sample No.	Trench	Unit No.	Sample Location (horiz., vert.)	Provenience/ Description	Analysis
PD-R12	West	7, 8	28.9 m, 3.6 m	Bulk sample from soil S5 developed on distal P2 and P1 colluvium; minimum for P1	Macrofloral
PD-R11	West	7, 8	26.9 m, 4.2 m	Bulk sample from soil S5 developed on distal P2 and P1 colluvium; minimum for P1	Macrofloral
PD-R14	West	7	23.4 m, 5.5 m	Bulk sample from soil S4 developed on P2 colluvium; minimum for P2, maximum for P1	Macrofloral Microcharcoal
PD-R9	West	7	22.9 m, 5.6 m	Bulk sample from soil S4 developed on P2 colluvium; minimum for P2, maximum for P1	Macrofloral Microcharcoal
PD-R10	West	6	23.6 m, 4.8 m	Bulk sample from soil S3 developed on P3 colluvium; minimum for P3, maximum for P2	Macrofloral Microcharcoal
PD-R8	East	6	6.2 m, 3.5 m (west wall)	Bulk sample from soil S3 developed on P3 colluvium; minimum for P3, maximum for P2	Macrofloral Microcharcoal
PD-R5	East	6	5.6 m, 3.6 m	Bulk sample from soil S3 developed on P3 colluvium; minimum for P3, maximum for P2	Macrofloral Microcharcoal
PD-R15	West	5	25.1 m, 3.4 m	Bulk sample from soil S2 developed on P4 colluvium; minimum for P4, maximum for P3	Macrofloral
PD-R6	East	5	6.7 m, 2.8 m	Bulk sample from soil S2 developed on P4 colluvium; minimum for P4, maximum for P3	Macrofloral
PD-R2	West	3	31.2 m, 2.2 m	Charcoal from soil S1 developed on Provo boulder gravel; possible minimum age for P5	Charcoal ID
PD-R16	West	3	26.0 m, 2.6 m to 29.6 m, 2.0 m	Gastropod shells from Provo boulder gravel	Shell

TABLE 1 (Continued)

Sample No.	Trench	Unit No.	Sample Location (horiz., vert.)	Provenience/ Description	Analysis
PD-R4	West	3	24.9 m, 2.8 m	Gastropod shell fragments from soil S1 developed on Provo boulder gravel; possible minimum age for P5	Shell
PD-R7	East	4	6.6 m, 2.2 m	Bulk sample from soil S1 developed on P5 colluvium; minimum age for P5	Macrofloral
PD-R1	East	4	6.3 m, 2.0 m	Charcoal fragment from soil S1 developed on P5 colluvium; minimum age for event P5	Charcoal ID
PD-R3	East	4	7.4 m, 2.4 m	Charcoal from soil S1 developed on P5 colluvium; minimum age for P5	Charcoal ID
PD-R13	West	4	24.8 m, 3.0 m	Bulk sample from soil S1 possibly developed on distal P5 colluvium; possible minimum age for P5	Macrofloral

horiz. = horizontal

vert. = vertical

S1 = oldest soil

S5 = youngest soil

P1 = youngest prehistoric surface-faulting earthquake

P5 = oldest prehistoric surface-faulting earthquake

TABLE 2
MACROFLORAL REMAINS FROM THE PENROSE DRIVE TRENCH SITE, SALT LAKE CITY, UTAH

Sample No.	Identification	Part	Charred		Uncharred		Weights/ Comments
			W	F	W	F	
PD-R12	Liters Floated						0.85 L
Unit 7, 8	Light Fraction Weight						1.44 g
Soil S5	FLORAL REMAINS:						
	Poaceae C	Caryopsis	1				0.0001 g
	cf. Poaceae C	Caryopsis	1	2			0.0002 g
	Unidentified N	Seed	4	1			0.0004 g
	Vitrified tissue			4			0.0002 g
	Cheno-am	Seed				1	< 0.0001 g
	<i>Medicago</i>	Seed			1		0.0017 g
	<i>Sambucus</i>					1	0.0007 g
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	<i>Artemisia</i>	Charcoal		3			0.0010 g
	Unidentified hardwood - small	Charcoal		3			0.0006 g
	Unidentified	Charcoal		X			0.0033 g
	Unidentified hardwood	Wood				1	0.0004 g
	NON-FLORAL REMAINS:						
	Insect	Chitin				18	
	Rock/Gravel					X	Moderate
	Snail shell - depressed				1		0.0014 g

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred		Uncharred		Weights/ Comments
			W	F	W	F	
PD-R11	Liters Floated						0.70 L
Unit 7, 8	Light Fraction Weight						0.84 g
Soil S5	FLORAL REMAINS:						
	<i>Descurainia</i>	Seed			1		< 0.0001 g
	Roots					X	Few
	Rootlets					X	Moderate
	CHARCOAL/WOOD:						
	<i>Quercus</i>	Charcoal		1			0.0010 g
	Unidentified hardwood	Charcoal		21			0.0005 g
	NON-FLORAL REMAINS:						
	Bone - 0.05 mm					1	0.0018 g
	Insect	Insect				5	
	Insect	Puparium				3	
	Rock/Gravel					X	Moderate
PD-R14	Liters Floated						1.00 L
Unit 7	Light Fraction Weight						1.74 g
Soil S4	Microcharcoal Screen Content Weight						151.48 g
	FLORAL REMAINS:						
	Vitrified tissue > 0.25 mm			1			0.0001 g
	Rootlets					X	Moderate
	CHARCOAL/WOOD:						
	Unidentified hardwood - small	Charcoal		X			0.0006 g
	NON-FLORAL REMAINS:						
	Rock/Gravel					X	Moderate
	Snail shell - depressed, 0.05 mm				4	2	0.006 g
	Snail shell in heavy fraction					X	Moderate

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred		Uncharred		Weights/ Comments
			W	F	W	F	
PD-R9	Liters Floated						0.50 L
Unit 7	Light Fraction Weight						1.10 g
Soil S4	Microcharcoal Screen Content Weight						120.23 g
	FLORAL REMAINS:						
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Total charcoal ≥ 2 mm						
	Unidentified hardwood - small	Charcoal		4			0.0003 g
	NON-FLORAL REMAINS:						
	Insect	Chitin				1	
	Insect	Egg			1		
	Rock/Gravel					X	Moderate
	Snail shell - depressed				4	1	0.0050 g
PD-R10	Liters Floated						0.80 L
Unit 6	Light Fraction Weight						0.82 g
Soil S3	Microcharcoal Screen Content Weight						107.30 g
	FLORAL REMAINS:						
	Parenchymous tissue			3			0.0006 g
	<i>Prunus</i> -type	Seed		1			0.0005 g
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.25 mm						0.0002 g
	Unidentified hardwood	Charcoal		8			0.0002 g
PD-R10	NON-FLORAL REMAINS:						
Unit 6	Bone					1	0.008 g
Soil S3	Insect	Egg			X		Moderate
	Rock/Gravel					X	Moderate
	Snail shell - depressed ≥ 1 mm					3	0.002 g
	Snail shell in heavy fraction				1	X	Moderate

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred		Uncharred		Weights/ Comments
			W	F	W	F	
PD-R8	Liters Floated						1.00 L
Unit 6	Light Fraction Weight						3.63 g
Soil S3	Microcharcoal Screen Content Weight						101.76 g
	FLORAL REMAINS:						
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Unidentified hardwood - small	Charcoal		6			0.0002 g
	NON-FLORAL REMAINS:						
	Rock/Gravel					X	Moderate
	Snail shell					1	0.005 g
	PD-R5	Liters Floated					
Unit 6	Light Fraction Weight						1.06 g
Soil S3	Microcharcoal Screen Content Weight						136.27 g
	FLORAL REMAINS:						
	Parenchymous tissue > 0.25 mm			3			0.0001 g
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Unidentified hardwood - small	Charcoal		24			0.0005 g
	NON-FLORAL REMAINS:						
	Insect	Chitin				1	
	Insect	Egg			X		Moderate
	Rock/Gravel					X	Moderate
	Snail shell - depressed > 1 mm				5		0.006 g
Snail shell - depressed > 0.5 mm				8	2		
Snail shell in heavy fraction					X	Moderate	

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred		Uncharred		Weights/ Comments
			W	F	W	F	
PD-R15	Liters Floated						1.20 L
Unit 5	Light Fraction Weight						1.62 g
Soil S2	FLORAL REMAINS:						
	Parenchymous tissue > 0.25 mm			1			0.0003 g
	Vitrified tissue > 0.25 mm			3			0.0002 g
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Unidentified hardwood - small	Charcoal		11			0.0012 g
	NON-FLORAL REMAINS:						
	Snail shell - depressed ≥ 1 mm				2	3	0.009 g
	Snail shell - depressed < 1 mm					10	
	Snail shell in heavy fraction				X	Moderate	
PD-R6	Liters Floated						1.20 L
Unit 5	Light Fraction Weight						10.67 g
Soil S2	FLORAL REMAINS:						
	Cheno-am	Perisperm		2			< 0.0001 g
	Unidentified P	Seed	1				< 0.0001 g
	Celtis - outer	Seed coat				26	0.2692 g
	Celtis - inner	Seed coat			1		0.0213 g
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.5 mm						0.0080 g
	Unidentified hardwood	Charcoal		14			0.0029 g
	Unidentified twig - small, vitrified	Charcoal		6			0.0031 g
	NON-FLORAL REMAINS:						
	Bone					2	0.0035 g
	Rock/Gravel					X	Moderate
	Snail shell - depressed				15		0.0089 g
Snail shell - oblong					1	0.0010 g	
Snail shell < 1 mm					X	Moderate	

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred		Uncharred		Weights/ Comments
			W	F	W	F	
PD-R2	Sample Weight						0.04 g
Unit 3	CHARCOAL/WOOD:						
Soil S1	cf. Rosaceae	Charcoal		2			0.0037 g
	Unidentified hardwood	Charcoal		8			0.0012 g
PD-R16	Water-screened Sample Weight						2.61 g
Unit 3	NON-FLORAL REMAINS:						
	Snail shell - oblong				13	65	0.757 g
	Sediment					X	1.853 g
PD-R4	Water-screened Sample Weight						0.43 g
Unit 3	NON-FLORAL REMAINS:						
	Snail shell					X	0.076 g
PD-R7	Liters Floated						0.80 L
Unit 4	Light Fraction Weight						7.05 g
Soil S1	Microcharcoal Screen Content Weight						122.24 g
	FLORAL REMAINS:						
	Unidentified	Endosperm		1			0.0001 g
	Monocot/Herbaceous dicot - vitrified	Stem		1			< 0.0001 g
	Parenchymous tissue ≥ 0.5 mm			2			0.0005 g
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Unidentified hardwood	Charcoal		21			0.0012 g
	Unidentified hardwood root - vitrified	Charcoal		1			0.0010 g
	Unidentified hardwood twig - small, vitrified	Charcoal		2			0.0007 g
Unidentifiable - vitrified	Charcoal		1			< 0.0001 g	

Sample No.	Identification	Part	Charred		Uncharred		Weights/ Comments
			W	F	W	F	
	NON-FLORAL REMAINS:						
	Bone > 0.5 mm	Puparium				2	0.003 g
	Insect				1		
	Rock/Gravel					X	Few
	Snail shell - depressed > 1 mm				2	1	0.008 g
	Snail shell < 1 mm					X	Numerous
	Snail shell in heavy fraction					X	Numerous
PD-R1	Sample Weight						0.53 g
Unit 4	CHARCOAL/WOOD:						
Soil S1	Total charcoal \geq 2 mm						
	Unidentified hardwood - small, friable	Charcoal		8			0.0040 g
PD-R3	Sample Weight						2.27 g
Unit 4	CHARCOAL/WOOD:						
Soil S1	Unidentified hardwood	Charcoal		18			0.0035 g
PD-R13	Liters Floated						0.90 L
Unit 4	Light Fraction Weight						2.45 g
Soil S1	FLORAL REMAINS:						
	Parenchymous tissue > 0.25 mm - vitrified			74			0.0111 g
	CHARCOAL/WOOD:						
	Unidentified hardwood - small	Charcoal		7			0.0002 g
	NON-FLORAL REMAINS:						
	Insect	Chitin				1	
	Rock/Gravel					X	Moderate
	Snail shell - depressed > 1 mm				1		0.001 g
	Snail shell in heavy fraction					X	Moderate

W = Whole

F = Fragment

X = Presence noted in sample

g = grams

mm = millimeters

L = liters

TABLE 3
INDEX OF MACROFLORAL REMAINS RECOVERED FROM THE PENROSE DRIVE TRENCH SITE,
SALT LAKE CITY, UTAH

Scientific Name	Common Name
FLORAL REMAINS:	
<i>Celtis</i>	Hackberry
Cheno-am	Includes goosefoot and amaranth families
<i>Descurainia</i>	Tansy mustard, Flixweed
Monocot/Herbaceous dicot	A member of the Monocotyledonae class of Angiosperms, which include grasses, sedges, lilies, and palms/A non-woody member of the Dicotyledonae class of Angiosperms
<i>Medicago</i>	Burclover, Alfalfa
Poaceae C	Members of the grass family with small caryopses, such as <i>Agrostis</i> (bentgrass), <i>Muhlenbergia</i> (muhly grass), <i>Poa</i> (bluegrass), etc.
<i>Prunus</i> -type	Similar to Cherry
<i>Sambucus</i>	Elderberry
Parenchymous tissue	Relatively undifferentiated tissue composed of many similar thin-walled cells—occurs in different plant organs in varying amounts, especially large fleshy organs such as roots and stems
Vitrified tissue	Charred material with a shiny, glassy appearance due to fusion by heat
CHARCOAL/WOOD:	
<i>Artemisia</i>	Sagebrush
<i>Quercus</i>	Oak
Rosaceae	Rose family
Unidentified hardwood	Wood from a broad-leaved flowering tree or shrub
Unidentified hardwood - small	Wood from a broad-leaved flowering tree or shrub, fragments too small for further identification
Unidentified hardwood - vitrified	Wood from a broad-leaved flowering tree or shrub, exhibiting a shiny, glassy appearance due to fusion by heat
Unidentifiable - vitrified	Charcoal exhibiting a shiny, glassy appearance due to fusion by heat

TABLE 3 (Continued)

Scientific Name	Common Name
NON-FLORAL REMAINS:	
Insect puparium	A rigid outer shell made from tough material that includes chitin (a natural polymer found in insect exoskeleton and crab shells) and hardens from a larva's skin to protect the pupa as it develops into an adult insect

TABLE 4
 DATABLE CHARCOAL, CHARRED ORGANIC MATERIAL, AND MICROCHARCOAL RECOVERED
 IN SAMPLES FROM THE PENROSE DRIVE TRENCH SITE, SALT LAKE CITY, UTAH

Sample No.	Provenience/ Description	Charred organic material/ Charcoal and Weight		Microcharcoal Weight
PD-R12	Bulk sample from soil S5 developed on distal P2 and p1 colluvium; minimum for P1	<i>Artemisia</i> charcoal	0.0010 g	
		Unidentified charcoal	0.0033 g	
		Unid. hardwood charcoal	0.0006 g	
PD-R11	Bulk sample from soil S5 developed on distal P2 and p1 colluvium; minimum for P1	<i>Quercus</i> charcoal	0.0010 g	
		Unidentified hardwood charcoal	0.0005 g	
PD-R14	Bulk sample from soil S4 developed on P2 colluvium; minimum for P2, maximum for P1	Unidentified hardwood charcoal	0.0006 g	0.0102 g
PD-R9	Bulk sample from soil S4 developed on P2 colluvium; minimum for P2, maximum for P1	Unidentified charcoal	0.0003 g	0.0022 g
PD-R10	Bulk sample from soil S3 developed on P3 colluvium; minimum for P3, maximum for P2	<i>Prunus</i> -type seed	0.0005 g	0.0029 g
		Parenchymous tissue	0.0006 g	
		Unid. hardwood charcoal	0.0002 g	
PD-R8	Bulk sample from soil S3 developed on P3 colluvium; minimum for P3, maximum for P2	Unidentified hardwood charcoal	0.0002 g	0.0017 g
PD-R5	Bulk sample from soil S3 developed on P3 colluvium; minimum for P3, maximum for P2	Parenchymous tissue	0.0001 g	0.0003 g
		Unidentified hardwood charcoal	0.0005 g	(do not use)
PD-R15	Bulk sample from soil S2 developed on P4 colluvium; minimum for P4, maximum for P3	Parenchymous tissue	0.0003 g	
		Unidentified hardwood charcoal	0.0012 g	
PD-R6	Bulk sample from soil S2 developed on P4 colluvium; minimum for P4, maximum for P3	Unid. twig charcoal	0.0029 g	
		Unidentified hardwood charcoal	0.0031 g	
PD-R16	Gastropod shells from Provo boulder gravel	Snail shell	0.757 g	
PD-R4	Gastropod shell fragments from soil S1 developed on Provo boulder gravel; possible minimum age for P5	Snail shell	0.076 g	
PD-R2	Charcoal from soil S1 developed on Provo boulder gravel; possible minimum age for P5	cf. Rosaceae charcoal	0.0037 g	
		Unidentified hardwood charcoal	0.0012 g	

TABLE 4 (Continued)

Sample No.	Provenience/ Description	Charred organic material/ Charcoal and Weight	Microcharcoal Weight
PD-R13	Bulk sample from soil S1 possibly developed on distal P5 colluvium; possible minimum age for P5	Parenchymous tissue 0.0111 g Unidentified hardwood charcoal 0.0002 g	
PD-R7	Bulk sample from soil S1 possibly developed on distal P5 colluvium; possible minimum age for P5	Unid. hardwood charcoal 0.0012 g Unid. hardwood twig - vitrified 0.0007 g	
PD-R3	Charcoal from soil S1 developed on P5 colluvium; minimum age for P5	Unidentified hardwood charcoal 0.0035 g	
PD-R1	Charcoal fragment from soil S1 developed on P5 colluvium; minimum age for event P5	Unidentified hardwood charcoal 0.0040 g	

Unid. = Unidentified

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APPENDIX C

SUMMARY OF RADIOCARBON DATING, PENROSE DRIVE SITE

Sample No.	NOSAMS ¹ Accession No.	Trench	Station ² (m)	Depth (m)	Unit Sampled ³	Material Sampled		Organic Material Dated ⁴	Sample Weight (mg)	Pre-Treatment Method	$\delta^{13}\text{C}$ ⁵	Relation to Earthquake ⁶	Age ⁷ (¹⁴ C yr B.P., $\pm 1\sigma$)	Age ⁸ (cal yr B.P., $\pm 2\sigma$)
						Soil/sediment sampled	Notes							
PD-R1	OS-84833	East	6.28, 2.02	4.1	S1	Charcoal from S1 on scarp-colluvium unit 4	Macro-charcoal sample	8 fragments unidentified hardwood charcoal	4	Acid-base-acid	-26.4	Min - PD5, Max - PD4	9940 \pm 65	11,410 \pm 260
PD-R2	OS-84840	West	31.15, 2.20	2.3	S2 (top)	Charcoal from top of S2 on boulder gravel unit 3	Macro-charcoal sample	2 fragments <i>Rosaceae</i> charcoal	3.7	Acid-base-acid	-24.21	Min - PD5, Max - PD4	9390 \pm 45	10,620 \pm 120
PD-R3	OS-84846	East	7.14, 2.35	4.0	S1	Charcoal from S1 on scarp-colluvium unit 4	Macro-charcoal sample	18 fragments unidentified hardwood charcoal	3.5	Acid-base-acid	-25.61	Min - PD5	9550 \pm 55	10,910 \pm 240
PD-R4	<i>Sample not dated</i>	West	24.93, 2.75	3.8	S1	Shell from S1 on boulder gravel unit 3	-	Gastropod shell	76	Acid-base-acid	-		-	-
PD-R5	OS-85007	East	5.60, 3.55	2.2	S3	Soil sediment from S3 on scarp-colluvial unit 6b	~22-cm wide, 8-cm high sample area	24 fragments unidentified hardwood charcoal	0.5	Acid-base-acid	-25†	Max - PD2	3560 \pm 45	3850 \pm 140
PD-R6a	OS-85006	East	6.65, 2.75	3.4	S2	Soil sediment from S2 on scarp-colluvial unit 5	~22-cm wide, 8-cm high sample area	14 fragments unidentified hardwood charcoal	2.9	Acid-base-acid	-25.99	Max PD3/PD3b	9350 \pm 50	10,570 \pm 140
PD-R6b	OS-84835	East	6.65, 2.75	3.4	S2	Soil sediment from S2 on scarp-colluvial unit 5	~22-cm wide, 8-cm high sample area	6 fragments unidentified twig, vitrified	3.1	Acid-base-acid	-25.85	Max PD3/PD3b	8990 \pm 55	10,120 \pm 200
PD-R7	<i>Sample not dated</i>	East	6.58, 2.23	4.0	S1	Soil sediment from S1 on scarp colluvial unit 4	~16-cm wide, 8-cm high sample area	Many fragments unidentified hardwood charcoal	1.2	-	-	-	-	-
PD-R8	OS-87068	East (west wall)	6.17, 3.52	2.1	S3	Soil sediment from S3 on scarp-colluvial unit 6b (same position as R5)	~22-cm wide, 6-cm high sample area	Microcharcoal	1.7	Acid-base-acid	-28.9	Max - PD2	5480 \pm 50	6280 \pm 120
PD-R9a	<i>Sample too small to date</i>	West	22.94, 5.56	1.5	S4	Soil sediment from S4 on scarp-colluvial unit 7	~18-cm wide, 8-cm high sample area	4 fragments unidentified hardwood charcoal	0.3	Acid-base-acid	-	-	-	-
PD-R9b	OS-87069	West	22.94, 5.56	1.5	S4	Soil sediment from S4 on scarp-colluvial unit 7	~18-cm wide, 8-cm high sample area	Microcharcoal	2.2	Acid-base-acid	-29.14	Max - PD1	3960 \pm 45	4420 \pm 160
PD-R10a	OS-85121	West	23.6, 4.80	2.0	S3	Soil sediment from S3 on scarp-colluvial unit 6b	~25-cm wide, 8-cm high sample area	1 fragment <i>Prunus</i> -type seed, charred	0.5	Acid-base-acid	-25†	Max - PD2	5800 \pm 75	6600 \pm 180
PD-R10b	OS-87060	West	23.6, 4.80	2.0	S3	Soil sediment from S3 on scarp-colluvial unit 6b	~25-cm wide, 8-cm high sample area	Microcharcoal	2.9	Acid-base-acid	-28.64	Max - PD2	5470 \pm 40	6270 \pm 80
PD-R11	OS-84850	West	26.85, 4.20	1.7	S1	Soil sediment from base of S1, developed on scarp colluvium	~16-cm wide, 6-cm high sample area	1 fragment <i>Quercus</i> charcoal	1.0	Acid-base-acid	-24.84	Min - PD1	490 \pm 35	530 \pm 40
PD-R12	OS-84847	West	28.85, 3.55	1.6	S1	Soil sediment from base of S1, developed on scarp colluvium	~16-cm wide, 7-cm high sample area	3 fragments <i>Artemisia</i> charcoal	1.0	Acid-base-acid	-25.42	Min - PD1	495 \pm 30	530 \pm 40
PD-R13	OS-85008	West	24.83, 3.03	3.5	S1	Soil sediment from near top of S1 on boulder gravel unit 3	~20-cm wide, 6-cm high sample area	7 fragments unidentified hardwood charcoal	0.2	Acid-base-acid	-25†	Min - PD5, Max - PD4	10,000 \pm 75	11,510 \pm 320
PD-R14a	OS-85124	West	23.41, 5.46	1.5	S4	Soil sediment from S4 on scarp-colluvial unit 7	12-cm high, 8-cm wide sample area	Many fragments unidentified hardwood charcoal	0.6	Acid-base-acid	-25†	Max - PD1	3790 \pm 65	4180 \pm 220
PD-R14b	OS-87000	West	23.41, 5.46	1.5	S4	Soil sediment from S4 on scarp-colluvial unit 7	12-cm high, 8-cm wide sample area	Microcharcoal	10.2	Acid-base-acid	-28.89	Max - PD1	3790 \pm 40	4170 \pm 140
PD-R15	OS-84849	West	25.00, 3.40	3.1	S2	Soil sediment from S2 on scarp-colluvial unit 5	~22-cm wide, 7-cm high sample area	11 fragments unidentified hardwood charcoal	1.2	Acid-base-acid	-25.95	Max PD3/PD3b	9400 \pm 50	10,630 \pm 140
PD-R16	<i>Sample not dated</i>	West	26.0, 3.0 to 29.6, 2.0	3.5–2.8	S1	Shells from S1 and boulder-gravel unit 3; location not shown on log	-	Many gastropod shells	757	-	-	-	-	-

¹ National Ocean Sciences Accelerator Mass Spectrometry Facility, Woods Hole Oceanographic Institution (Woods Hole, Massachusetts).
² Station coordinates are horizontal and vertical meter marks along arbitrary reference grid for trench site (see plate 1).
³ See appendix A for descriptions of stratigraphic units.
⁴ Separation and identification by Paleo Research Institute (Golden, Colorado).
⁵ Measured delta ¹³C values. † Assumed value.
⁶ Min (max) indicates minimum (maximum) limiting time constraint for a surface-faulting earthquake (e.g., PD1).
⁷ Laboratory-reported radiocarbon age with one standard deviation uncertainty. B.P. is before present (AD 1950).
⁸ Mean calendar-calibrated age and two-sigma uncertainty, rounded to nearest decade, determined using OxCal calibration software (v. 4.1; Bronk Ramsey, 2009) and the IntCal09 atmospheric data set (Reimer and others, 2009).

APPENDIX D

SUMMARY OF LUMINESCENCE DATING, PENROSE DRIVE SITE

Sample No. ¹	Trench	Station ² (m)	Depth (m)	Unit Sampled ³	Material Sampled	Stratigraphic Position	Water Content ⁴ (%)	K ⁵ (ppm)	U ⁵ (ppm)	Th ⁵ (ppm)	Cosmic Dose Additions ⁶ (Gy/ka)	Total Dose Rate OSL ⁷ (IRSL) ⁸ (Gy/ka)	Equivalent Dose OSL ⁷ (IRSL) ⁸ (Gy)	n ⁹	Relation to Earthquake ¹⁰	Laboratory Age OSL ⁷ (IRSL) ⁸ ± 1σ (yr before 2010)
PD-L1	West	9.15, 9.40	1.0	1	Fine to medium sand laminae	Upper part of pre-Bonneville alluvial fan	1 (35)	1.42 ± 0.03	2.12 ± 0.08	4.60 ± 0.13	0.25 ± 0.02	2.37 ± 0.04 (3.36 ± 0.05)f	>180 (452 ± 9.04)	16 (20)	-	>76,990 ± 3920 (134,730 ± 6850)
PD-L2	West	10.11, 9.33	0.9	1	Fine sand laminae	Same stratigraphic position as L1	11 (38)	1.36 ± 0.03	2.18 ± 0.08	5.14 ± 0.13	0.25 ± 0.02	2.35 ± 0.04	163 ± 9.13	23 (24)	-	69,310 ± 4040
PD-L3	West	11.84, 9.35	0.6	1	Medium-fine sand lense	Similar stratigraphic position as L1 & L2	10 (31)	1.39 ± 0.03	2.10 ± 0.08	4.89 ± 0.13	0.25 ± 0.02	2.39 ± 0.04	154 ± 9.24	25 (25)	-	64,370 ± 3980
PD-L4	West	18.93, 7.66	0.5	1	Sandy gravel horizon	Slightly lower stratigraphic position than L1-L3	8 (37)	1.33 ± 0.03	1.80 ± 0.08	4.25 ± 0.12	0.26 ± 0.02	2.21 ± 0.04 (3.08 ± 0.05)f	130 ± 2.99 (680 ± 9.72)	24 (25)	-	58,790 ± 1700 (220,780 ± 9880)
PD-L5	West	28.24, 1.77	3.6	2	Bonneville silty sand	Immediately below boulder gravel (Provo stage)	12 (31)	1.61 ± 0.03	1.54 ± 0.07	5.22 ± 0.13	0.21 ± 0.01	2.48 ± 0.04	42.1 ± 1.56	25 (25)	Max - PD6	16,990 ± 680
PD-L6	West	30.96, 1.59	3.0	2	Bonneville silty sand	Immediately below boulder gravel (Provo stage)	10 (37)	1.60 ± 0.03	1.44 ± 0.07	4.95 ± 0.13	0.19 ± 0.01	2.38 ± 0.04 (3.24 ± 0.05)f	42.3 ± 2.98 (50.2 ± 0.60)	32 (33)	Max - PD6	17,770 ± 340 (15,490 ± 610)
PD-L7	East	7.10, 2.75	3.5	5	Scarp colluvium	Upper part of unit 5 colluvial wedge	14 (31)	1.22 ± 0.03	1.72 ± 0.07	3.72 ± 0.11	0.18 ± 0.01	2.00 ± 0.03 (2.83 ± 0.05)f	21.9 ± 1.14 (63.2 ± 1.92)	22 (25)	Max - PD3b/PD3, Min - PD4	10,950 ± 600 (22,340 ± 1560)
PD-L8	East	7.03, 3.52	2.7	6a	Scarp colluvium	Upper part of 6a colluvial wedge	9 (35)	1.30 ± 0.03	2.16 ± 0.08	5.41 ± 0.13	0.20 ± 0.01	2.27 ± 0.04	16.7 ± 0.97	18 (20)	Max - PD3a, Min - PD3b/PD3	7360 ± 440
PD-L9	East	5.88, 3.44	2.4	6b	Scarp colluvium	Upper-middle part of 6b colluvial wedge	10 (37)	1.40 ± 0.08	1.45 ± 0.11	5.00 ± 0.21	0.20 ± 0.01	2.21 ± 0.06	18.5 ± 0.91 (23.9 ± 0.51)	19 (20)	Max - PD2, Min - PD3a/PD3	8390 ± 640 (8140 ± 570)

¹ Analyses by U.S. Geological Survey Luminescence Dating Laboratory (Denver, Colorado).
² Station coordinates are horizontal and vertical meter marks along arbitrary reference grid for trench (see plate 1).
³ See appendix A for descriptions of stratigraphic units.
⁴ Field moisture; complete sample saturation percent in parentheses.
⁵ Analyses obtained using laboratory gamma spectrometry (high-resolution Ge detector) and readings are delayed after 21 days of being sealed in the planchet (used for dose rates).
⁶ Cosmic doses and attenuation with depth were calculated using the methods of Prescott and Hutton (1994); Gy – gray.
⁷ Dose rate and optically stimulated luminescence (OSL) age for fine-grained (90–125 microns) quartz sand; linear + exponential fit used on equivalent dose, single aliquot regeneration; ages rounded to nearest decade, errors to one sigma.
⁸ Dose rate and infrared stimulated luminescence (IRSL) age for fine grains (4–11 microns) of polymineral silt; exponential fit used for equivalent dose, multiple aliquot additive dose; ages rounded to nearest decade, errors to one sigma; fade tests indicate no correction.
⁹ Number of replicated equivalent dose (De) estimates used to calculate the mean; total number of measurements made, including failed runs with unusable data, in parentheses.
¹⁰ Min (max) indicates minimum (maximum) limiting time constraint for a surface-faulting earthquake (e.g., PD6).

APPENDIX E

OXCAL MODELS FOR THE SALT LAKE CITY SEGMENT

OxCal models for the Penrose Drive, Little Cottonwood Canyon, and South Fork Dry Creek (SFDC) sites were created using OxCal calibration and analysis software (version 4.1; Bronk Ramsey, 1995, 2001; using the IntCal09 calibration curve of Reimer and others, 2009). The models include *C_Date* for luminescence ages, *R_Date* for radiocarbon ages, and *Boundary* for undated events (paleoearthquakes). For the SFDC model, *Delta_R* accounts for the bulk-soil residence time following DuRoss and others (2011). These components are arranged into ordered sequences based on the relative stratigraphic positions of the samples. The sequences may contain *phases*, or groups where the relative stratigraphic ordering information for the individual radiocarbon ages is unknown. The models are presented here in reverse stratigraphic order, following the order in which the ages and events are evaluated in OxCal.

OxCal Input

Penrose Drive Version 4b – 7 Events (preferred)

```
Plot()
{
  Sequence("SLCS_Penrose_v4b_post_Bonneville.oxcal")
  {
    Boundary("start");
    Phase("Unit 2 - Bonn. silt")
    {
      C_Date("L6, 17.8+/-0.7 ka",-15760,340);
      C_Date("L5, 17.0+/-1.4 ka",-14980,680);
    };
    Boundary("P6");
    C_Date("Godsey et al., 2005", -13619,1360);
    Boundary("P5");
    Phase("Soil S1")
    {
      R_Date("R13, 10000+/-75",10000,75);
      R_Date("R1, 9940+/-65",9940,65);
      //R_Date("R2, 9390+/-45",9390,45);
      R_Date("R3, 9550+/-55",9550,55);
    };
    Boundary("P4");
    C_Date("L7, 11.0+/-1.2 ka",-8940,600);
    Phase("Soil S2")
    {
      R_Date("R15, 9400+/-50",9400,50);
      R_Date("R6a, 9350+/-50",9350,50);
    }
  }
}
```

```

R_Date("R6b, 8990+/-55",8990 ,55 );
};
Boundary("P3b");
C_Date("L8, 7.4+/-0.9 ka",-5350,440);
Boundary("P3a");
C_Combine("L9")
{
C_Date("R9-OSL, 8.4 ka", -6380, 640);
C_Date("R9-IRSL, 8.1 ka", -6130, 570);
};
Phase("Soil S3")
{
R_Date("R8, 5480+/-50", 5480, 50);
R_Date("R10a, 5800+/-75", 5800, 75);
R_Date("R10b, 5470+/-40", 5470, 40);
};
Boundary("P2");
Zero_Boundary("Unit 7");
Phase("Soil S4")
{
R_Date("R9b, 3960+/-45", 3960,45);
R_Date("R14a, 3790+/-65", 3790, 65);
R_Date("R14b, 3790+/-40", 3790, 40);
};
Boundary("P1");
Zero_Boundary("Unit 8");
Phase("Soil S5")
{
R_Date("R11, 490+/-35", 490,35);
R_Date("R12, 495+/-30", 495,30);
};
Boundary("Begin Historical Record",1847 AD);
};
};

```

Penrose Drive Version 4c – 6 Events

```

Plot()
{
Sequence("SLCS_Penrose_v4c_post_Bonneville.oxcal")
{
Boundary("start");
Phase("Unit 2 - Bonn. silt")
{
C_Date("L6, 17.8+/-0.7 ka",-15760,340);
C_Date("L5, 17.0+/-1.4 ka",-14980,680);

```

```

};
Boundary("P6");
C_Date("Godsey et al., 2005", -13619,1360);
Boundary("P5");
Phase("Soil S1")
{
  R_Date("R13, 10000+/-75",10000,75);
  R_Date("R1, 9940+/-65",9940,65);
  //R_Date("R2, 9390+/-45",9390,45);
  R_Date("R3, 9550+/-55",9550,55);
};
Boundary("P4");
C_Date("L7, 11.0+/-1.2 ka",-8940,600);
Phase("Soil S2")
{
  R_Date("R15, 9400+/-50",9400 ,50 );
  R_Date("R6a, 9350+/-50",9350 ,50 );
  R_Date("R6b, 8990+/-55",8990 ,55 );
};
Boundary("P3b");
C_Date("L8, 7.4+/-0.9 ka",-5350,440);
C_Combine("L9")
{
  C_Date("R9-OSL, 8.4 ka", -6380, 640);
  C_Date("R9-IRSL, 8.1 ka", -6130, 570);
};
Phase("Soil S3")
{
  R_Date("R8, 5480+/-50", 5480, 50);
  R_Date("R10a, 5800+/-75", 5800, 75);
  R_Date("R10b, 5470+/-40", 5470, 40);
};
Boundary("P2");
Zero_Boundary("Unit 7");
Phase("Soil S4")
{
  R_Date("R9b, 3960+/-45", 3960,45);
  R_Date("R14a, 3790+/-65", 3790, 65);
  R_Date("R14b, 3790+/-40", 3790, 40);
};
Boundary("P1");
Zero_Boundary("Unit 8");
Phase("Soil S5")
{
  R_Date("R11, 490+/-35", 490,35);
  R_Date("R12, 495+/-30", 495,30);
};

```



```

};
Boundary("Begin Historical Record",1847 AD);
};
};

```

Little Cottonwood Canyon

```

Plot()
{
Sequence("SLCS LCC ver . 4; ET predates Flood")
{
Boundary("Sequence start ");
R_Date("Bonneville reaches trench elev.", 16800, 250);
R_Date("Bonneville highstand", 15000, 250);
Boundary("ET");
R_Date("Bonneville Flood", 14500, 250);
(Boundary("ET"); –ET postdates Bonneville Flood in version 4b)
R_Date("C13; 5cACb5", 12150, 70);
R_Date("C26; 5cAC", 12160, 60);
Phase("Soil on upper 5c")
{
R_Date("C28; 5cAkb5", 11980, 50);
R_Date("C10; 5cAkb5", 10320, 60);
R_Date("C12; 5cAb5", 10260, 330);
R_Date("C3; 5cAb5", 9960, 50);
R_Date("C11; 5cAb5", 9540, 60);
R_Date("C1; 6btb4", 8680, 60);
};
Boundary("EU");
R_Date("C5; 7c lower", 8350, 50);
R_Date("C6; 7c upper", 8070, 50);
//ZB: Min age (C25) closer constraint on EV time
Zero_Boundary("V");
Boundary("EV");
R_Date("C25; W7fAb4", 6640, 180);
//ZB: Min age (C20) closer constraint on EW time
Zero_Boundary("W");
Boundary("EW");
R_Date("C20; E8Ab2", 4560, 40);
//ZB: Min ages (C19,C21) closer constraint on EX time
Zero_Boundary("X");
Boundary("EX");
R_Date("C21; E9bABb1", 3820, 120);
R_Date("C19; E9bAb1", 3000, 40);
R_Date("C24; W9Ab2", 2280, 40);
Boundary("EY");

```

```

//ZB: Max age (C24) closer constraint on EY time
Zero_Boundary("Y");
R_Date("C16; E10a", 1890, 80);
Phase("EY colluv./EZ fissure")
{
  R_Date("C26a; younger FF", 1570, 70);
  R_Date("C17; E10b", 1440, 70);
  R_Date("C23; W10Ab1", 1130, 70);
};
Boundary("EZ");
R_Date("C18; E11", 1540, 40);
C_Date("Historic constraint AD 1850", 1850, 5);
Boundary("Sequence end");
};
};

```

South Fork Dry Creek/Dry Gulch

```

Plot()
{
  Sequence("SLCS SFDC ver. 6f ")
  {
    Boundary("Sequence start ");
    Phase("Soil on fan deposits; DC-1, DC-2")
    {
      Delta_R("MRT-200yr1", 200, 200);
      R_Date("DC-1-R1", 5230, 160);
      R_Date("DC-1-R2", 4910, 200);
      R_Date("DC-2-R1", 4710, 180);
      Delta_R("MRT-0yr", 0, 100);
      R_Date("DC-1-R6", 4520, 120);
    };
    Boundary("EW");
    //ZB: Max ages closer constraint on EW time
    Zero_Boundary("W");
    Delta_R("MRT-150yr1", 150, 75);
    R_Date("DC2-2-R1", 3810, 180);
    Boundary("EX");
    Phase("post EX deposits; DC2-4")
    {
      Delta_R("MRT-300yr1", 300, 300);
      R_Date("DC2-4-R3", 3910, 140);
      R_Date("DC2-4-R4", 3760, 160);
    };
    Phase("Soil on fan - pre EY; DC2-5, DG")
    {

```

```

Delta_R("MRT-200yr2", 200, 200);
R_Date("DC2-5-R3", 3090, 120);
Delta_R("MRT-100yr2", 100, 50);
R_Date("APST-BS2", 2370, 140);
R_Date("APST-BS3", 2410, 120);
};
Boundary("EY");
//ages removed - stratigraphically out of place
#Delta_R("MRT-200yr", 200, 200);
#R_Date("DC2-5-R1", 2570, 140);
#R_Date("DC2-1-R1", 3000, 160);
//ZB: Max ages closer constraint on EY time
Zero_Boundary("Y");
Phase("soil on fan/colluvium pre EZ");
{
Delta_R("MRT-200yr3", 200, 200);
R_Date("DC-1-R4", 2310, 140);
R_Date("DC-1-R3", 1830, 160);
Delta_R("MRT-150yr2", 150, 150);
R_Date("DC2-1-R2", 1850, 120);
Delta_R("MRT-200yr4", 200, 200);
R_Date("DC-2-R3", 1640, 100);
Delta_R("MRT-100yr3", 100, 50);
R_Date("APST-BS1", 1770, 120);
R_Date("DC2-3-R2", 1420, 160);
//These ages removed as per discussion in Black et al.
#Delta_R("MRT-0yr", 0, 0);
#R_Date("DC-2-R2", 1170, 120);
#R_Date("DC-1-R5", 930, 120);
};
Boundary("EZ");
Phase("Post EZ deposits");
{
Delta_R("MRT-300yr2", 300, 300);
R_Date("DC2-4-R2", 1620, 100);
R_Date("DC2-2-R2", 1570, 120);
Delta_R("MRT-100yr5", 100, 50);
R_Date("DC2-3-R1", 1240, 140);
Delta_R("MRT-200yr5", 200, 200);
R_Date("DC2-3-R3", 1160, 160);
};
C_Date("Historic constraint AD 1850", 1850, 5);
Boundary("Sequence end");
};
};

```

Penrose Drive Version 4b (7 event model)	Unmodelled (BP)		Modelled (BP)		Agreement
	Mean	1s	Mean	1s	
Boundary start			18350	1090	
Phase Unit 2 - Bonn. silt					
C_Date L6, 17.8±0.7 ka	17710	340	17590	320	98.9
C_Date L5, 17.0±1.4 ka	16930	680	17240	530	103.4
Boundary P6			16480	960	
C_Date Godsey et al., 2005	15570	1360	14970	1100	104.3
Boundary P5			12080	810	
Phase Soil S1					
R_Date R13, 10000±75	11510	160	11460	140	103.7
R_Date R1, 9940±65	11410	130	11390	120	105.4
R_Date R3, 9550±55	10910	120	11000	100	99.1
Boundary P4			10870	120	
C_Date L7, 11.0±1.2 ka	10890	600	10750	100	135.5
Phase Soil S2					
R_Date R15, 9400±50	10630	70	10610	60	100.4
R_Date R6a, 9350±50	10570	70	10560	70	101.6
R_Date R6b, 8990±55	10120	100	10150	90	111.6
Boundary P3b			9700	560	
C_Date L8, 7.4±0.9 ka	7300	440	7820	360	72.4
Boundary P3a			7520	380	
C_Combine L9	8190	430	7330	350	32.3
Phase Soil S3					
R_Date R8, 5480±50	6280	60	6280	50	100.5
R_Date R10a, 5800±75	6600	90	6600	90	100.2
R_Date R10b, 5470±40	6270	40	6270	40	99.8
Boundary P2			5890	350	
Zero_Boundary Unit 7			4840	410	
Phase Soil S4					
R_Date R9b, 3960±45	4420	80	4380	80	86.4
R_Date R14a, 3790±65	4180	110	4210	100	104
R_Date R14b, 3790±40	4170	70	4190	70	98.5
Boundary P1			4000	260	
Zero_Boundary Unit 8			1770	870	
Phase Soil S5					
R_Date R11, 490±35	530	20	520	20	99.7
R_Date R12, 495±30	530	20	530	20	99.5
Boundary Historical Record, 1847	100	0	100	0	100

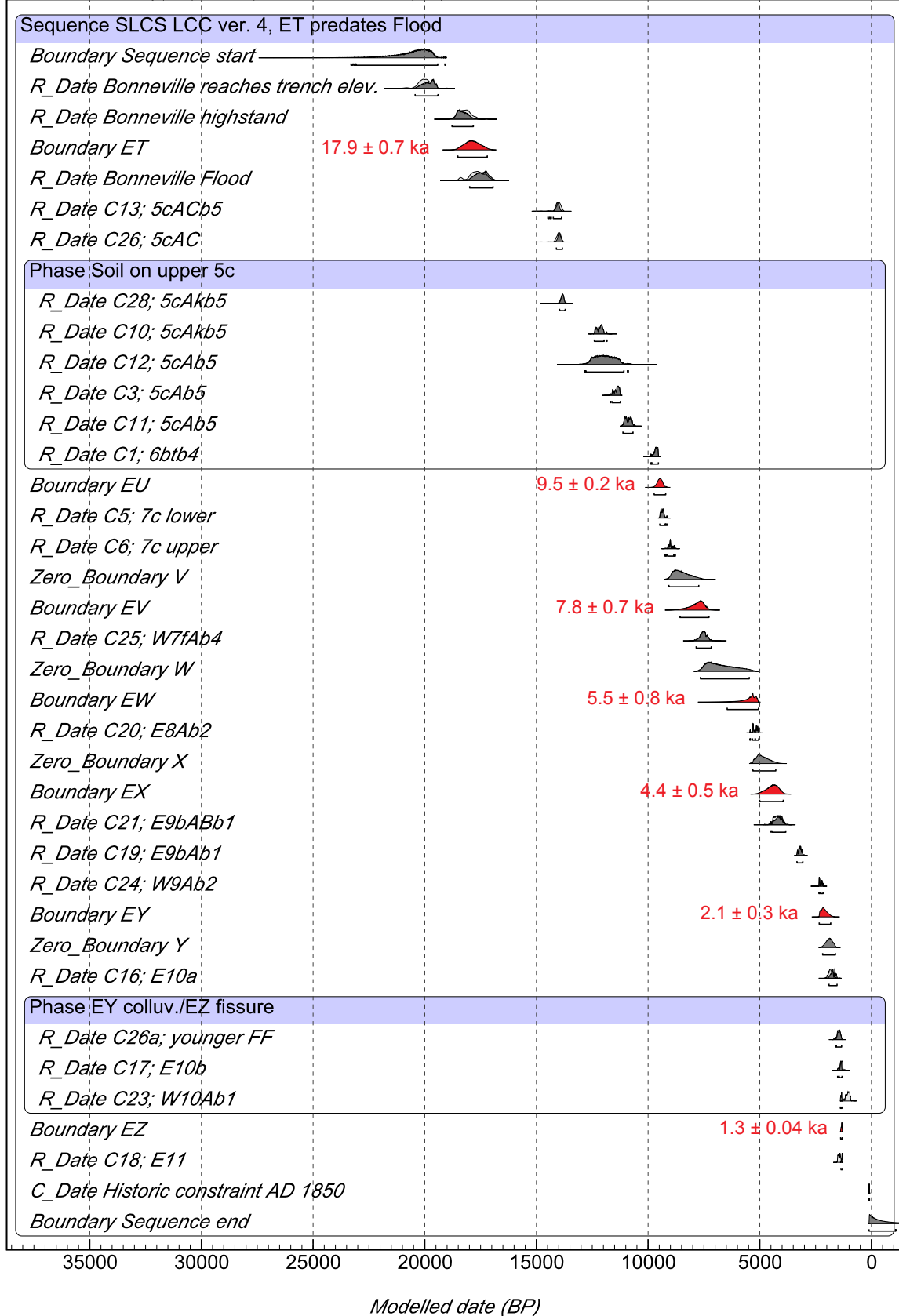
Penrose Drive Version 4c (6 event model)	Unmodelled (BP)		Modelled (BP)		Agreement
	Mean	1s	Mean	1s	
Boundary start			18420	1180	
Phase Unit 2 - Bonn. silt					
C_Date L6, 17.8±0.7 ka	17710	340	17600	330	99.1
C_Date L5, 17.0±1.4 ka	16930	680	17240	530	103.2
Boundary P6			16460	970	
C_Date Godsey et al., 2005	15570	1360	14960	1100	104.1
Boundary P5			12070	810	
Phase Soil S1					
R_Date R13, 10000±75	11510	160	11460	140	103.6
R_Date R1, 9940±65	11410	130	11390	120	105.7
R_Date R3, 9550±55	10910	120	11000	100	98.7
Boundary P4			10880	120	
C_Date L7, 11.0±1.2 ka	10890	600	10750	110	135.7
Phase Soil S2					
R_Date R15, 9400±50	10630	70	10610	60	100.7
R_Date R6a, 9350±50	10570	70	10560	70	101.5
R_Date R6b, 8990±55	10120	100	10140	90	107.4
Boundary P3			9370	770	
C_Date L8, 7.4±0.9 ka	7300	440	7860	340	67.7
C_Combine L9	8190	430	7600	330	61.1
Phase Soil S3					
R_Date R8, 5480±50	6280	60	6280	50	100.2
R_Date R10a, 5800±75	6600	90	6600	90	100
R_Date R10b, 5470±40	6270	40	6270	40	99.7
Boundary P2			5770	410	
Zero_Boundary Unit 7			4820	390	
Phase Soil S4					
R_Date R9b, 3960±45	4420	80	4380	80	85.7
R_Date R14a, 3790±65	4180	110	4210	90	104.1
R_Date R14b, 3790±40	4170	70	4190	70	98.5
Boundary P1			4010	250	
Zero_Boundary Unit 8			1770	870	
Phase Soil S5					
R_Date R11, 490±35	530	20	520	20	99.8
R_Date R12, 495±30	530	20	530	20	99.6
Boundary Historical Record, 1847	100	0	100	0	100

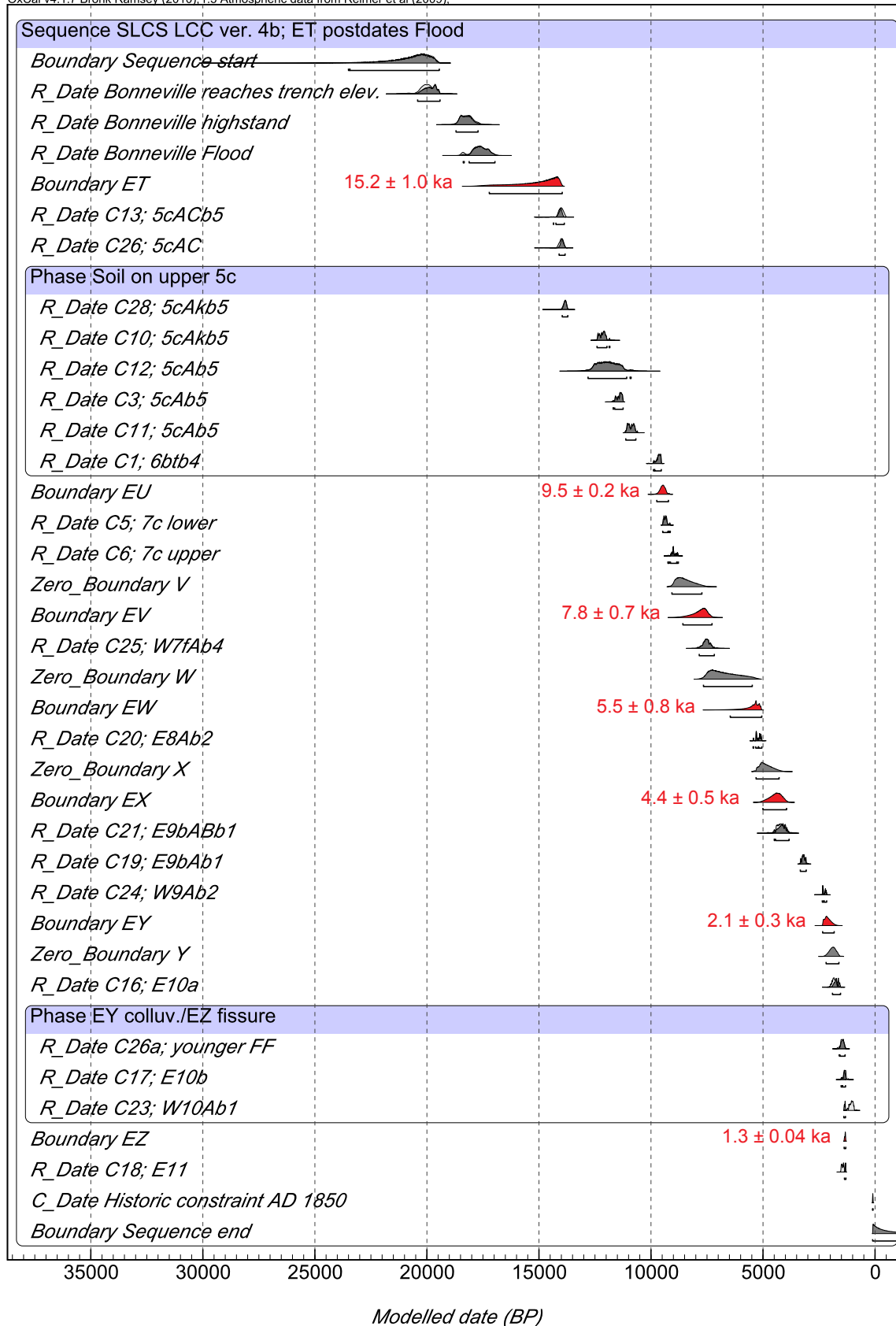
Little Cottonwood Canyon	Unmodelled (BP)		Modelled (BP)		Agreement
Version 4	Mean	1s	Mean	1s	
Boundary Sequence start			20720	1110	
R_Date Bonneville reaches trench elev.	19980	310	19840	290	99.2
R_Date Bonneville highstand	18210	280	18320	240	103.5
Boundary ET			17880	340	
R_Date Regression to Provo shoreline	17650	350	17460	280	100.1
R_Date C13; 5cACb5	14010	130	14080	140	93.2
R_Date C26; 5cAC	14010	110	13970	70	108
<hr/>					
<i>Version 4b</i>					
<i>Boundary Sequence start</i>			<i>20880</i>	<i>1200</i>	
<i>R_Date Bonneville reaches trench elev.</i>	<i>19980</i>	<i>310</i>	<i>19870</i>	<i>290</i>	<i>100.5</i>
<i>R_Date Bonneville highstand</i>	<i>18210</i>	<i>280</i>	<i>18250</i>	<i>250</i>	<i>103.4</i>
<i>R_Date Regression to Provo shoreline</i>	<i>17650</i>	<i>350</i>	<i>17600</i>	<i>310</i>	<i>105.2</i>
Boundary ET			15220	1000	
<i>R_Date C13; 5cACb5</i>	<i>14010</i>	<i>130</i>	<i>14070</i>	<i>120</i>	<i>97.3</i>
<i>R_Date C26; 5cAC</i>	<i>14010</i>	<i>110</i>	<i>13970</i>	<i>70</i>	<i>107.6</i>
<hr/>					
Version 4 (and 4b) continued					
Phase Soil on upper 5c					
R_Date C28; 5cAkb5	13840	70	13830	60	104.5
R_Date C10; 5cAkb5	12170	140	12170	140	100
R_Date C12; 5cAb5	11930	460	11940	460	100
R_Date C3; 5cAb5	11420	120	11420	120	100
R_Date C11; 5cAb5	10900	130	10900	130	99.9
R_Date C1; 6btb4	9660	90	9680	100	94.4
Boundary EU			9470	120	
R_Date C5; 7c lower	9360	70	9340	80	94.3
R_Date C6; 7c upper	8960	100	9010	100	101.4
Zero_Boundary V			8490	360	
Boundary EV			7830	330	
R_Date C25; W7fAb4	7530	160	7520	160	100.4
Zero_Boundary W			6720	610	
Boundary EW			5530	400	
R_Date C20; E8Ab2	5200	100	5210	100	99.4
Zero_Boundary X			4860	270	
Boundary EX			4440	270	
R_Date C21; E9bABb1	4220	170	4140	160	95.8
R_Date C19; E9bAb1	3200	70	3200	70	99.7
R_Date C24; W9Ab2	2270	60	2280	60	105.9
Boundary EY			2110	140	

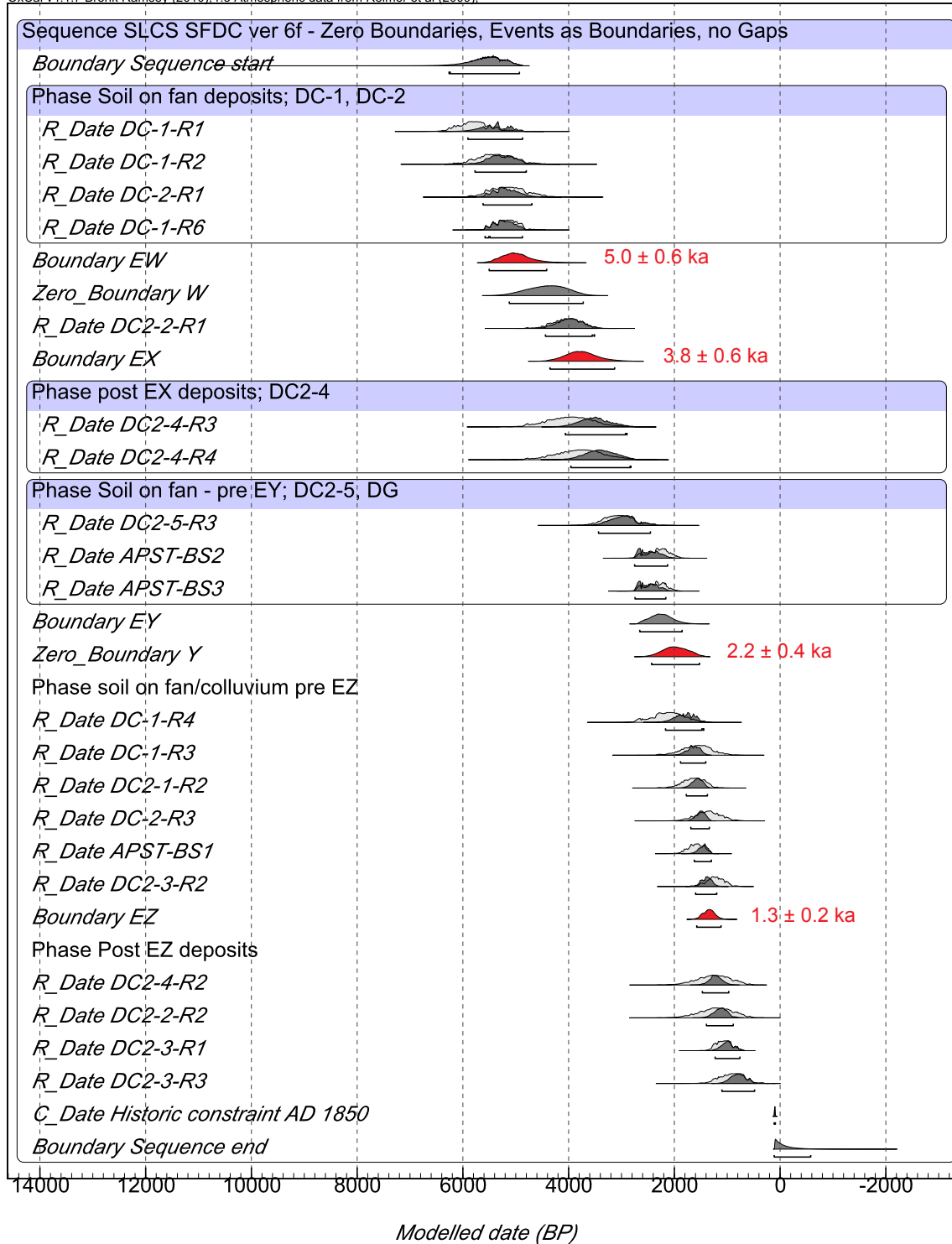
Zero_Boundary Y			1890	150	
R_Date C16; E10a	1830	100	1720	100	74.1
Phase EY colluv./EZ fissure					
R_Date C26a; younger FF	1470	70	1460	60	105.8
R_Date C17; E10b	1360	70	1390	50	92.1
R_Date C23; W10Ab1	1060	80	1350	20	
Boundary EZ			1340	20	
R_Date C18; E11	1440	50	1330	20	15.8
C_Date Historic constraint AD 1850	100	10	100	10	92.6
Boundary Sequence end			-310	350	

South Fork Dry Creek/Dry Gulch Version 6f	Unmodelled (BP)		Modelled (BP)		Agreement
	Mean	1s	Mean	1s	
Boundary Sequence start			5560	360	
Phase Soil on fan deposits; DC-1, DC-2					
Delta_R MRT-200yr1	200	200	333.386	162.56	94.7
R_Date DC-1-R1	5780	300	5410	270	65.6
R_Date DC-1-R2	5370	350	5270	250	109.4
R_Date DC-2-R1	5140	340	5190	240	115.3
Delta_R MRT-0yr	-1.82E-07	100	-8.88798	92.0309	104
R_Date DC-1-R6	5170	210	5220	190	102
Boundary EW			4980	280	
Zero_Boundary W			4410	360	
Delta_R MRT-150yr1	150	75	151.566	73.6144	100.9
R_Date DC2-2-R1	4020	270	3990	230	106.2
Boundary EX			3760	300	
Phase post EX deposits; DC2-4					
Delta_R MRT-300yr1	300	300	580.637	222.109	86
R_Date DC2-4-R3	3970	430	3510	290	81.1
R_Date DC2-4-R4	3780	440	3400	290	91.6
Phase Soil on fan - pre EY; DC2-5, DG					
Delta_R MRT-200yr2	200	200	250.972	178.804	104.5
R_Date DC2-5-R3	3050	280	2960	240	102.8
Delta_R MRT-100yr2	100	50	75.4261	49.7092	93.9
R_Date APST-BS2	2310	200	2470	180	86
R_Date APST-BS3	2360	190	2480	170	92.6
Boundary EY			2250	210	
Zero_Boundary Y			1980	230	
Phase soil on fan/colluvium pre EZ					
Delta_R MRT-200yr3	200	200	280.756	135.383	110.5
R_Date DC-1-R4	2110	300	1800	180	82.3
R_Date DC-1-R3	1580	280	1640	120	123.8
Delta_R MRT-150yr2	150	150	172.553	108.534	113.6
R_Date DC2-1-R2	1640	210	1570	100	121.5
Delta_R MRT-200yr4	200	200	66.1274	110.7	104.4
R_Date DC-2-R3	1360	240	1500	90	111.7
Delta_R MRT-100yr3	100	50	101.061	48.0054	102
R_Date APST-BS1	1590	140	1460	90	95.1
R_Date DC2-3-R2	1230	170	1390	100	82.4
Boundary EZ			1350	110	
Phase Post EZ deposits					
Delta_R MRT-300yr2	300	300	342.961	136.187	127.6
R_Date DC2-4-R2	1250	320	1220	120	131.6

R_Date DC2-2-R2	1210	320	1120	130	129.5
Delta_R MRT-100yr5	100	50	106.959	48.9048	100.6
R_Date DC2-3-R1	1060	150	990	120	102.1
Delta_R MRT-200yr5	200	200	271.902	169.895	105.1
R_Date DC2-3-R3	920	230	780	160	107
C_Date Historic constraint AD 1850	100	10	100	10	92.5
Boundary Sequence end			-100	230	







APPENDIX F

SUMMARY OF OXCAL MODELING RESULTS FOR THE SALT LAKE CITY SEGMENT

	Mean¹ (cal yr B.P.)	2σ¹ (yr)	RMS² (yr)	5th (cal yr B.P.)	50th (cal yr B.P.)	95th (cal yr B.P.)	Mode³ (cal yr B.P.)
Penrose Drive (PD)							
PD1	3998	497	260	3530	4070	4245	4095
PD2	5888	705	353	5135	6005	6250	6205
PD3	7515	760	381	6890	7515	8150	7520
PD4	9705	1113	559	8385	9910	10,185	10,155
PD5	10,866	239	119	10,675	10,870	11,055	10,920
PD6	12,081	1587	808	11,400	11,805	13,830	11,620
PD7	16,468	1912	964	14,580	16,680	17,655	17,140
Little Cottonwood Canyon (LCC)							
LCC1 (Z)	1339	39	19	1315	1340	1375	1325
LCC2 (Y)	2105	284	142	1845	2125	2310	2155
LCC3 (X)	4440	545	272	4035	4420	4935	4370
LCC4 (W)	5532	806	404	5130	5410	6410	5315
LCC5 (V)	7826	665	333	7380	7765	8480	7655
LCC6 (U)	9473	243	121	9285	9470	9680	9460
LCC7 (T) ⁴	16,547	3048	1525	14,175	17,285	18,325	17,915
South Fork Dry Creek (SFDC)							
SFDC1 (D)	1347	227	113	1165	1345	1530	1330
SFDC2 (C)	2247	414	207	1890	2255	2580	2300
SFDC3 (B)	3756	604	301	3230	3775	4230	3830
SFDC4 (A)	4984	548	275	4490	5010	5400	5050

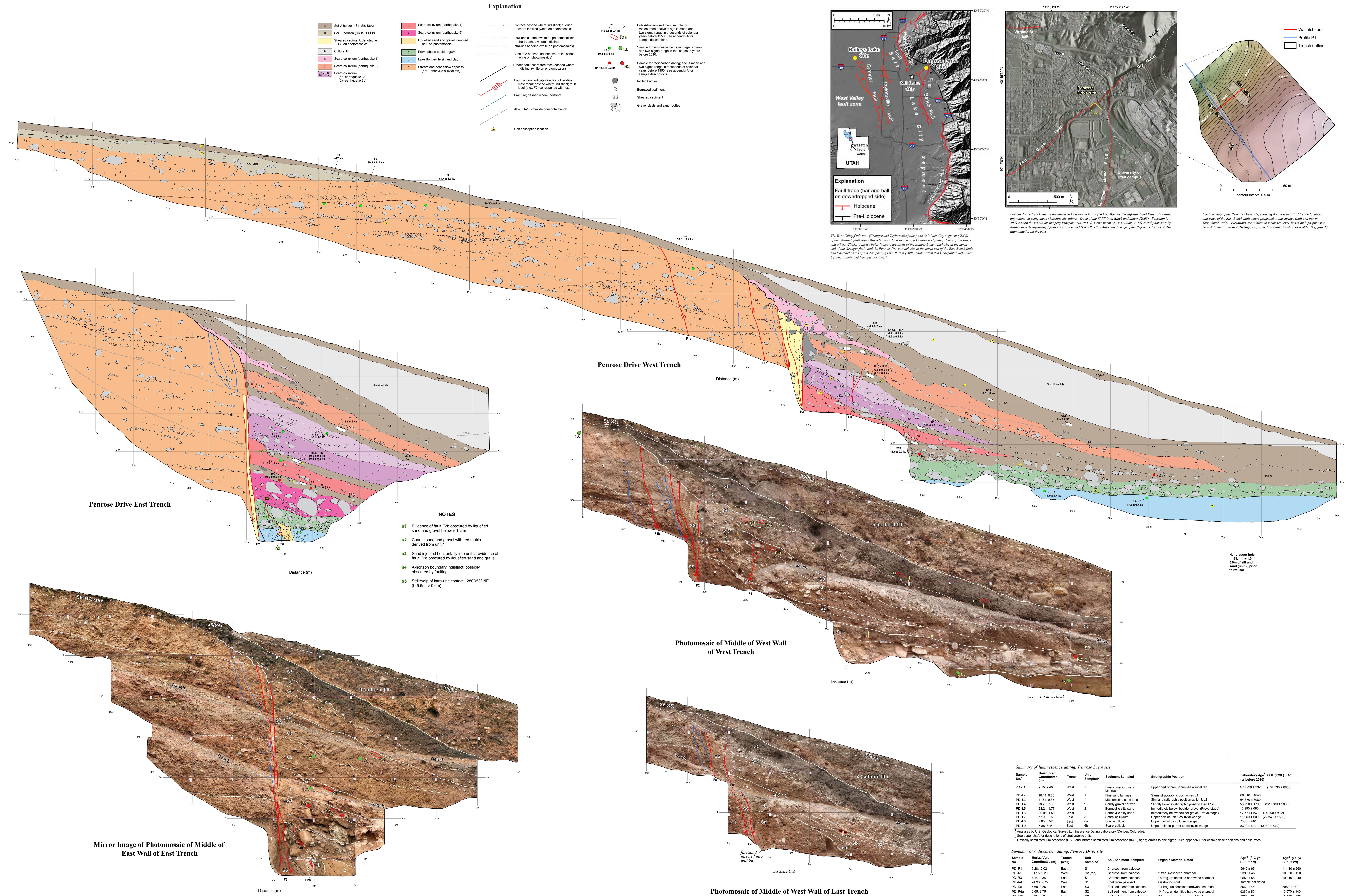
¹ Mean and two-sigma earthquake times based on exported probability density functions (PDFs) from the OxCal models (appendix E).

See DuRoss and others (2011) for discussion of methods.

² RMS is square root of the sum of the squared deviations from the mean, using the OxCal timing PDFs.

³ 5th, 50th, and 95th percent values and modal earthquake times are based on exported OxCal earthquake-timing PDFs.

⁴ LCC event T is based on the summed results of two separate OxCal models (see text for discussion).



Late Quaternary Paleoseismology of the West Valley Fault Zone—Insights from the Baileys Lake Trench Site

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Late Quaternary Paleoseismology of the West Valley Fault Zone—Insights from the Baileys Lake Trench Site

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Charles G. Oviatt, Shannon A. Mahan, Anthony J. Crone, and Stephen F. Personius*

ABSTRACT

The West Valley fault zone (WVFZ) and the Salt Lake City segment (SLCS) of the Wasatch fault zone comprise Holocene-active normal faults that bound an intrabasin graben in northern Salt Lake Valley, Utah, and have evidence of recurrent, large-magnitude ($M \sim 6-7$) surface-faulting earthquakes. Despite significant progress in our understanding of earthquake hazards along the Wasatch Front, outstanding research questions in Salt Lake Valley include the timing, displacement, and recurrence of Holocene earthquakes on the WVFZ and northern SLCS, and whether the WVFZ is seismically independent of, or moves coseismically with, the SLCS. To improve paleoseismic data for the WVFZ and better understand the seismogenic relation between the WVFZ and SLCS, we conducted a fault-trench investigation at the Baileys Lake site and compared earthquake timing and displacement data with data from the SLCS, including new data from the Penrose Drive site on the northern SLCS.

The Baileys Lake site is near the northern end of the westernmost traces of the WVFZ, collectively referred to as the Granger fault. At this site, we excavated three trenches across two small (<1 -m-high) east-facing fault scarps. At least four surface-faulting earthquakes postdate deposition of Lake Bonneville highstand clay at ~ 19 ka: earthquake BL4 occurred at 15.7 ± 3.4 ka (2σ), and was a sublacustrine event (Provo phase); BL3 occurred at 13.0 ± 1.1 ka, after Lake Bonneville's regression to very low levels and before transgression of the Gilbert-episode lake across the site; and BL2 and BL1 occurred at 12.3 ± 1.1 ka (during the Gilbert episode) and 5.5 ± 0.8 ka (post-Gilbert), respectively. Average per-event vertical displacement for the Granger fault at the Baileys Lake site is 0.5 ± 0.1 m. Combining the Baileys Lake data with previous paleoseismic data yields a paleoearthquake chronology comprising six late Quaternary earthquakes for the WVFZ as a whole (W1–W6): five on the Granger fault and one (W2) on the Taylorsville fault (eastern trace of the WVFZ). Mean recurrence over different time intervals ranges from 3.6 to 5.4 kyr for the Granger fault, and from 2.0 to 3.6 kyr for the WVFZ as a whole. The variability in recurrence intervals may result from differences in surface-faulting activity on the numerous strands that make up the fault zone, as well as from a paleo-

seismic record that is likely incomplete due to the small number of sites where earthquake timing has been documented.

Several WVFZ earthquakes have times that are similar to those of SLCS earthquakes. Specifically, the mean earthquake times and two-sigma ranges for WVFZ earthquakes W1, W2, W3, W4, and W6 are similar to those of SLCS earthquakes S1, S2, S4, S8, and S9, respectively. Earthquake W5 lacks a clear temporal association with a SLCS earthquake. However, W5 occurred in the latest Pleistocene (~ 13 ka), a period in which the SLCS record may be incomplete. Although earthquake-timing uncertainties preclude determining an unequivocal coseismic link between the WVFZ and SLCS, our results suggest that large earthquakes on the WVFZ that are coseismic with or triggered by fault movement on the SLCS have a higher likelihood than WVFZ earthquakes that occur completely independent of movement on the SLCS. When considered together with mechanical and geometric models of the fault system, the paleoseismic data support a high likelihood for synchronous rupture of the WVFZ with the SLCS.

INTRODUCTION

Purpose and Scope

The West Valley fault zone (WVFZ) and the Salt Lake City segment (SLCS) of the Wasatch fault zone comprise Holocene-active normal faults that together form an intrabasin graben in the northern part of Salt Lake Valley (figures 1, 2, and 3). These faults trend through the most densely populated part of Utah and have evidence of recurrent, large-magnitude ($M \sim 6-7$) surface-faulting earthquakes, but because of urbanization, have received limited paleoseismic study. At the time of this investigation there were significant questions regarding the paleoseismic histories of both faults, including (1) the timing of Holocene earthquakes on the WVFZ and northern SLCS (previous SLCS paleoseismic data were limited to the southern of three subsections of the fault segment), (2) the timing, recurrence, and displacement of mid-Holocene to latest Pleistocene earthquakes on both faults, and (3) whether the WVFZ is seismically independent of or ruptures coseismically with

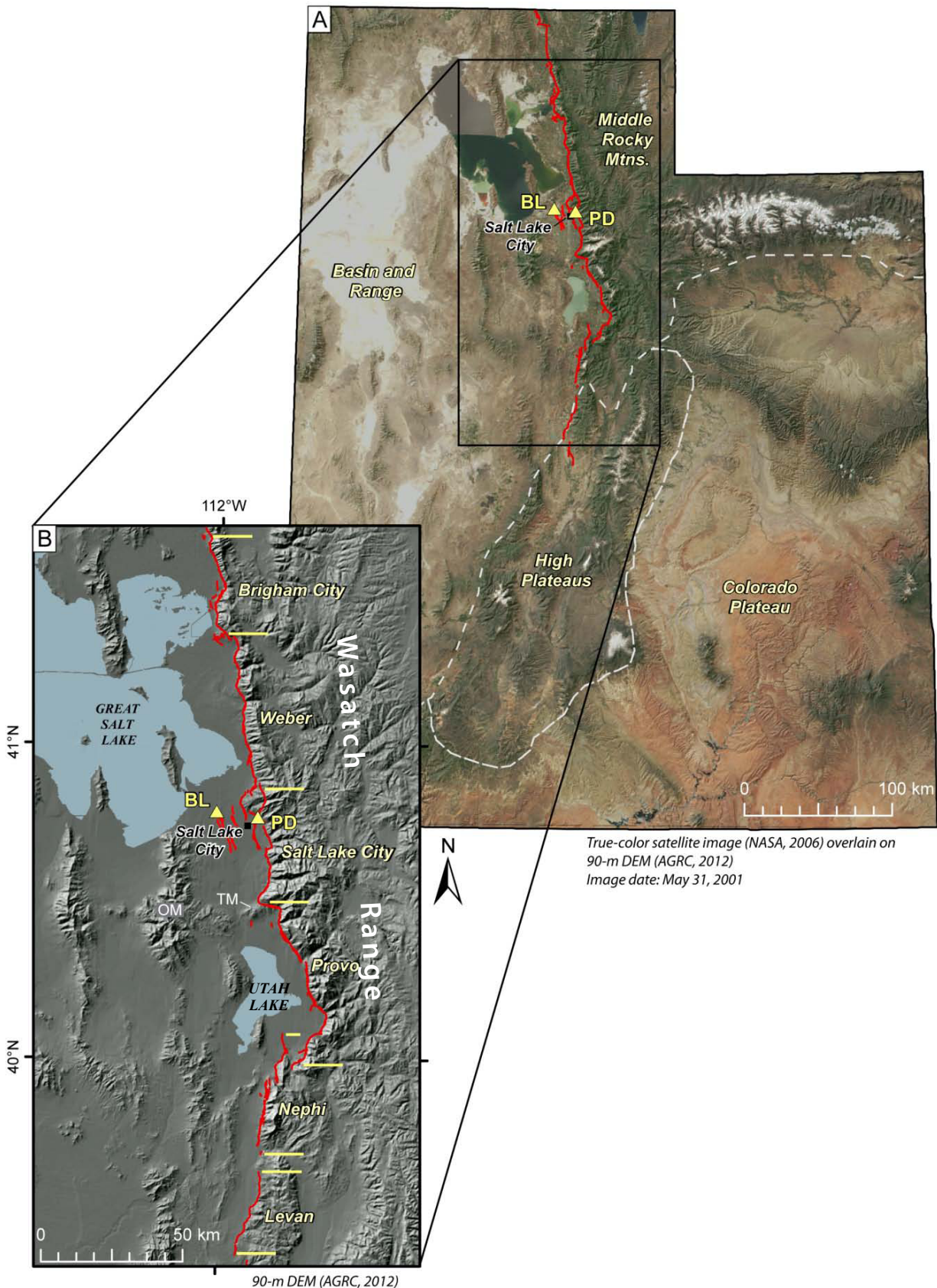


Figure 1. Regional setting of the Wasatch and West Valley fault zones. A. Physiographic provinces of Utah, and the Wasatch and West Valley fault zones (red lines). BL, Baileys Lake trench site on the West Valley fault zone (this study); PD, Penrose Drive trench site on the Wasatch fault zone (DuRoss and others, 2014). B. Central segments of the Wasatch fault zone, and West Valley fault zone west of the Salt Lake City segment, showing locations of the Baileys Lake and Penrose Drive trench sites. OM, Oquirrh Mountains; TM, Traverse Mountains. Fault traces from Black and others (2003).

the SLCS. Understanding these fault characteristics is necessary for quantifying the seismic hazard of the central Wasatch Front.

To improve the quality and resolution of paleoseismic data for the WVFZ and SLCS, as well as our understanding of the seismogenic relation between them, the Utah Geological Survey (UGS) and USGS conducted fault-trench investigations at two sites—one on the WVFZ (Baileys Lake site) and one on the SLCS (Penrose Drive site) (figures 2 and 3). These investigations included (1) detailed topographic and geologic mapping of the trench sites, (2) scarp profiling, (3) excavating five trenches—three at Baileys Lake and two at Penrose Drive, (4) mapping the trench-wall exposures in detail, (5) sampling organic remains and fine-grained detrital sediment for radiocarbon and luminescence dating, respectively, (6) developing probabilistic models of earthquake times using OxCal software, and (7) determining earthquake chronologies, vertical displacement, recurrence, and fault slip rate.

This report presents data and results from the Baileys Lake site. Data and results from the Penrose Drive site on the SLCS are presented in the companion report (DuRoss and others, 2014) in this UGS Special Study. These two reports supersede the initial release of the study results in a Final Technical Report to the USGS (DuRoss and Hylland, 2012). Together, the new data from the Baileys Lake and Penrose Drive sites improve our understanding of earthquake behavior and interaction on the WVFZ and SLCS, and ultimately allow for a more accurate assessment of earthquake probabilities and hazard for the central Wasatch Front.

Geologic Setting

Salt Lake Valley occupies one of several north-south trending grabens at the eastern margin of the actively extending Basin and Range Province. The Wasatch Range and Oquirrh Mountains bound the valley on the east and west, respectively; Great Salt Lake lies to the north, and the east-west trending Traverse Mountains separate Salt Lake Valley from Utah Valley to the south (figure 1). Two Quaternary geologic features that have been particularly important in producing the modern physiography of the region are the Wasatch fault zone and late Pleistocene Lake Bonneville.

The Wasatch fault zone is the longest active normal-slip fault in the western United States and the most active fault in Utah, forming the structural boundary between the actively extending Basin and Range Province and the relatively more stable Middle Rocky Mountain and Colorado Plateau provinces. Extending 350 km from southern Idaho to central Utah, the Wasatch fault zone comprises 10 segments, each of which is thought to be seismogenically independent (Swan and others, 1980; Schwartz and Copper-smith, 1984; Machette and others, 1992; Wheeler and Krysinik, 1992). The SLCS, one of the central five segments

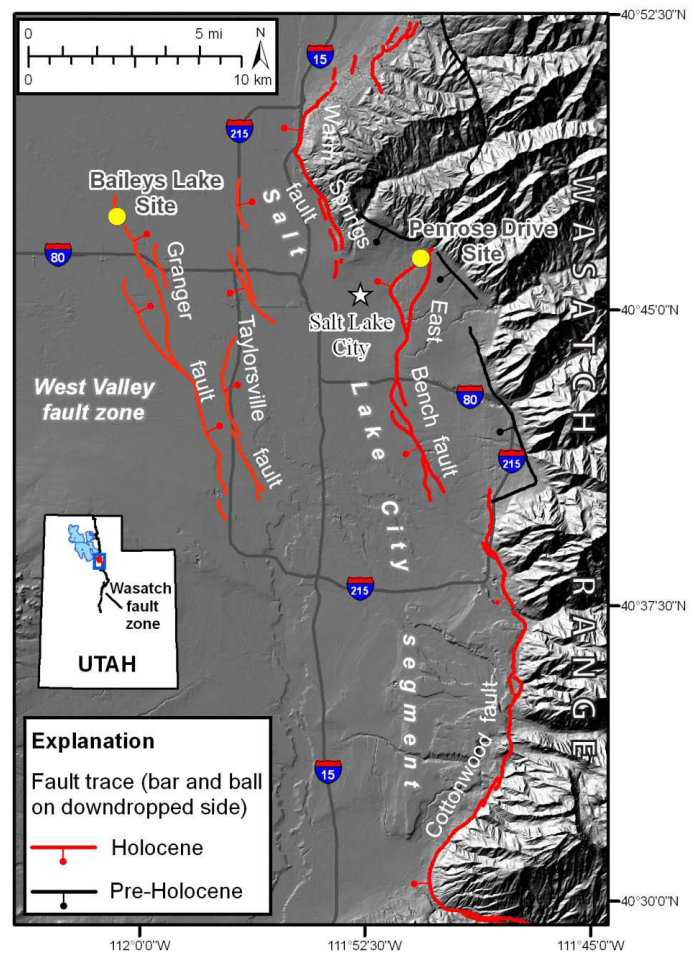


Figure 2. The West Valley fault zone comprises two strands on the floor of northern Salt Lake Valley: the Granger and Taylorsville faults. The Salt Lake City segment, one of the central, most active segments of the Wasatch fault zone, comprises three strands along the base of the Wasatch Range: the Warm Springs, East Bench, and Cottonwood faults. In 2010, the UGS conducted fault trenching studies at the Baileys Lake site at the north end of the Granger fault (this study), and also at the Penrose Drive site at the north end of the East Bench fault (DuRoss and others, 2014).

of the Wasatch fault zone that have evidence of repeated Holocene earthquakes (Machette and others, 1992), generally forms the eastern margin of Salt Lake Valley. Since the mid-Holocene (~6.5 ka), surface-faulting earthquakes on individual segments of the Wasatch fault zone have occurred on average every 1300–2500 years, and average vertical slip rates range from about 0.5 to 2.2 mm/yr (Machette and others, 1992; Friedrich and others, 2003; Lund, 2005).

Climatic conditions during the Pleistocene were conducive to the episodic formation of pluvial lakes in the eastern Great Basin, and Lake Bonneville was the most recent and largest of these (Gilbert, 1890). Details of Lake Bonneville's history are the subjects of ongoing research, but the general record of the rise and fall of the lake is well established. As summarized by Currey (1990) and Oviatt and others (1992) and recently updated by Godsey and others (2005, 2011), Oviatt and others

(2005), Benson and others (2011), and Miller and others (2013), the Bonneville lake cycle began around 30 ka. Over time, the lake rose and eventually reached its highest level at the Bonneville shoreline (~1550 m [5090 ft]) shortly before 18 ka. At the Bonneville highstand level, lake water overflowed the Bonneville basin threshold at Zenda in southeastern Idaho, spilling into the Snake–Columbia River drainage basin.

The Zenda threshold failed catastrophically at about 18 ka, resulting in a rapid drop in lake level of approximately 110 m during the Bonneville Flood (O'Connor, 1993). The lake level stabilized when erosional downcutting was impeded by a bedrock-controlled threshold at Red Rock Pass, about 2.5 km south of Zenda, or possibly about 9 km farther south near Swan Lake (Janecke and Oaks, 2011). Lake Bonneville remained at or near this level until about 15 or 16 ka (Godsey and others, 2005, 2011; Miller and others, 2013), forming the Provo shoreline (~1450 m [4760 ft]).

A climatic change to warmer and drier conditions caused the lake to regress rapidly from the Provo shoreline to near desiccation levels by the end of the Pleistocene (Eardley, 1962; Currey and others, 1988b; Currey, 1990). A small rise in lake level to an elevation of 1295 m (4250 ft) marked the Gilbert episode, which culminated around

11.6 ka (Oviatt and others, 2005; Oviatt, 2014), after which the lake regressed to near modern Great Salt Lake levels (historical average elevation 1280 m [4200 ft]). As a whole, the remarkable stratigraphic and geomorphic records of Lake Bonneville have proven extremely valuable in reconstructing paleoseismic histories of faults in the Bonneville basin, particularly along the central segments of the Wasatch fault zone.

On the floor of northern Salt Lake Valley, the WVFZ consists of intrabasin normal faults that span an area about 16 km long by 1–6 km wide (figure 2). The two subparallel, north-west-trending main traces of the fault zone and their associated subsidiary traces are known as the Granger fault (western traces) and Taylorsville fault (eastern traces). Both faults have scarps on post-Bonneville lake cycle (latest Pleistocene to Holocene) lacustrine and alluvial deposits, and previous paleoseismic studies have documented multiple Holocene surface-faulting earthquakes (Keaton and others, 1987; Keaton and Currey, 1989). The scarps are typically about 0.5–1.5 m high, but have a maximum height of 6 m near the southern end of the Granger fault. Scarps on the Granger fault face east, and scarps on the Taylorsville fault face both east and west. As a whole, the WVFZ is considered to be an antithetic structure to the west-dipping SLCS, with the SLCS acting as the master or controlling fault (figure 3).

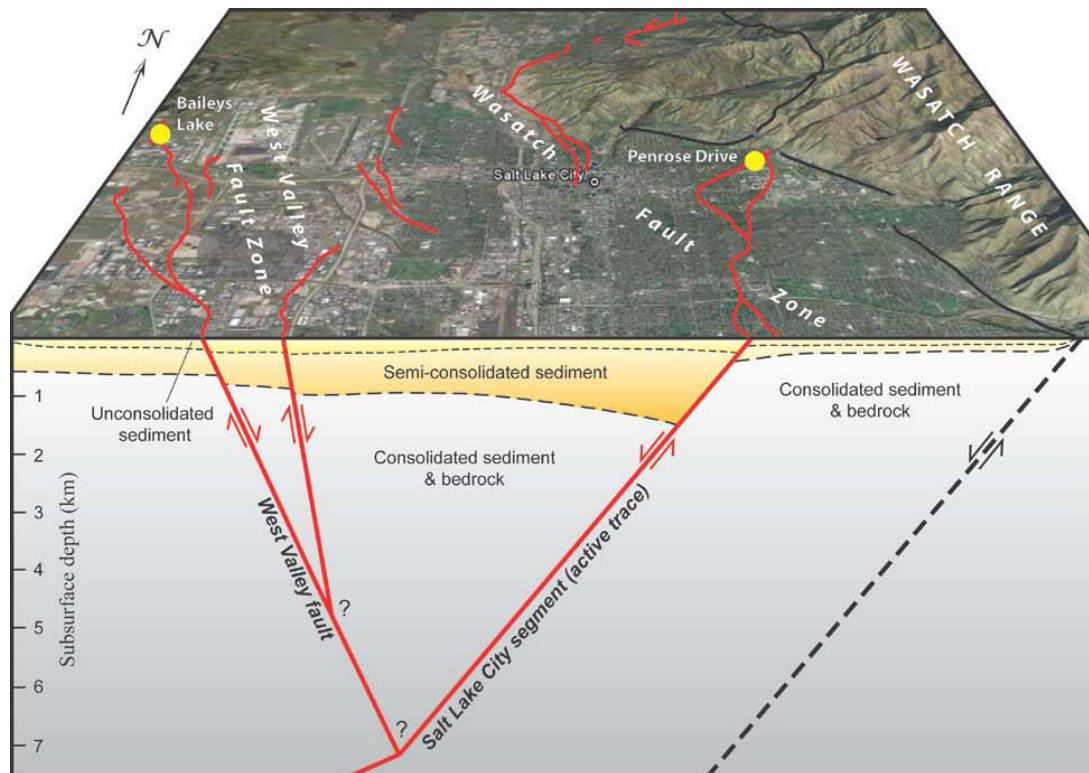


Figure 3. Generalized schematic diagram of likely subsurface geometry of the Wasatch–West Valley fault system, based largely on figure 1 of Bruhn and Schultz (1996). The West Valley fault zone is antithetic to the west-dipping Salt Lake City segment (master fault), forming an intrabasin graben in northern Salt Lake Valley. Mapped fault traces from Black and others (2003), superimposed on a Google Earth image. Map scale varies; no vertical exaggeration implied.

Previous Studies of the West Valley Fault Zone

Previous studies have constrained the long-term (140 kyr) cumulative displacement and slip rate for the WVFZ, but timing and displacement data for individual surface-faulting earthquakes have been lacking. Previous detailed paleoseismic investigations of the WVFZ include those of Keaton and others (1987) and Keaton and Currey (1989) (figure 4). On the Granger fault, Keaton and others (1987) investigated two sites on the southern part of the fault where they excavated two trenches, drilled 10 boreholes, and supplemented these data with 1:24,000-scale geomorphic mapping of key sites on both the Granger and Taylorsville faults. Their study also included thermoluminescence (four samples) and amino acid racemization (three samples) dating of mostly pre-Bonneville-cycle lacustrine deposits. In a follow-up study, Keaton and Currey (1989) drilled a total of 24 boreholes at three sites on the northern part of the Granger fault. The trenches revealed discrete, planar faulting, but yielded no individual earthquake timing data and only minimum values of per-event displacement. The boreholes indicated cumulative vertical displacements of 0.7–3 m offset on “post-Bonneville” (<12 ka) deposits, 5–7 m of offset on Bonneville lake-cycle deposits (12–28 ka), and 13–14 m of offset on a paleosol developed on Cutler Dam (pre-Bonneville) lake-cycle deposits (60 ± 20 ka). Significantly, Keaton and others (1987) found no evidence of differential displacements within Bonneville lake-cycle sediments in their boreholes near the south end

of the Granger fault, which they interpreted as indicating a period of tectonic quiescence on this part of the fault during Lake Bonneville time. On the Taylorsville fault, Keaton and others (1987) excavated four trenches at two locations near the middle and at the south end of the fault. These trenches showed evidence for mostly monoclinial folding with minor discrete faulting in near-surface sediments. At the site near the middle of the fault, Keaton and others (1987) determined that post-Gilbert deposits (<12 ka) were vertically offset 1.2–1.5 m by a single surface-faulting earthquake.

Two trenches excavated by consultants have yielded useful earthquake timing data for the WVFZ where the UGS was able to sample organic sediment for radiocarbon dating (figure 4). A trench on the Granger fault yielded a radiocarbon age that suggests a surface-faulting earthquake occurred around 1.4 ka (unpublished UGS data; appendix H), and a trench on the Taylorsville fault yielded radiocarbon ages that suggest a surface-faulting earthquake occurred around 2.2 ka (Solomon, 1998; appendix H). The dating results suggest a similarity in the times of these WVFZ earthquakes and the two most recent surface-faulting earthquakes on the SLCS (around 1.3 and 2.2 ka; see DuRoss and others, 2014). However, these trenches were open only briefly, precluding detailed logging, so the geologic context of the samples is not well defined. Because of this, as well as the nature of the radiocarbon ages (apparent mean residence time [AMRT] ages from bulk-soil

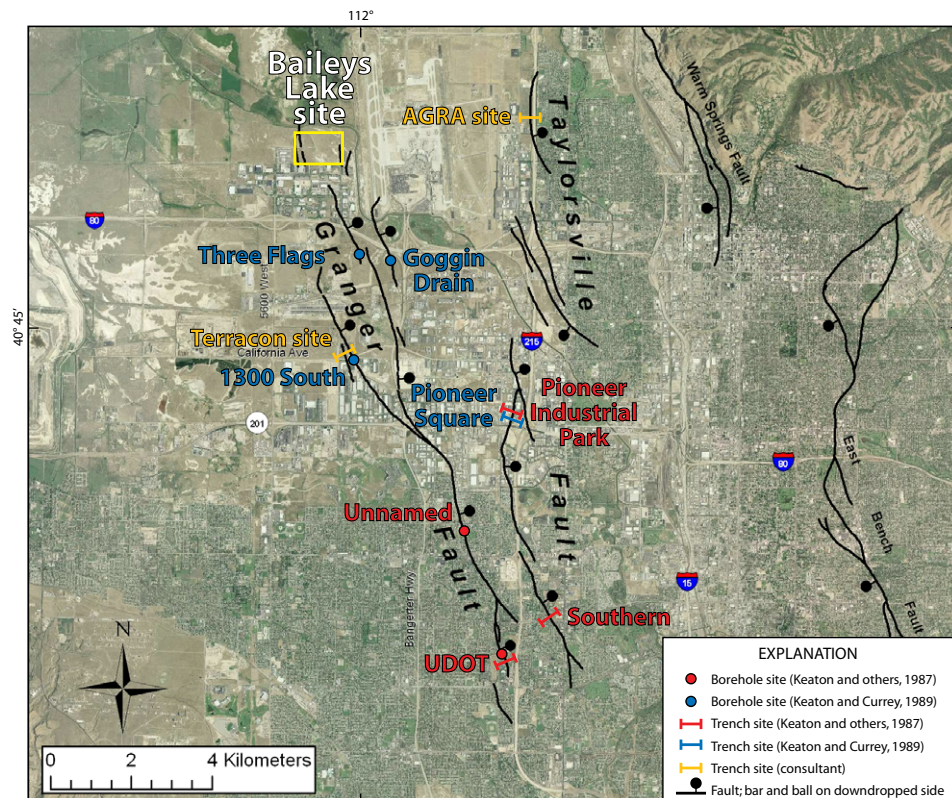


Figure 4. Locations of West Valley fault zone borehole and trench sites evaluated by paleoseismic investigations of Keaton and others (1987) and Keaton and Currey (1989), and the Baileys Lake trench site (this study; see figure 5). Also shown are locations of consultants' trenches that yielded earthquake timing information. Base is high-resolution (1 ft) orthophoto (2009; National Agriculture Imagery Program).

samples), relatively large uncertainty exists in the relation between the radiocarbon ages and earthquake timing.

OVERVIEW AND METHODS

Units of measurement in this report are generally in the metric (SI) system; however, we report shoreline elevations in terms of both meters and feet above mean sea level (AMSL) to facilitate their use with USGS 7.5-minute quadrangle maps. Elevations of shorelines near the Baileys Lake site have not been adjusted for isostatic rebound, as most or all of the rebound associated with the regression of Lake Bonneville would have taken place by the time these basin-floor shorelines formed (e.g., Oviatt and others, 1992; Miller and others, 2013). All ages in this report are in calendar-calibrated kilo-annum (thousand years; ka). Lastly, the rise and fall of lake water during the Gilbert episode has been variously assigned as the latest and lowest lake-level rise of Lake Bonneville (e.g., Oviatt, 1997; Oviatt and others, 2001) or the earliest and highest lake-level rise of Great Salt Lake (e.g., Currey, 1990; Oviatt and others, 1992, 2005). Herein, we follow the convention of Oviatt (2014) and consider the Gilbert to be a separate lake episode in the Bonneville basin—it was about 1500 yr younger than the post-Provo-shoreline regression of Lake Bonneville, but was higher and less saline than Holocene Great Salt Lake.

Trench Investigations

We identified potential trench sites using (1) fault-trace and surficial-geologic mapping by Keaton and others (1987), Keaton and Currey (1989), Personius and Scott (1992), and S.S. Olig (written communication, June 2008); (2) our interpretation of 1937 (Agricultural Stabilization and Conservation Service, 1937) and 1970s (low-sun-angle) aerial photographs (Cluff and others, 1970; included in Bowman and others, 2009) and 2006–2009 orthophotography from the National Agricultural Imagery Program (NAIP) (U.S. Department of Agriculture [USDA], 2012; Utah Automated Geographic Reference Center [AGRC], 2012); (3) 2006 1- and 2-m-posting LiDAR data for Salt Lake Valley (AGRC, 2012); and (4) our own field reconnaissance. Discussions and analyses of WVFZ and SLCS paleoseismic data by the Utah Quaternary Fault Parameters Working Group (UQFPWG; e.g., Lund, 2005, 2007) helped guide our decisions regarding trench-site locations. Of several possible sites on the WVFZ, we selected the Baileys Lake site as our preferred trench site because of the relatively undisturbed nature of fault scarps at the site, the potential to document evidence for earthquakes of different ages associated with two different scarps, and access considerations.

The Baileys Lake site, named for a nearby wetland area, is a 0.8-km² parcel of vacant Salt Lake City-owned land immediately west of the Salt Lake City International Airport and near the northern end of the mapped trace of the Granger fault. In the vicinity of the site, the Granger fault comprises four sub-parallel strands that offset fine-grained Lake Bonneville and

post-Bonneville deposits (figure 5; plate 1). However, scarps associated with the two easternmost strands are modified by human disturbance and post-faulting erosion and are in restricted and difficult-to-access areas, so we trenched only the two western traces. Although the Baileys Lake site is crossed by a drainage canal, power lines, natural gas and petroleum pipelines, and associated service roads, and has extensive areas of fill, significant portions of the two scarps that cross the site remain unmodified.

We excavated three trenches at the Baileys Lake site in September 2010 to expose fault-related sediments and document vertical displacement on the two traces of the Granger fault at the site. Two trenches crossed the westernmost scarp: a 44-m-long northern trench—designated the West(N) trench—and 10 m to the south, a 21-m-long, parallel, southern trench—designated the West(S) trench. The third trench—designated the East trench—was a 52-m-long trench excavated across the scarp about 0.5 km to the east of the two western trenches (figure 5). Because the site is on the floor of the Great Salt Lake basin, shallow groundwater was a logistical concern for trenching. For planning purposes, we installed two piezometers at the site and monitored groundwater levels on a monthly basis for a year prior to trenching (data available at http://geology.utah.gov/databases/groundwater/site.php?site_id=50). Maximum depth to groundwater ranged from 3.2 to 3.4 m below the ground surface. This depth is lower than typical historical groundwater levels in this area, and was likely a direct reflection of the low level of nearby Great Salt Lake. At the time of our trenching, Great Salt Lake was near its historical lowstand, having a surface elevation of approximately 1278 m based on USGS gage data (Utah Water Science Center: ut.water.usgs.gov/greatsaltlake/elevations/). Our piezometer data provided us with target depths to keep the trench floors above the potentiometric groundwater surface, and helped avoid trench flooding and caving problems. The West(N) trench was about 2 m deep whereas the West(S) trench was locally deepened to 3.3 m to maximize exposure of the fault zone. Shallow groundwater limited the depth of the East trench to 1.5 m.

We used a total station (Trimble TTS 500) to map the trench-wall exposures by measuring the positions of markers (e.g., nails and flagging) along the upper and lower limits of the trench wall and projecting those points to a vertical plane that represented the average orientation of the trench wall. The total station and averaged vertical plane were then used to set up a 1-m square grid on the trench wall, which we used as a reference grid to construct 1:20-scale photomosaics. The fine-grained nature of the exposed deposits and the fine detail visible on the photomosaics allowed us to map stratigraphic contacts and structure on clear acetate overlays using the photomosaics as a base. We mapped the north-facing wall of the West(S) trench, the entire north-facing wall and middle part (area of fault zone) of the south-facing wall of the West(N) trench, and the north-facing wall of the East trench. Plate 1 shows maps and photomosaics of the exposures with a single

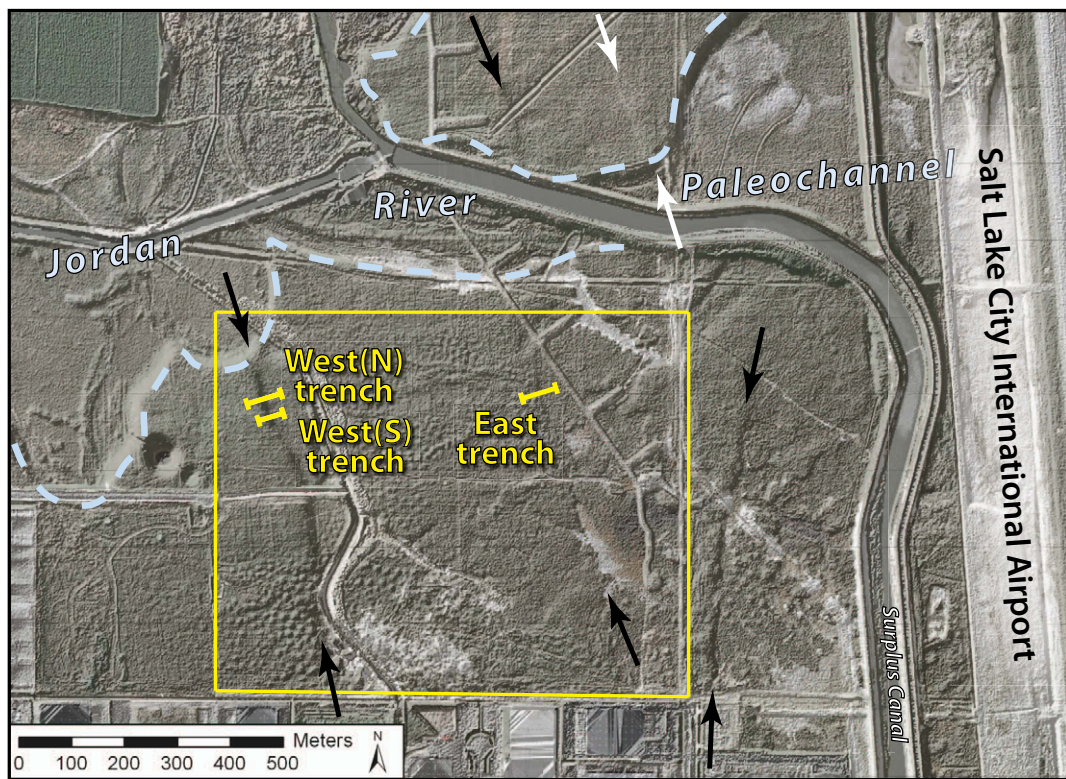


Figure 5. The Granger fault in the vicinity of the Baileys Lake site (yellow box) comprises three east-facing fault scarps (black arrows) and one west-facing scarp (white arrows). With the exception of the westernmost scarp, the fault scarps are geomorphically very subtle and have vertical offsets of just a few tens of centimeters. For this study, we trenched the two east-facing scarps that cross the site, excavating two trenches across the larger western scarp and one trench across the smaller eastern scarp. Base image is combined high-resolution (1 m) orthophoto (2009) and LiDAR data (2006, 2-m posting, illuminated from the northwest), both from Utah Automated Geographic Reference Center.

coordinate system for the West(N) and West(S) trenches and a different coordinate system for the East trench, referenced herein using horizontal (h-) and vertical (v-) meter marks. Stratigraphic units and pedogenic soils are described in appendices A and B and summarized on plate 1.

Numerical Dating

Radiocarbon Dating

We sampled lacustrine, wetland, and scarp-colluvial deposits as well as buried soil A-horizon sediment for radiocarbon (^{14}C) dating to estimate deposit and soil ages and provide limits on the timing of paleoearthquakes (appendices C and D). For discussions of common sources of uncertainty in radiocarbon dating and paleoseismic studies, see Trumbore (2000), Nelson and others (2006), and DuRoss and others (2011). At the Baileys Lake site, we collected bulk-sediment samples and dated (using accelerator mass spectrometry [AMS]) a total of seven charcoal samples consisting of discrete fragments separated from the bulk samples. The charcoal separation was conducted by PaleoResearch Institute (Golden, Colorado), who also attempted to identify the separated charcoal fragments to increase the likelihood of dating locally derived charcoal (e.g., phreatophytes) rather than non-local (detrital) charcoal (e.g., conifer species transported from the basin margins). Locally

derived charcoal fragments are more likely burned in-place or very near the location where they are sampled, and therefore are less likely to have an inherited, older age (Puseman and Cummings, 2005). Six of the seven charcoal samples from the Baileys Lake site only produced collections of small, unidentifiable charcoal fragments, and the seventh sample (BL-R5) lacked datable organic material (appendix C). The individual charcoal fragments from each bulk sample were combined into samples of at least ~0.5 mg, which then yielded composite charcoal ages.

We submitted the charcoal samples to the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) Facility of the Woods Hole Oceanographic Institution (Woods Hole, Massachusetts) for AMS radiocarbon dating. In our text discussions, the radiocarbon age results are reported as the mean and two-sigma (2σ) uncertainty rounded to the nearest century in thousands of calendar years before 1950 using the Reimer and others (2009) terrestrial calibration curve applied in OxCal calibration software (Bronk Ramsey, 1995, 2001, 2009).

Luminescence Dating

We collected 16 samples to estimate burial ages of lacustrine, loess, and paleosol sediment using optically stimulated lumi-

nescence (OSL) dating (appendix E). OSL dating relies on the cumulative dose of in situ natural radiation in sediment to estimate the time when the sediment was last exposed to sunlight during erosion and transport before final deposition (Huntley and others, 1985). Ideally, the sunlight exposure was sufficiently long (about 10 minutes) during erosion and transport to fully reset or “zero” any preexisting luminescence signal in the grains, and thus the luminescence age should represent the time when the sediment was deposited (Aitken, 1994). If the sediment’s exposure to sunlight was not long enough (e.g., because of rapid deposition, a short travel path, or filtered light in turbid water) to fully reset the luminescence signal, the sediment may retain an inherited signal (Forman and others, 1991; Duller, 2008) and OSL dating will produce an overestimated (maximum) age for the deposit. In contrast, underestimated (minimum) ages result if the luminescence signal becomes saturated, where the signal does not increase despite continued exposure of the sediment to radiation (Duller, 2008). Saturation results in a maximum age limit for OSL dating of ~75–300 ka, depending on the radiation dose rate and mineral dated (Rhodes, 2011).

Luminescence dating of the Baileys Lake samples included OSL ages on quartz grains (quartz OSL) as well as infrared-stimulated luminescence (IRSL) ages on feldspar grains, measured as a check of the OSL ages. We consider the quartz OSL ages to be more reliable because the IRSL signal takes longer to “zero” than the OSL signal—after sunlight-exposure times of about tens of seconds to minutes, there is a 1–2 order-of-magnitude difference in the remaining OSL and IRSL luminescence signals (Duller, 2008). However, OSL and IRSL ages that overlap within error limits provide an additional degree of confidence that partial bleaching (insufficient sunlight exposure) is not a problem in the sediments.

Our luminescence samples were processed at the USGS Luminescence Dating Laboratory (Denver, Colorado). A portable gamma-ray spectrometer was not available at the time of our field sampling, so background radiation from potassium, uranium, and thorium isotopes, as well as moisture content representative of field conditions, was measured in the laboratory. To correct for the amount of time the sediment was below the water table and thereby improve accuracy of the luminescence ages, we estimated a water-saturation history for the sampled sediment using the Lake Bonneville hydrograph of Oviatt (1997) and the Great Salt Lake hydrograph of Murchison (1989), adjusted using our groundwater monitoring data from the site (see discussion in Hylland and others, 2012). Appendix E presents the OSL ages as the mean and one-sigma uncertainty rounded to the nearest decade; where discussed in the text, however, the error is doubled (2σ rounded to the nearest century) for continuity with the calendar-calibrated radiocarbon ages and the modeling of earthquake times using OxCal. In discussing the OSL ages, we report the ages in thousands of calendar years before the sample processing date (2011) and do not adjust for the 61-year difference in

the processing date versus the reference standard for ^{14}C (1950); this difference is minor compared to the large OSL age uncertainties (generally about 1–5 kyr at 2σ), and is accounted for in OxCal modeling of earthquake times.

OxCal Modeling Methods

To evaluate earthquake timing and associated uncertainties, we used OxCal radiocarbon calibration and analysis software (version 4.1.7; Bronk Ramsey, 1995, 2001, 2009; using the IntCal09 calibration curve of Reimer and others, 2009). OxCal probabilistically models the timing of undated events (e.g., earthquakes) by weighting the time distributions of chronological constraints (e.g., radiocarbon and luminescence ages and historical constraints) included in a stratigraphic model (Bronk Ramsey, 2008). The program generates a probability density function (PDF) for each event in the model—i.e., the likelihood that an earthquake occurred at a particular time—using the chronologic and stratigraphic constraints and a Markov Chain Monte Carlo sampling method (Bronk Ramsey, 2008). For more detailed discussions of the application of OxCal modeling to paleoseismic data, see Lienkaemper and Bronk Ramsey (2009) and DuRoss and others (2011).

The OxCal depositional model for the Baileys Lake site (appendix G) uses stratigraphic ordering information, radiocarbon and OSL ages, and a historical constraint that no large surface-faulting earthquakes ($\geq M \sim 6.5$) have occurred since 1847, to define the time distributions of earthquakes identified at the site. We correlated depositional units between trenches and constructed a single OxCal model. Where necessary, we removed numerical-age outliers using geologic judgment (knowledge of sediments, soils, and sample contexts), the degree of inconsistency with other ages in the model for comparable deposits (e.g., stratigraphically inverted ages), and an agreement index between the original (unmodeled) and modeled numerical ages (Bronk Ramsey, 1995, 2008). Similarly, we constructed two additional OxCal models to determine earthquake times based on available radiocarbon ages from consultants’ trenches (appendix H). We report earthquake time ranges as the mean and two-sigma uncertainty in thousands of calendar years B.P. rounded to the nearest century.

Biostratigraphic Dating

In addition to the numerical dating described above, we used ostracode biostratigraphy to provide a relative temporal framework for the Lake Bonneville deposits at the Baileys Lake site. The taxonomic nomenclature used herein follows that of R.M. Forester (USGS), who with other researchers has identified faunal assemblages that are useful in stratigraphic correlation to the various phases of the well-documented Bonneville lake cycle (Spencer and oth-

ers, 1984; Forester, 1987; Thompson and others, 1990; see also Oviatt, 1991). Ostracode identifications and interpretations are summarized in appendix F.

BAILEYS LAKE TRENCH SITE

Surface Faulting and Geology

The Baileys Lake site is at the northern end of the Granger fault, and is crossed by two parallel scarps that trend about N. 10° W. and are about 0.5 km apart. The nearly flat site lies at an elevation of 1285 to 1288 m (figure 6), which coincides with the elevation of the Holocene highstand of Great Salt Lake (approximately 2–3 ka) as estimated by Currey and others (1988a; 1287 m [4221 ft]) and Murchison (1989; 1287 m [4223 ft]). However, we found no clear geomorphic or stratigraphic evidence of the Holocene highstand at this site (Hylland and others, 2011). The site is approximately 9 m below the elevation of the Gilbert shoreline at the Magna Spit (Currey, 1982; Murchison, 1989), which is about 8 km south of the Baileys Lake site. An east-west trending paleochannel of the Jordan River crosses the northern part of the site, and this channel was likely occupied around the time of the Holocene highstand of Great Salt Lake (Murchison, 1989) (figure 5). The active channel of the Jordan River has since migrated 6 km eastward, possibly due to tectonic tilting and subsidence associated with normal faulting along the SLCS (Keaton, 1987).

Geologic deposits at the Baileys Lake site consist of fine-grained lacustrine sediment of Lake Bonneville overlain by Holocene loess, playa clays, and minor sandy alluvium. Soils on these deposits are alkali to saline (Woodward and others, 1974). Miller (1980) mapped the surficial deposits in the vicinity of the Baileys Lake site as consisting mostly of fine-grained Holocene deltaic deposits; where present, these deposits may be associated with a “late Gilbert paleodelta” (Murchison, 1989). Eolian erosion of the fine-grained surficial deposits has locally created shallow topographic depressions, or deflation basins, which in turn become ephemeral ponds during periods of high water table and/or after rainstorms or snowmelt. Sandy, fine-grained alluvium is present on the floor of the Jordan River paleochannel where it crosses the site.

Granger Fault Scarps and Surface Offset

The two fault scarps that cross the Baileys Lake site are part of the distributed system of fault traces that characterize the northern half of the Granger fault. Both scarps are east facing. The larger western scarp has about 0.9 m of vertical surface offset based on projections of the upper and lower ground surfaces along a northeast-trending profile (figure 7). The Jordan River paleochannel truncates the western scarp, and the scarp does not continue immedi-

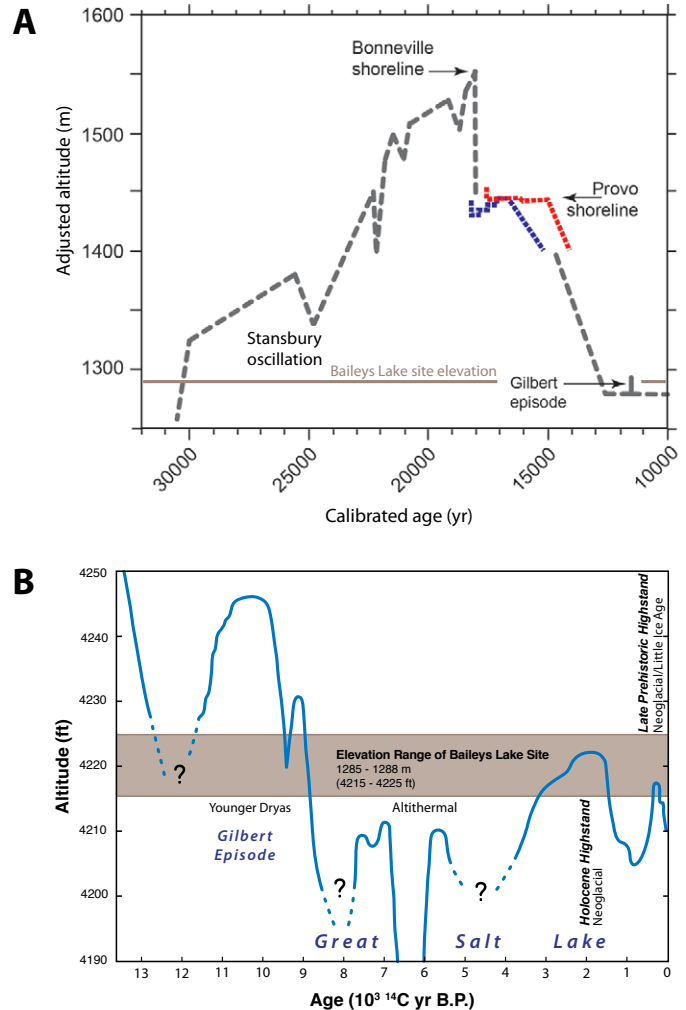


Figure 6. Lake Bonneville and Great Salt Lake hydrographs showing relation of water depth to elevation of the Baileys Lake site. **A.** Lake Bonneville hydrograph showing lake-level changes in the Bonneville basin since about 30 ka (modified from Reheis and others, in press). Altitudes adjusted for differential isostatic rebound. Red and blue lines are from Miller and others (2013) and indicate two datasets related to the Provo shoreline. **B.** Great Salt Lake hydrograph (from Murchison, 1989) showing lake-level changes in the Great Salt Lake basin since about 12 ka, and associated climate intervals and stadials (after Hylland and others, 2012). Although Murchison (1989) and Currey and others (1988a) estimated Great Salt Lake reached a level of about 1287 m (4221–4223 ft) in the late Holocene, we found no geomorphic or stratigraphic evidence of this late Holocene highstand at the Baileys Lake site. Also, data from the northeastern shore of Great Salt Lake indicate that the culmination of the Gilbert episode was relatively short-lived, possibly lasting just a few centuries at most (Oviatt and others, 2005; Oviatt, 2014).

ately north of the paleochannel. About 1.5 km to the northwest, however, several geomorphically subtle, east-facing scarps lie on-trend with the western scarp, and these are likely fault scarps as opposed to fluvial scarps (McKean and Hylland, 2013). Development in the Salt Lake International Center industrial area obscures the western scarp south of the Baileys Lake site, but pre-development aerial photography indicates the fault trace connects with the 0.5-

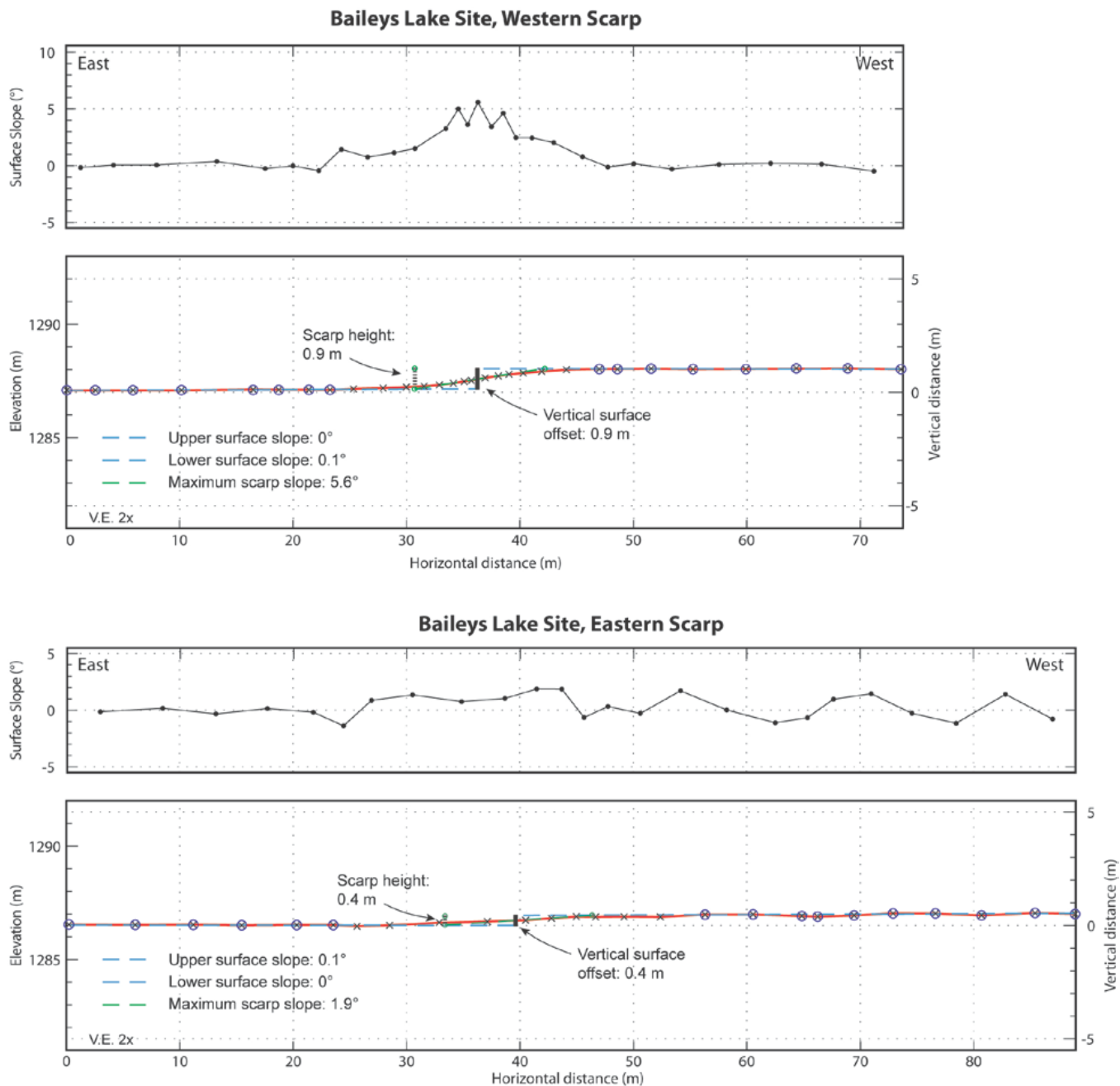


Figure 7. Scarp profiles and surface slope plots across the western and eastern fault scarps at the Baileys Lake site; profile locations shown on plate 1. Profile points (Xs) measured using high-precision GPS (August 31, 2010). Elevation is relative to mean sea level, vertical distance is relative to minimum surface elevation along each profile. Blue circles indicate profile points used to determine upper and lower surface slopes. Scarp height is the vertical distance between the intersections of the maximum scarp slope with the upper and lower surface-slope projections (green circles). Vertical exaggeration = 2x.

to 0.8-m-high, east-facing scarp at the Three Flags locality (see figure 4) of Keaton and Currey (1989) approximately 3 km to the south (McKean and Hylland, 2013). The smaller eastern scarp is geomorphically very subtle, and a northeast-trending scarp profile indicates about 0.4 m of vertical surface offset (figure 7). The northern continuation of the eastern scarp is locally obscured by service roads and a canal that occupies the Jordan River paleochannel (figure 5), but a short segment of this scarp is apparent immediately north of the canal. Development in

the Salt Lake International Center industrial area obscures the eastern scarp south of the Baileys Lake site.

As noted above, two other fault scarps lie near the eastern boundary of the Baileys Lake site (figure 5). We identified an extremely subtle scarp on the north side of the Jordan River paleochannel during our review of the LiDAR data. This scarp faces west, forming a graben with the eastern trenched scarp, and likely extended southward but was destroyed by the service road along the eastern boundary of

the Baileys Lake site (McKean and Hylland, 2013). The other scarp lies just east of the Baileys Lake site, is east facing, and has been modified by human disturbance and post-faulting erosion.

Trench Stratigraphy and Structure

Collectively, our three trenches at the Baileys Lake site exposed five distinct packages of sediment: (1) pre-Bonneville wetland/alluvial-marsh deposits, (2) Bonneville lacustrine deposits, (3) Gilbert-episode lacustrine deposits, (4) post-Gilbert loess, and (5) scarp-derived colluvium (colluvial wedges). The exposed stratigraphy correlates very well between the trenches, so we describe the stratigraphy for the site as a whole. The following stratigraphic discussion is modified from Hylland and others (2012). See plate 1 for maps and photomosaics of the exposed stratigraphy, and appendix A for descriptions of the stratigraphic units.

Pre-Bonneville Wetland/Alluvial-Marsh Deposits

We exposed pre-Bonneville deposits (unit 1) only in the footwall of the West(S) trench, where we excavated the trench to the maximum depth allowed by the water table. These deposits consist of massive to laminated, gray to brown clay with thin interbeds of white, fine-grained sand. The clay contains charophyte stem encrustations and decayed root filaments, *Scirpus*-type (bulrush) seed fragments, and fragmented and carbonate-coated ostracodes (*Candona rawsoni*). Numerous small fragments of oxidized clay scattered throughout the lower part of the exposure indicate local burrowing. Collectively, the sedimentology and organic material indicate deposition in a wetland or alluvial-marsh environment. Charcoal from the upper part of the unit yielded an age of 35.8 ± 0.8 ka (BL-R4).

Bonneville Lacustrine Deposits

A nearly complete section of Lake Bonneville deposits overlies the pre-Bonneville wetland/alluvial-marsh deposits (figure 8). The Lake Bonneville section at the Baileys Lake trench site is 2.5–4.0 m thick, similar to thicknesses of the Bonneville section measured in basin-floor outcrops elsewhere in the northern Bonneville basin (Oviatt and Miller, 1997), in nearby basin-floor boreholes (e.g., Eardley and others, 1973, as reinterpreted by Oviatt and others, 1999; Spencer and others, 1984; Balch and others, 2005; Oviatt and Thompson, 2005, and unpublished data), and as imaged in high-resolution lake-floor seismic-reflection profiles (Colman and others, 2002).

Transgressive phase: The basal part of the Lake Bonneville section consists of a 0.8-m-thick sequence of ripple-laminated, locally cross-bedded silty sand with clay interbeds (unit 2a). This unit contains gastropod shell fragments and ostracodes (*C. rawsoni*, *Limnocythere staplini*, and *Cytherissa lacustris*) and generally fines upward into a 0.5-m-thick bed of massive

greenish clay containing the ostracodes *L. staplini*, *L. ceriotuberosa*, and *Candona caudata*(?). The ostracode assemblage is consistent with the early transgressive phase of the Bonneville lake cycle (e.g., Spencer and others, 1984; Forester, 1987; Thompson and others, 1990), as are OSL ages ranging from 31.6 ± 3.3 ka (BL-L1) to 31.0 ± 3.9 ka (BL-L16).

The middle part of the Lake Bonneville section consists of 1.8 m of massive, gray to reddish-brown clay with thin interbeds of silt and fine sand (units 2b, 2c, 2d, and 2e). These sediments represent deep-water deposition during the transgressive phase of the Bonneville lake cycle. The sedimentary character of the silt and sand interbeds varies and likely results from both depositional and post-depositional processes. All of the interbeds have abrupt contacts with the enclosing clay, and some exhibit basal flame structures and numerous tabular clay clasts suspended in graded sand and silt. In some places, the clay clasts are isolated and are likely rip-up clasts transported and deposited with the sand and silt, and in other places groupings of clasts are subhorizontal and appear to be fragments of formerly intact clay stringers (figure 9). The sharp basal contacts, graded bedding, and possible rip-up clasts suggest sudden, rapid pulses of coarser-grained sedimentation in a depositional environment otherwise dominated by clay (i.e., quiet and/or deep water). We interpret the interbeds as turbidites associated with the episodic influx of silt and sand; possible mechanisms of turbidite deposition include strong flood-stage river discharge, delta-front slumping, and destabilization of lake-margin deposits by lake-level fluctuations or earthquakes. Similar interbeds within the deep-water Bonneville clays elsewhere in the Bonneville basin have also been interpreted as turbidites (e.g., Oviatt and others, 2005). The thickest interbed at the Baileys Lake site (20 cm; unit 2d) is also the most sand rich, and is a composite interbed containing disrupted (disturbed, but not transported) clay stringers. We attribute the bedding disruption to fluidization as the result of earthquake-induced liquefaction.

The clay beds of the middle part of the Lake Bonneville section contain the ostracodes *L. staplini*, *L. ceriotuberosa*, *C. caudata*(?), and *C. adunca*, and the assemblage in the uppermost part of the section (unit 2e) is consistent with the mid- to late-transgressive phase of the Bonneville lake cycle (e.g., Spencer and others, 1984; Forester, 1987; Thompson and others, 1990). The silt interbeds yielded OSL ages ranging from 24.4 ± 5.0 ka (BL-L3) at the base of unit 2c to 19.3 ± 0.8 ka (BL-L7) in unit 2e.

The top of the deep-water clay sequence (top of unit 2e) is marked by a nearly planar contact (figure 10) that is overlain by a thin (generally <2 cm), fine-grained breccia layer consisting of sand and small (<1 mm thick) carbonate fragments; for logging purposes, this breccia layer is included as the basal part of unit 3. Beneath the contact, unit 2e displays open, upright folds, the tops of which are truncated at the contact; we observed this relation in both the western and eastern trenches. We hypothesize that the folding and truncation were

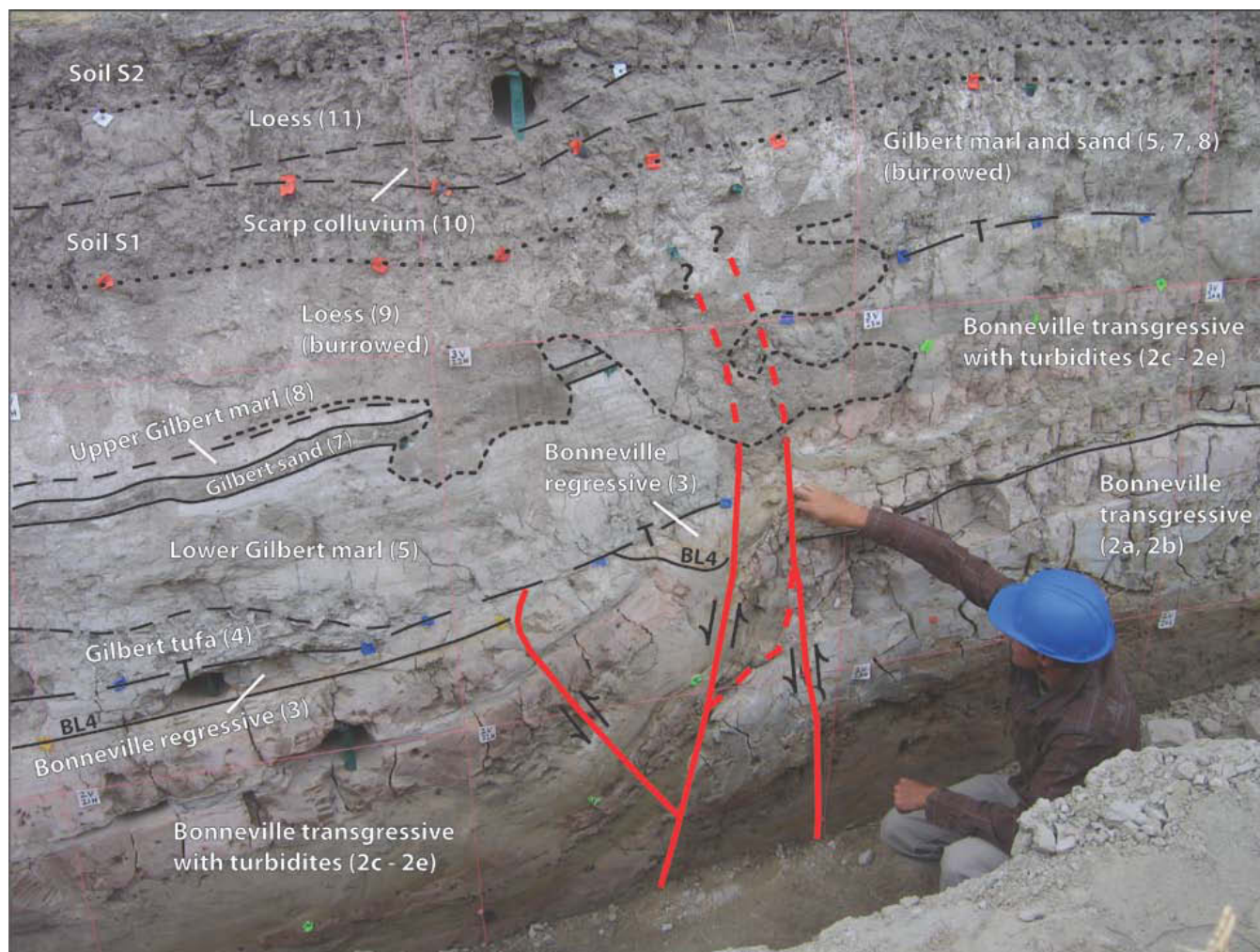


Figure 8. Fault-zone exposure in the south wall of the Baileys Lake West(N) trench, showing nearly complete Lake Bonneville section (see Hylland and others, 2012). Unit numbers given in parentheses; see appendix A for unit descriptions and appendix B for descriptions of pedogenic soils. We interpret contact labeled “BL4” as an event horizon associated with earthquake BL4 (see “Chronology of Surface-Faulting Earthquakes” section in text). T indicates erosional unconformity with overlying (mostly very thin) tufa deposit; in the fault footwall, this unconformity has removed Bonneville regressive deposits (unit 3) as well as the BL4 event horizon. Upper two dotted lines mark base of the exposure. Grid-line spacing is 1 m.

nearly contemporaneous and associated with a single earthquake on the Granger fault—the folding resulting from disturbance of the lake-floor deposits by strong ground shaking during earthquake BL4 (see “Chronology of Surface-Faulting Earthquakes” below), and the truncation occurring immediately after the earthquake and resulting from subaqueous erosion associated with strong lake-bottom currents triggered by fault-related offset of the lake floor. Also at the top of unit 2e, vertical fractures penetrate downward to about 10 cm below the upper contact, and the reddish-brown clay of unit 2e has been chemically reduced to a greenish-gray color in the vicinity of the fractures (figure 10). Many of these fractures extend upward through the overlying Bonneville regressive deposits (unit 3). Hylland and others (2012) interpreted the fractures to be desiccation cracks that formed after the regressive phase of Lake Bonneville, when the sediment column dried out during the lake’s lowstand prior to the Gilbert transgression.

Regressive phase: The transgressive, deep-water clay sequence is overlain by finely laminated, greenish clay with silt and sand (unit 3) (figures 10 and 11). This unit averages about 40 cm thick but ranges from 2 to 60 cm thick, the variability resulting from an overlying erosional unconformity (discussed below under “Gilbert-Episode Deposits”). Ostracodes in this unit include *L. ceriotuberosa*, *C. caudata*(?), *C. adunca*, and *C. lacustris*; many are broken and unidentifiable fragments, suggesting reworking from older deposits. This assemblage indicates deposition during the regressive phase of the Bonneville lake cycle, while the Provo shoreline was forming or during the immediate post-Provo regressive phase (very early in the post-Provo regressive phase of the lake) (e.g., Oviatt and Miller, 1997). OSL ages of 14.1 ± 1.6 ka (BL-L8) and 13.0 ± 1.2 ka (BL-L9) likewise indicate deposition during late Provo-shoreline time and/or during the post-Provo regressive phase.

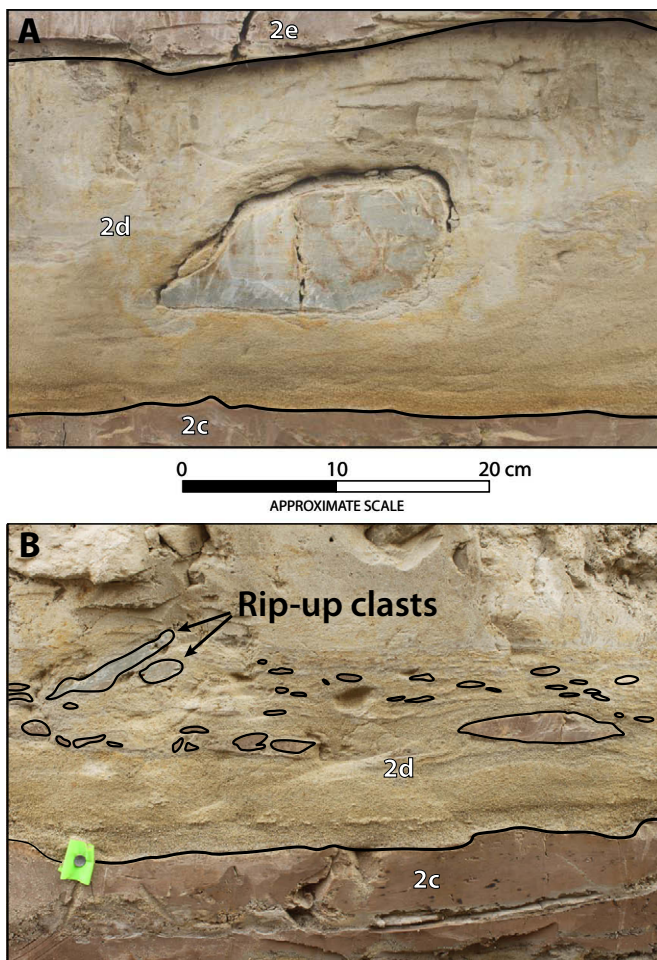


Figure 9. Sedimentology of the thickest and most sand-rich turbidite interbed (unit 2d) within the deep-water transgressive Bonneville clays exposed in the Baileys Lake trenches. **A.** Greenish-gray clay rip-up clast suspended in sand and silt matrix, exposed in the south wall of the West(N) trench (h-20.2 m, v-1.5 m). Turbidite bed grades from medium sand at the base to silt at the top. **B.** Greenish-gray rip-up clasts (transported) and disrupted reddish-brown clay stringers (disturbed, but not transported) suspended in sand and silt matrix, exposed in the south wall of the West(S) trench (h-23.4 m, v-1.5 m); clast boundaries outlined to highlight shape and orientation.

Gilbert-Episode Deposits

The Bonneville regressive deposits are overlain by a sequence of lacustrine deposits comprising, from bottom to top, a layer consisting mostly of tufa (unit 4), a laminated marl (unit 5), a thin bed of dark-gray sand (unit 7), and an upper, thin bed of laminated marl (unit 8) (figure 11). The tufa layer, which also includes clay, silt, and fine to coarse sand, consists mostly of a “hash” of broken (reworked) tufa fragments, but locally the tufa comprises intact, in situ pods or “mats” as much as several tens of centimeters thick. The tufa was deposited on an undulating unconformity; laminae in the silty clay beneath the unconformity are cut by the unconformity, whereas laminae in the marl above the tufa conformably drape the underlying topography. In the western trenches, the unconformity

cuts down-section only into unit 3 on the hanging wall of the fault, but it has completely stripped unit 3 and most of unit 2e from the footwall. The tufa is present in all of the trenches, indicating persistence across the site. We interpret the tufa as having formed in the shorezone when lake water transgressed across the site during the Gilbert episode; the shorezone must have remained at the elevation of the tufa deposit (approximately 1286–1287 m [4219–4222 ft]) for a sufficient duration to allow accumulation of precipitated calcium carbonate. Alternatively, the tufa deposition may be related to spring flow immediately prior to the Gilbert transgression (Hylland and others, 2012).

Carbonate-rich, laminated clay and silt (marl; unit 5) conformably overlies the tufa. The laminated marl was deposited during the Gilbert episode based on the presence of unidentifiable, carbonate-coated ostracode fragments (reworked) and an OSL age of 12.5 ± 1.8 ka (BL-L13). The marl is in turn overlain by a distinctive, thin (<10 cm), dark-gray, medium to coarse sand composed predominantly of subangular quartz grains (unit 7; figure 11). The sand is massive to thinly bedded, has an abrupt lower contact with the underlying marl, and locally comprises one or more graded beds. The sand is present in all of the trenches, although it generally thins westward and is difficult to identify on the footwall side of the western trenches. In the East trench, the sand grades laterally to silt in the western part of the trench (facies change at h-38; plate 1). The sand yielded an OSL age of 11.5 ± 5.2 ka (BL-L14) (the large uncertainty in the age results from a relatively small number of aliquots measured). A <15-cm-thick unit of carbonate-rich, finely laminated clay and silt (marl; unit 8) overlies the dark sand, and is very similar to the marl that underlies the sand.

The OSL age of the unit 7 sand, its stratigraphic position between two lacustrine marls, and its abrupt lower contact indicate that the sand likely formed in a shorezone that crossed the site during a second transgression of the Gilbert episode (Hylland and others, 2012), similar to the double transgression interpreted by Oviatt and others (2005) in Gilbert-age deposits on the northeastern shore of Great Salt Lake (Public Shooting Grounds site). The thin lacustrine marl (unit 8) overlying the shorezone sand appears to represent deeper-water deposition during higher levels of the Gilbert episode, which culminated at about 11.6 ka (Oviatt and others, 2005; Oviatt, 2014).

Post-Gilbert Loess

The Gilbert lacustrine sequence is overlain primarily by deposits of massive silt and clay (loess; units 9 and 11) (figure 8) that have a cumulative thickness of 0.4–1.0 m. The lower loess (unit 9) has a moderate degree of soil carbonate development (up to stage II; after Machette [1985] and Birkeland and others [1991]). A soil A horizon (soil unit S2) is developed in the top of the upper loess (unit 11) at the modern ground surface, and a buried paleosol with blocky to prismatic structure (weakly developed Bt horizon; soil unit S1) was evident in the western trench exposures about 0.4 m below the ground

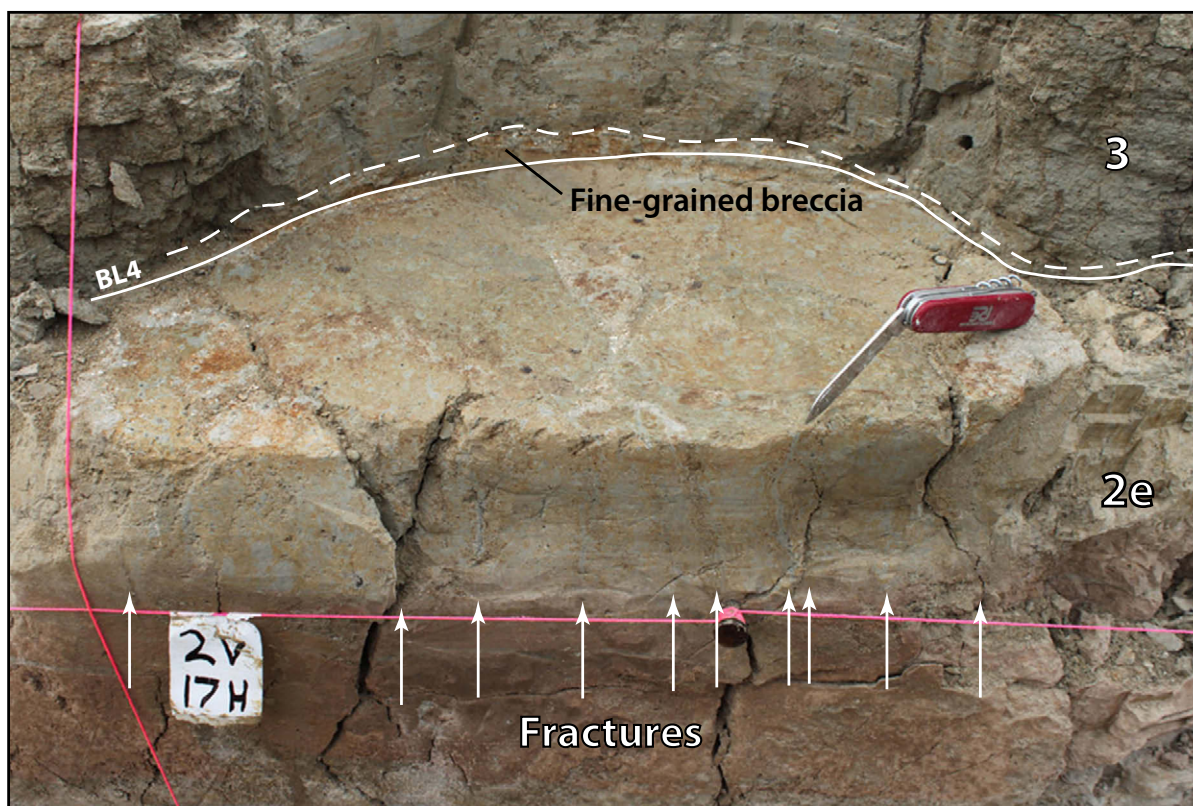


Figure 10. Exhumed surface of the planar contact (solid white line) between reddish-brown, massive, Bonneville transgressive clay (unit 2e) and overlying greenish, laminated, Bonneville regressive clay and silt (unit 3), exposed in the West(S) trench. A thin, fine-grained breccia containing small carbonate fragments immediately overlies the planar contact, which we interpret as an event horizon associated with earthquake BL4 (see “Chronology of Surface-Faulting Earthquakes” section in text). Vertical fractures extend downward about 10 cm into the top of unit 2e and appear to control the depth to which the clay has been chemically reduced to a gray color.

surface. The loess (unit 9) below soil S1 yielded an OSL age of 12.5 ± 1.4 ka (BL-L11); because this unit overlies Gilbert-episode deposits, its true age must be near the young end of the two-sigma uncertainty range. The loess (unit 11) above soil S1 yielded an OSL age of 3.2 ± 0.5 ka (BL-L10). Charcoal from soil S1 yielded an age of 6.2 ± 0.1 ka (BL-R1), and the soil matrix yielded an OSL age of 6.0 ± 1.0 ka (BL-L12).

Scarp-Derived Colluvium

Scarp-derived colluvium comprises two separate colluvial wedges (units 6 and 10; figure 12), each providing evidence for a surface-faulting earthquake on the Granger fault. The colluvial units, which have different thicknesses and wedge-shaped geometries, are both overlain by loess deposits (units 9 and 11) which in turn have pedogenic soil horizons developed on them. We observed the two colluvial wedges only in the West(N) trench; pervasive burrowing obscured stratigraphic details in the upper part of the fault zone in the West(S) trench, and the lack of surface rupture in the East trench precluded colluvial-wedge formation there (see “Granger Fault—Eastern Trace” below). The youngest colluvial wedge (unit 10) is not faulted, whereas the older wedge (unit 6) has been faulted

down-to-the-east along the western trace of the Granger fault.

Unit 6—the oldest scarp colluvium—is a distinct, layered mixture of colluvium and organic-rich sediment (figure 12). The colluvium consists of disaggregated, fine-gravel to sand-size fragments of clay, silt, and sand derived from unit 5; the source of the organic-rich, fine-grained “soil stringers” is uncertain. The sediment layers are inclined at about 30° . However, units 7 and 8 (and therefore also unit 6) appear to have been warped in the hanging wall by the most recent surface-faulting earthquake such that they dip eastward 7° – 11° more steeply within about 2 m of the fault zone; therefore, the original depositional dip of the colluvial-wedge sediments was likely about 19° – 23° . We interpret the distinctive fabric of the scarp colluvium as resulting from sloughing of wet scarp-face material as the scarp eroded back over a relatively short period of time. Because unit 6 is both underlain and overlain by Gilbert-episode marl, the scarp colluvium must have been deposited during a time of low lake level between the two Gilbert-episode transgressions (see discussion above; Oviatt and others, 2005; Hylland and others, 2012). Unit 6 tapers from 0.5 to 0 m thick over a horizontal distance of about

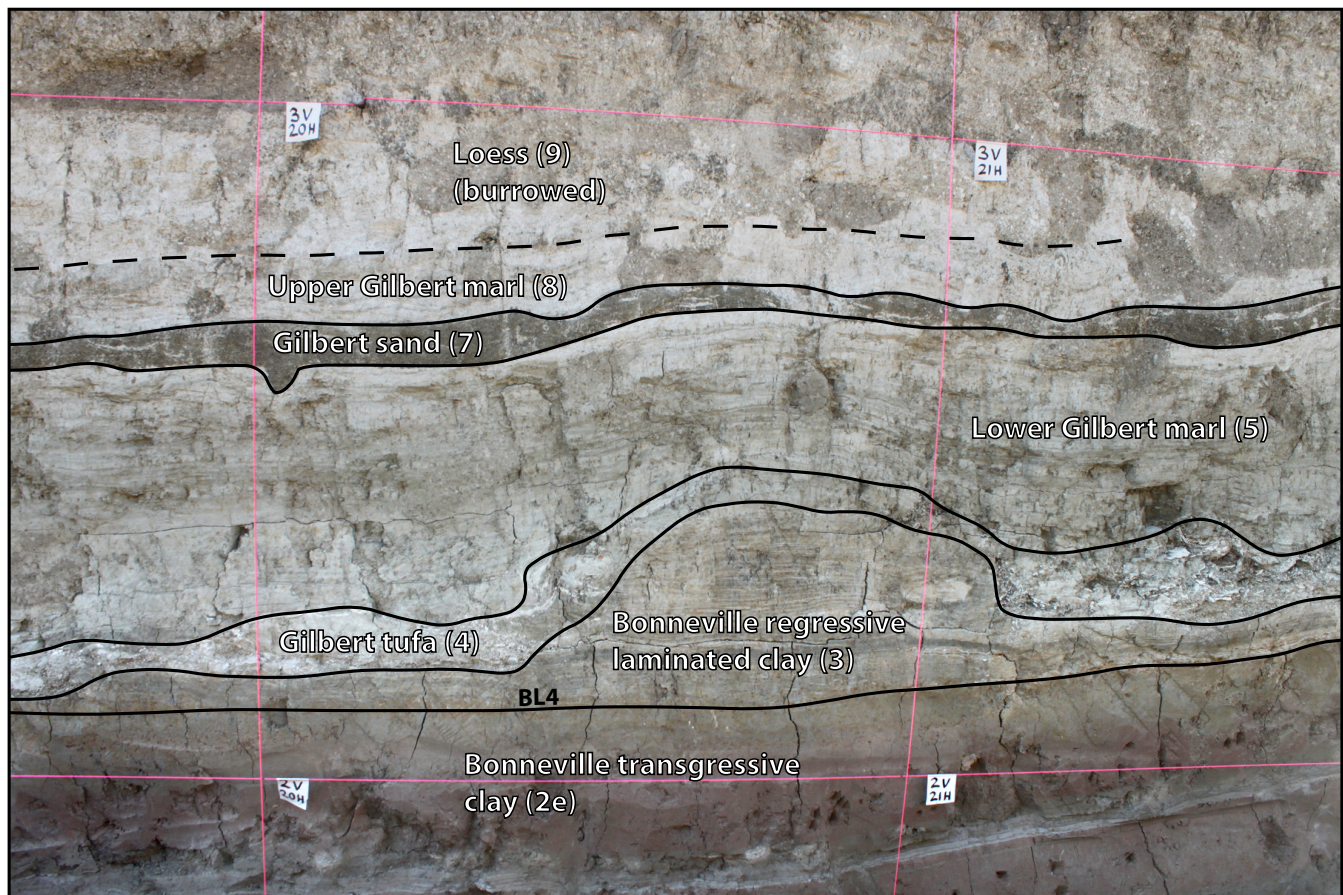


Figure 11. Gilbert-episode stratigraphic section (units 4, 5, 7, and 8) exposed in the West(N) trench. Unit numbers given in parentheses; see appendix A for unit descriptions. Laminated Bonneville regressive clay is cut by a transgression-related unconformity at the base of the Gilbert tufa, whereas units above the tufa conformably drape the underlying topography. The dark-gray Gilbert shorezone sand likely represents a second Gilbert-episode transgression across the site. We interpret the contact labeled “BL4” as an event horizon associated with earthquake BL4 (see “Chronology of Surface-Faulting Earthquakes” section in text). Grid-line spacing is 1 m.

0.8 m, and the toe of the wedge may grade into the Gilbert shorezone sand (unit 7), although this relation is obscured by burrowing and overprinting by soil carbonate development (stage II). Burrowing is also evident within the colluvial wedge itself. Two subsamples of unidentifiable charcoal from the colluvium yielded ages of 0.6 ± 0.1 ka (BL-R2-1) and 1.7 ± 0.1 ka (BL-R2-2); based on the ages of overlying deposits, these radiocarbon ages are much too young and likely indicate contamination from young organic material associated with burrowing. We observed this colluvial wedge only in the north wall of the West(N) trench; pervasive burrowing apparently obliterated this deposit in the south wall.

Unit 10—the youngest scarp colluvium—consists of granular (sand and fine gravel) soil blocks derived from unit S1 that bury an eroded scarp free face (figure 12). Unit 10 is massive, with no apparent depositional fabric, and tapers from 17 to 0 cm thick over a horizontal distance of about 1.8 m. Two subsamples of unidentifiable charcoal from the colluvium yielded ages of 4.3 ± 0.1 ka (BL-R3-1) and 4.8 ± 0.1 ka (BL-R3-2). This colluvial wedge was most dis-

tinct in the north wall of the West(N) trench, but could also be recognized in the south wall.

Granger Fault

Western trace: In the two western trenches, the western trace of the Granger fault is a relatively narrow zone of steeply dipping, anastomosing fault planes within a broader zone of warping (plate 1). Based on measurements across the two trenches, the main fault zone strikes approximately N. 5° W. and comprises several well-defined, subparallel fault planes having an average apparent eastward dip of 80° – 85° in a 10- to 40-cm-thick zone. However, the faults generally steepen toward the ground surface, and locally are vertical to west dipping (75° – 85°). At least part of the west dip may be due to rotation associated with the broader down-to-the-east warping, which spans a zone 2 m wide at the West(S) trench and 7 m wide at the West(N) trench. We were able to delineate individual geologic units within the fault zone in the West(N) trench, and offset of these units shows that most of the fault displacement occurred on the eastern bounding fault of the main fault zone. In the West(S) trench, the faulted strata are

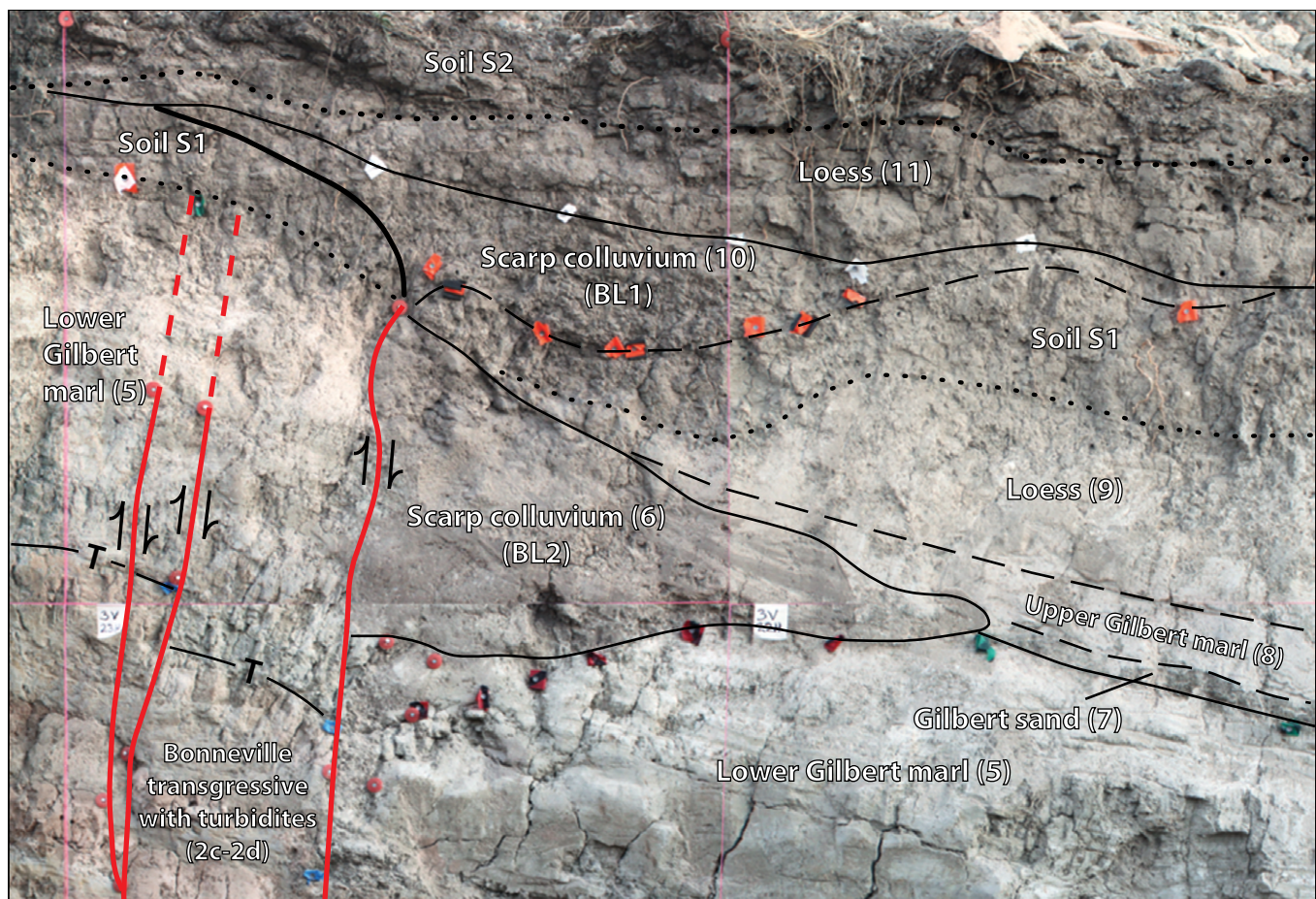


Figure 12. Fault-zone exposure in the north wall of the Baileys Lake West(N) trench, showing deposits of scarp-derived colluvium (units 6 and 10) associated with the two most recent surface-faulting earthquakes (BL1 and BL2). Unit numbers given in parentheses; see appendix A for unit descriptions and appendix B for descriptions of pedogenic soils. Dotted lines indicate base of modern soil (S2) and buried paleosol (S1); heavy black line indicates buried fault-scarp free face. T indicates erosional unconformity with overlying (mostly very thin) tufa deposit. Grid-line spacing is 1 m.

more intensely sheared and we could not delineate individual units within the fault zone.

Several west-dipping fault planes are present within about 1 m east of the main fault zone. Based on the exposure in the south wall of the West(N) trench (plate 1), these faults are splays of the eastern bounding fault of the main fault zone. The splay faults generally dip 60°–75° west but are locally vertical to steeply east dipping, and have apparent reverse displacements of about 5 cm. Unlike the faults that form the main fault zone, which offset post-Bonneville deposits up to and including the mid-Holocene-age paleosol (unit S1) as apparent in the north wall of the West(N) trench (plate 1), the splay faults only displace strata older than unit 4 (Gilbert tufa), and therefore pre-date the Gilbert lake transgression.

Faulting on the western trace of the Granger fault at the Baileys Lake site has produced both monoclinical folding and discrete shear on fault planes. The oldest fault-related deformation exposed in the trenches is monoclinical folding of the Bonneville transgressive deposits (unit 2). As apparent in the south wall of

the West(N) trench (h-21 to 22.7; plate 1), these deposits are folded to a greater degree than any of the younger deposits, indicating a deformational event older than the warping that affected the younger deposits. Combined with the absence of any scarp-derived colluvium associated with the older deformation, the folding indicates a sublacustrine event that deformed plastically and produced monoclinical folding but no surface rupture. Higher in the stratigraphic section, the two wedges of scarp-derived colluvium (units 6 and 10) are evidence of two later subaerial faulting events that produced surface rupture.

The presence of correlative strata across the fault zone allowed us to measure vertical displacement (throw) for different time periods, although erosion, burrowing, and soil development limit the number of useful marker horizons in the upper part of the trenches. By projecting the average footwall and hanging-wall dips of the basal contact of the Gilbert shorezone sand (unit 7), we measured 0.7–0.9 m of displacement across the fault zone in the West(S) trench and 0.9–1.1 m of displacement in the West(N) trench. This gives a latest Pleistocene–Holocene (post-13 ka) throw of 0.9 ± 0.2 m. By projecting the average footwall

and hanging-wall dips of the basal contact of the Bonneville clay with turbidites (unit 2c), we measured 1.7–2.0 m of displacement across the fault zone in the West(S) trench and 1.8–2.0 m of displacement in the West(N) trench. This gives a throw of 1.9 ± 0.2 m since about 24 ka (OSL sample BL-L3).

Dividing the cumulative vertical displacement by four faulting events (see “Chronology of Surface-Faulting Earthquakes” below) yields an average per-event displacement of 0.5 ± 0.1 m (2σ). The maximum thickness of the oldest colluvial wedge (unit 6), 0.5 m, is the same as the calculated per-event displacement, but the maximum thickness of the youngest colluvial wedge (unit 10), 0.17 m, is much less than the calculated per-event displacement. The thinness of the youngest wedge could reflect smaller vertical displacement in the corresponding surface-faulting event. However, as noted above, vertical displacement across the western trace of the Granger fault at the Baileys Lake site includes a component of warping. Exposures on both walls of the West(N) trench (plate 1) indicate that warping of units 7 and 8 (i.e., warping associated with the most recent faulting event) may account for vertical displacement of at least 0.3 m; combining this with the colluvial-wedge thickness results in a total minimum vertical displacement of 0.47 m. Alternatively, net cumulative displacement across the Granger fault in the most recent faulting event may have resulted from coseismic displacement on both the western and eastern traces.

Eastern trace: In the East trench, the fault-zone deformation of the eastern trace of the Granger fault is expressed as broad warping across an 8-m-wide deformation zone (h-17 to h-25; plate 1). We observed no discrete shear on fault planes, which would have been readily apparent in the well-stratified Bonneville lacustrine deposits at the base of the trench exposure. The base of the Bonneville regressive deposits (unit 3) was the best horizon for measuring the vertical offset across the warp zone; we projected this planar contact across the warp zone and measured 0.5 ± 0.1 m of offset. Geologic unit boundaries above unit 3 are much less planar, and are particularly convoluted near the middle of the warp zone. The disruption of the Holocene section in this trench was likely caused by ground oscillation accompanying liquefaction of the relatively sandy deposits above the Bonneville clays. The combination of liquefaction-related deformation, burrowing, and overprinting by stage II soil carbonate development made it difficult to determine if post-Bonneville deposits are warped the same amount as the Bonneville deposits.

The warping on the eastern trace of the Granger fault may indicate that either a small vertical displacement has occurred on this fault strand, and/or fault movement occurred when the water table was high and the fine-grained deposits were saturated and deformed plastically. Although we cannot be certain of the number of events responsible for this small amount of warping, we attribute it to a single post-Bonneville (Holocene) earthquake.

Paleoseismology of the Baileys Lake Site

Chronology of Surface-Faulting Earthquakes

At the Baileys Lake site, at least four large earthquakes associated with movement on the Granger fault occurred after deposition of Lake Bonneville highstand clay (unit 2e) at about 19 ka (figures 13 and 14; table 1). We found evidence for four earthquakes (BL1 through BL4) on the western trace of the fault and at least one earthquake on the eastern trace. As discussed above, although the amount of vertical offset (0.5 ± 0.1 m) across the eastern-trace warp zone is consistent with the average per-event vertical displacement across the western-trace fault zone, we cannot unequivocally attribute the eastern deformation to a single event. Also, the lack of data to narrowly constrain the time of the eastern deformation precludes correlation with faulting on the western trace. The time of the eastern deformation can only be defined as post-Bonneville (Holocene).

The two oldest earthquakes (BL4 and BL3) documented in the western trenches are based on structural and stratigraphic relations within the pre-Gilbert lacustrine section, whereas the two youngest earthquakes (BL2 and BL1) are based on scarp-colluvial deposits. Earthquake timing is based on OxCal modeling (appendix G).

Earthquake BL4 occurred at 15.7 ± 3.4 ka and is based on (1) the pronounced monoclinical folding of the Bonneville transgressive deposits (unit 2) in the fault zone (i.e., folded to a greater degree than overlying units), (2) the internal deformation in units 2d and 2e that is likely related to liquefaction, (3) the subaqueous erosion surface at the top of unit 2e, and (4) the thin breccia layer that immediately overlies the erosion surface at the top of unit 2e. The modeled earthquake time (around the time of occupation of the Provo shoreline) is consistent with the style of deformation (folding vs. fault-plane shear) and the lack of associated scarp-derived colluvium, which indicate a sublacustrine event. Also, the structural and stratigraphic relations (as described in the following paragraph) indicate BL4 occurred prior to deposition of Bonneville regressive deposits (unit 3) around 14 ka. An OSL age of 19.3 ± 0.8 ka (BL-L7) from a turbidite near the top of the Bonneville transgressive sequence provides a maximum limit on the earthquake time, and an OSL age of 14.1 ± 1.6 ka (BL-L8) from the base of unit 3 provides a relatively close minimum limit.

The four observations listed above that provide the basis for earthquake BL4 suggest the following scenario. Upward propagation of fault rupture formed a subaqueous scarp (characterized by monoclinical folding of Bonneville transgressive deposits) on the floor of Lake Bonneville. Strong ground shaking that accompanied the fault rupture triggered liquefaction in the sandy, relatively thick turbidite bed of unit 2d, and fluidization of this bed resulted in internal deformation (stretching and disruption of clay

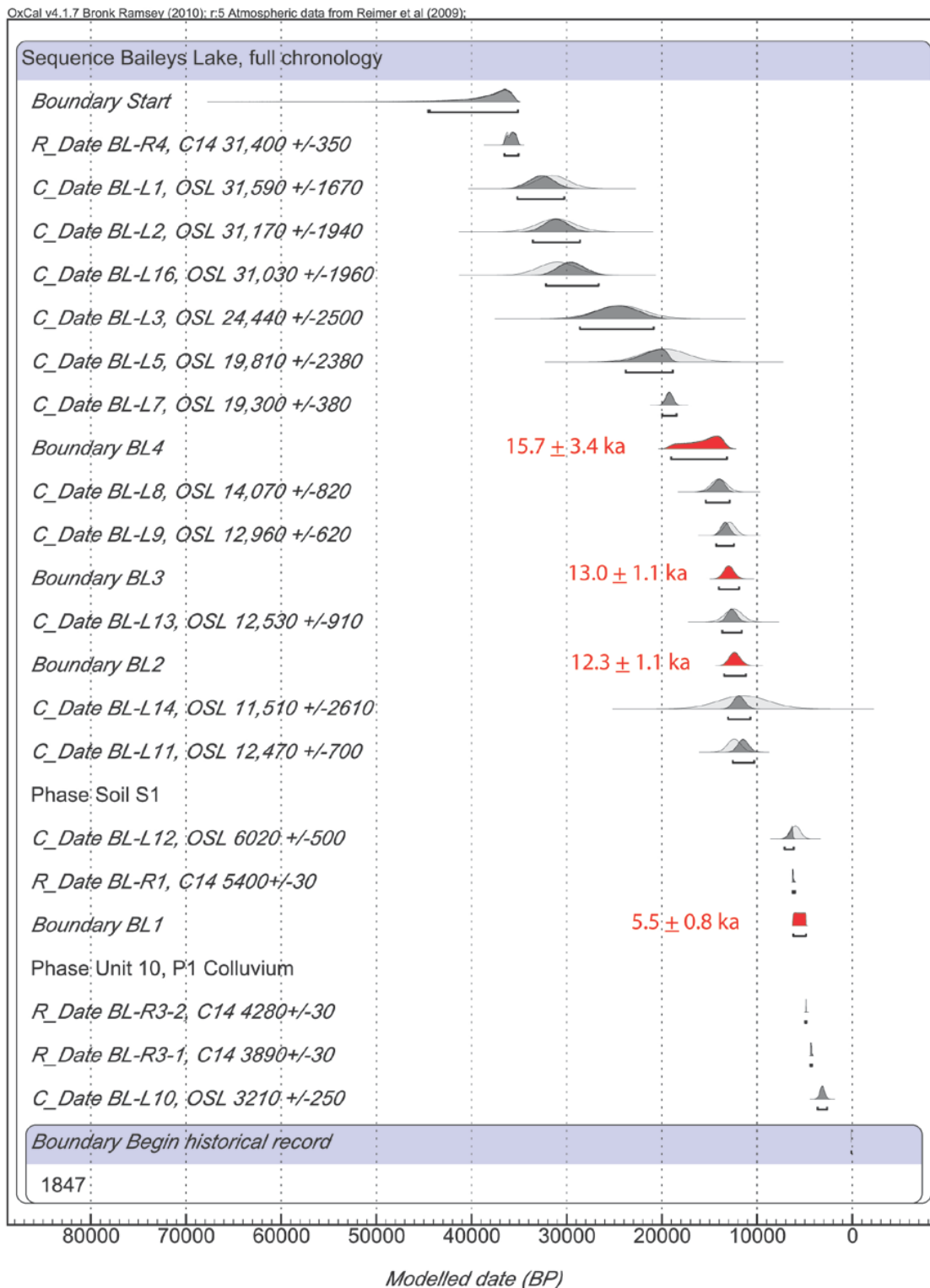


Figure 13. OxCal model for the Baileys Lake site, showing stratigraphic ordering of radiocarbon and luminescence ages (appendices D and E) and probability density functions (PDFs) for the timing of earthquakes BL1–BL4 (red). Appendix G presents a summary table of the model output. The model includes **C_Date** for luminescence ages, **R_Date** for radiocarbon ages, **Phase** for groups of ages where the relative stratigraphic ordering is unknown, and **Boundary** for undated events (e.g., earthquake BL1); see DuRoss and others (2011) for a general discussion of OxCal modeling applied to paleoseismic studies. Model constructed using OxCal version 4.1.7 (Bronk Ramsey, 2009) and the IntCal09 radiocarbon calibration curve (Reimer and others, 2009). Brackets below PDFs indicate 2σ time ranges.

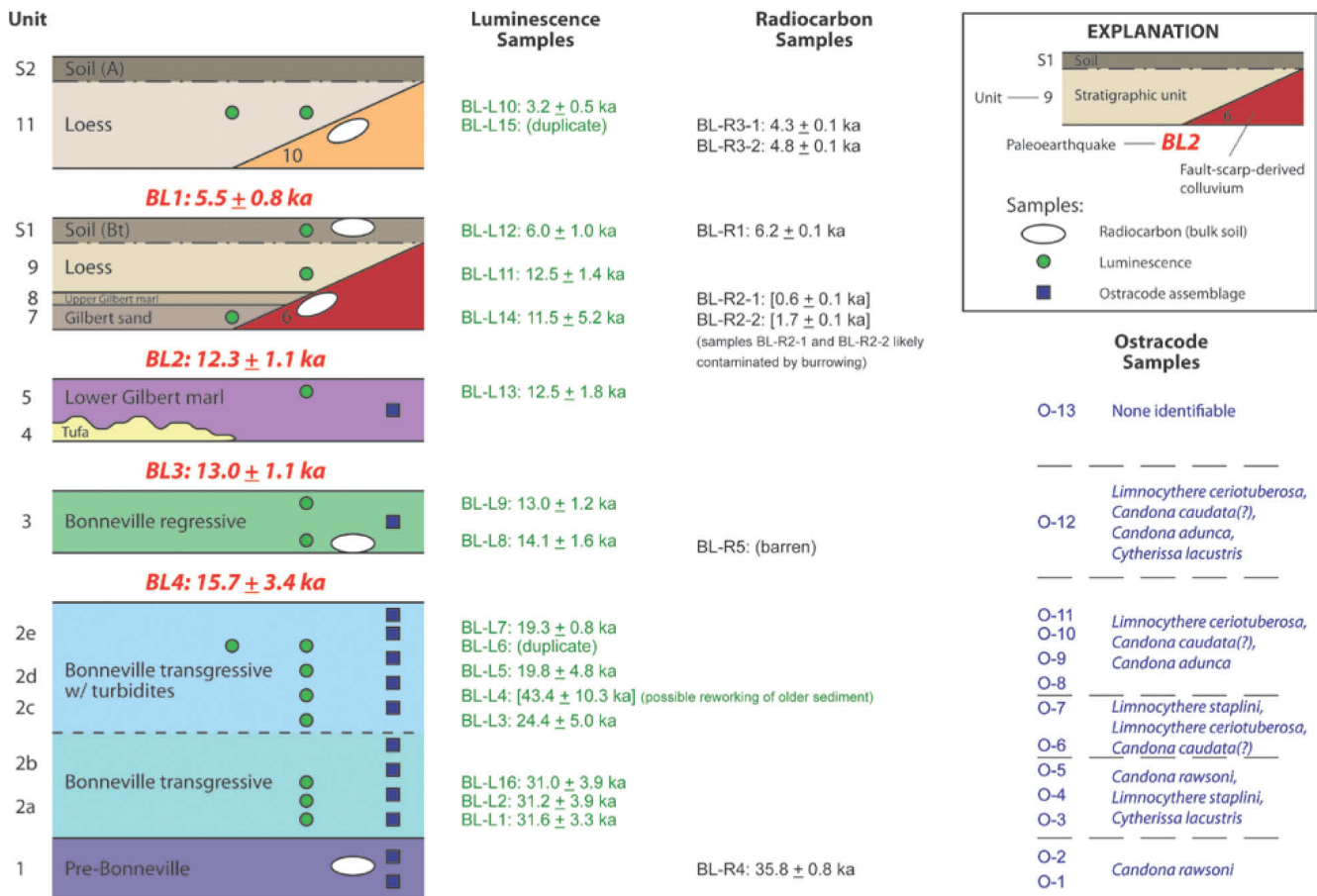


Figure 14. Chronostratigraphic summary for the Baileys Lake site, showing timing of earthquakes BL1 through BL4 as modeled in OxCal (see figure 13 and appendix G). Earthquake times and all numerical ages are reported with 2σ uncertainty; brackets indicate age out of stratigraphic order (within uncertainty limits)—note that these ages were not used as constraints in the OxCal modeling. Refer to appendices C and D (radiocarbon ages), appendix E (luminescence ages), and appendix F (ostracode identification and interpretation) for details.

Table 1. Summary of Baileys Lake earthquake timing and displacement data.

Event ¹	Mean ² (ka)	$\pm 2\sigma^2$ (kyr)	5% ² (ka)	95% ² (ka)	Displacement ³ (m)	Unit ⁴
BL1	5.54	0.80	4.86	6.19	0.4–0.6	10
BL2	12.34	1.14	11.17	13.47	0.4–0.6	6
BL3	12.96	1.06	11.88	14.02	0.4–0.6	–
BL4	15.70	3.38	13.16	19.05	0.4–0.6	–

¹ Earthquake identified at the Baileys Lake site and modeled in OxCal (figure 13; appendix G).

² Mean earthquake times, 2σ ranges, and 5th–95th percentile ranges based on the OxCal model (appendix G).

³ Per-event vertical displacement. Range based on average displacement, colluvial-wedge thickness data, and amount of warping associated with BL1 (see discussion in text).

⁴ Trench-log unit for scarp-derived colluvium associated with the earthquake (plate 1; appendix A).

stringers) as well as upright, open folds in the overlying unit 2e; these folds lie well beyond the fault deformation zone—for example, h-8 to h-9 in the West(N) trench, and the western half of the East trench (plate 1). The erosion surface at the top of unit 2e (observed in both the western and eastern trenches) truncates the open folds; this erosion also dramatically thinned unit 2e near the fault—for example, h-22.6, v-2.4, West(N) trench (plate 1)—indicating that a scarp produced by the monoclinical folding was present at the time of the erosional event. We hypothesize that the erosion occurred immediately after scarp formation during BL4 (i.e., the erosion surface is an event horizon associated with BL4), and was produced by strong lake-bottom currents that resulted from vertical offset of the lake floor. These currents were likely also responsible for transporting carbonate fragments to the site, which were deposited in the thin breccia layer that accumulated on top of the erosion surface as sediment eventually settled out of the turbid (post-earthquake) lake water. Collectively, the liquefaction in unit 2d, folding in unit 2e, subaqueous erosion at the top of unit 2e, and the breccia at the base of unit 3 resemble features of seismites that have been

described from the Dead Sea rift basin (e.g., Marco and Agnon, 1995, 2005; Agnon and others, 2006), and we interpret this stratigraphic sequence as a seismite associated with earthquake BL4.

The timing of BL4 is likely responsible for the apparent absence of a stratigraphic signature of the Bonneville Flood (~18 ka) in the Lake Bonneville section at the Baileys Lake site. Any stratigraphic evidence for the flood that might have existed would have been destroyed as the sediments at the top of the transgressive sequence were disturbed and redistributed during strong ground shaking and then eroded by the ensuing strong lake-bottom currents. Alternatively, Hylland and others (2012) noted that the two-sigma timing range (12.3–19.1 ka) of BL4 overlaps the time of the flood, so an earthquake (possibly a WVFZ–SLCS coseismic event) coincident with the flood cannot be ruled out.

Earthquake BL3 occurred at 13.0 ± 1.1 ka, prior to transgression of the Gilbert-episode lake across the site, and is based on two structural and stratigraphic relations: (1) A small block of Bonneville regressive marl (unit 3) is preserved in the hanging wall within the fault zone at h-22.6, v-2.5, West(N) trench (plate 1). Along with units 2e and 2d, the marl has been tightly folded by fault movement subsequent to the monoclinical folding of BL4. The tight folding does not involve, and therefore predates, the basal Gilbert erosional unconformity and the overlying Gilbert marl (unit 5). (2) A splay fault cuts unit 3 and older deposits, and is in turn truncated by the basal Gilbert unconformity; see h-22.2, v-2.3, West(N) trench (plate 1). Therefore, the fault movement postdates deposition of the Bonneville regressive marl and predates the Gilbert transgression. An OSL age of 13.0 ± 1.2 ka (BL-L9) provides a close maximum limit on the earthquake time, and an OSL age of 12.5 ± 1.8 ka (BL-L13) provides a minimum limit. BL3 occurred around the time that Lake Bonneville reached near-desiccation levels; the presence of fault-plane shear (i.e., brittle deformation) suggests that the lacustrine sediments may not have been saturated, and the faulting may have been a subaerial event. However, no scarp-derived colluvium associated with this earthquake is apparent in the trench exposures. If a colluvial wedge had formed, it likely was eroded during transgression of the Gilbert-episode lake across the site.

Earthquake BL2 occurred at 12.3 ± 1.1 ka and is based on a wedge of scarp-derived colluvium (unit 6) that accumulated between Gilbert marl depositional episodes (units 5 and 8) and before deposition of early Holocene loess (unit 9). An OSL age of 12.5 ± 1.8 ka (BL-L13) provides a relatively close maximum limit on the earthquake time, and OSL ages of 11.5 ± 5.2 ka (BL-L14) and 12.5 ± 1.4 ka (BL-L11) provide minimum limits. The distinctive sedimentary texture of the colluvial wedge (suggesting wet depositional conditions) is consistent with the earthquake occurring around the time of the Gilbert lake cycle, probably when the lake was below the elevation of the site and just prior to the second Gilbert

transgression. As noted above (“Scarp-Derived Colluvium” section), the stratigraphic relation between the colluvial wedge and Gilbert shorezone sand (unit 7) is unclear, and the radiocarbon ages for organic sediment from the colluvial wedge are unreliable, but the two units may be roughly contemporaneous.

Earthquake BL1—the most recent earthquake—occurred at 5.5 ± 0.8 ka. Evidence for BL1 includes unfaulted scarp colluvium (unit 10) and an eroded fault free face, fault offset of the BL2 scarp colluvium, and warping of post-BL2 deposits (e.g., unit 8). Unit 10 overlies soil S1, which yielded ages of 6.0 ± 1.0 ka (BL-L12) and 6.2 ± 0.1 ka (BL-R1); these ages provide a close maximum limit on the time of BL1. Unit 10 colluvium yielded ages of 4.3 ± 0.1 ka (BL-R3-1) and 4.8 ± 0.1 ka (BL-R3-2), which provide a close minimum limit on earthquake timing.

Earthquake Recurrence and Fault Slip Rate

We calculated recurrence intervals between individual Baileys Lake earthquakes (inter-event recurrence) and over several earthquake cycles (mean recurrence). Using the mean earthquake times, inter-event recurrence intervals for the Granger fault at the Baileys Lake site vary from 0.7 kyr for BL3–BL2 to 6.8 kyr for BL2–BL1 (table 2). Using the three intervals between BL4 and BL1, the mean post-Bonneville highstand recurrence interval for the Granger fault at the Baileys Lake site is 3.4 kyr. The mean Holocene recurrence interval is about 6 kyr (two earthquakes in about 12 kyr).

Because of the uncertainty in amount of displacement associated with earthquake BL1, we calculate only open-ended vertical slip rates for the Granger fault at the Baileys Lake site. The post-Bonneville highstand slip rate is about 0.09–0.12 mm/yr based on 1.7–2.1 m of displacement in 18 kyr, and the Holocene slip rate is about 0.06–0.09 mm/yr based on 0.7–1.1 m of displacement in about 12 kyr.

PALEOSEISMOLOGY OF THE WEST VALLEY FAULT ZONE

Correlation of Earthquakes

Fault-trench data document at least six large earthquakes on the WVFZ—five on the Granger fault and one on the Taylorsville fault—since the time of the Lake Bonneville highstand around 18 ka. The data are for the four (or more) earthquakes identified at the Baileys Lake site, and two earthquakes identified in consultants’ trenches excavated as part of pre-development fault-setback investigations required by local governments (discussed further in the “Earthquake Timing and Recurrence” section below; see also appendix H). By comparison, Keaton and others (1987) and Keaton and Currey (1989) postulated one to five post-Bonneville highstand earthquakes at various individual sites on the WVFZ, and six to seven earthquakes on the

Table 2. Chronology and recurrence of surface-faulting earthquakes at the Baileys Lake site.

Baileys Lake Earthquake	Earthquake Time (ka)	Chronology (ka)	Inter-event RI ¹ (kyr)
BL1	5.5 ± 0.8	5.5 (4.7–6.3)	–
BL2	12.3 ± 1.1	12.3 (11.2–13.4)	BL2–BL1: 6.8 (4.9–8.7)
BL3	13.0 ± 1.1	13.0 (11.9–14.1)	BL3–BL2: 0.7 (0–2.9)
BL4	15.7 ± 3.4	15.7 (12.3–19.1)	BL4–BL3: 2.7 (0–7.2)

Interval	Elapsed Time (kyr)	No. Intervals	Mean RI ² (kyr)	Notes
BL3–BL1	7.5	2	3.8	post-Provo shoreline (<14 ka)
BL4–BL1	10.2	3	3.4	post-Bonneville highstand (<18 ka)

¹ Recurrence interval (RI) calculated from mean earthquake times (bold), with minimum and maximum recurrence intervals calculated from 2σ ranges of earthquake times; RI = 0 results from overlapping 2σ ranges.

² Recurrence interval calculated from elapsed time between earthquakes (based on mean earthquake times) divided by number of inter-event time intervals.

WVFZ as a whole. However, the numbers of earthquakes determined in those two studies were primarily from geomorphic observations, total stratigraphic offset documented in boreholes, and an estimated average per-event vertical displacement of 1.2–1.5 m that was based on cross-cutting geomorphic relations and a single vertical displacement measurement from a trench exposure at the Pioneer Industrial Park site (figure 4; Keaton and others, 1987). Given the average per-event vertical displacement of the Baileys Lake earthquakes of 0.5 ± 0.1 m, and the single-event displacement from a consultant's trench on the northern part of the Taylorsville fault of 0.5–0.7 m (Solomon, 1998; unpublished UGS data), a displacement of 1.2–1.5 m may be more representative of maximum displacement than average displacement. Interestingly, two-dimensional boundary-element modeling by Bruhn and Schultz (1996) showed that, on average, net slip and surface offset on antithetic faults was about 20–30 percent of the net slip on an underlying listric master fault. Applying this reduction factor to SLCS displacements ranging from 0.8 to 2.2 m (DuRoss and others, 2014) predicts WVFZ displacements on the order of 0.2–0.7 m. Finally, because Keaton and others (1987) and Keaton and Currey (1989) were unable to more precisely determine the times of individual earthquakes, we cannot directly correlate their earthquakes, the Baileys Lake earthquakes, and the earthquakes documented in consultants' trenches.

Earthquake Timing and Recurrence

Because of the distributed nature of surface faulting across the WVFZ, a complete chronology of latest Quaternary earthquakes likely cannot be obtained from a single site. Keaton and others (1987) and Keaton and Currey (1989) demonstrated considerable differences, both east-to-west and north-to-south, in the possible number of earthquakes at different sites (i.e., between the Granger and Taylorsville faults and along the strike of the Granger fault, respectively). A relatively complete earthquake record could only be obtained by paleoseismic studies at numerous sites on both the Granger and Taylorsville

faults, and given the restrictions associated with site access, scarp modification related to development activities, and shallow groundwater, a complete record may never be obtained. Accordingly, the chronologies we present here for the Granger fault and WVFZ as a whole are incomplete (i.e., preliminary).

Table 3 shows a preliminary chronology of large earthquakes on the Granger fault, developed from our Baileys Lake data and earthquake-timing data from a consultant's trench in the middle part of the westernmost trace of the Granger fault (Terracon site; see figure 4 for site location). A bulk-soil sample collected in 1998 by UGS geologists from what was interpreted as scarp-derived colluvium yielded an AMRT radiometric age of 1880 ± 80 ¹⁴C yr B.P. (unpublished UGS data). UGS geologists had limited time in the trench and could not prepare a detailed log, so the geologic context of this sample is not well documented; the sample may have come from a soil A horizon buried beneath the colluvial wedge, rather than from the colluvium itself (appendix H). Given the uncertainty as to whether the age of the sampled sediment provides a minimum or maximum limit on earthquake timing, we constructed two OxCal models (appendix H) to account for both possibilities and use the mean of the two modeled earthquake times (1.4 ± 0.7 ka) for this earthquake.

The range of inter-event recurrence intervals for the five Granger-fault earthquakes is the same as for the Baileys Lake site: 0.7–6.8 kyr (tables 2 and 3). The variability in inter-event recurrence undoubtedly reflects differences in surface-faulting activity on different strands of the fault, as suggested by the apparent difference in timing of the most recent earthquake at the Terracon site with that at the Baileys Lake site (earthquake BL1). Mean recurrence intervals range from 3.6 to 5.4 kyr, but again, the earthquake chronology for the Granger fault is likely incomplete and actual mean recurrence intervals are likely shorter. Keaton and others (1987) and Keaton and Currey (1989) calculated average recurrence estimates of

2.6–14 kyr for the Granger fault. However, as discussed above, these recurrence estimates are based on an assumed number of faulting events within a given time period, so their estimates have large uncertainties.

Table 4 shows a preliminary chronology of surface-faulting earthquakes for the WVFZ as a whole, developed from our Baileys Lake data, the Terracon site data, and earthquake-timing data from a consultant's trench at the northern end of the Taylorsville fault (AGRA site; see

figure 4 for site location). In 1997, UGS geologists collected two bulk-soil samples from the AGRA trench: a sample of crack-fill sediment/fault-zone colluvium yielded an AMRT age of 2350 ± 80 ^{14}C yr B.P., and a sample from sag pond deposits beneath a possible colluvial wedge yielded an AMRT age of 2520 ± 70 ^{14}C yr B.P. (unpublished UGS data). Solomon (1998) reported the earthquake time as ~ 2.2 ka (the average of the two calendar-calibrated ages), and our OxCal model yielded a similar result (2.2 ± 0.2 ka; appendix H).

Table 3. Preliminary chronology and recurrence of surface-faulting earthquakes on the Granger fault.

Granger Fault Earthquake	Baileys Lake Site (ka)	Terracon Site ¹ (ka)	Preliminary Chronology ² (ka)	Inter-event RI ³ (kyr)
G1⁴	–	1.4 ± 0.7	1.4 (0.7–2.1)	–
G2	5.5 ± 0.8 (BL1)	–	5.5 (4.7–6.3)	G2–G1: 4.1 (2.6–5.6)
G3	12.3 ± 1.1 (BL2)	–	12.3 (11.2–13.4)	G3–G2: 6.8 (4.9–8.7)
G4	13.0 ± 1.1 (BL3)	–	13.0 (11.9–14.1)	G4–G3: 0.7 (0–2.9)
G5	15.7 ± 3.4 (BL4)	–	15.7 (12.3–19.1)	G5–G4: 2.7 (0–7.2)
Interval	Elapsed Time (kyr)	No. Intervals	Mean RI ⁵ (kyr)	Notes
G3–G1	10.9	2	5.4	latest Pleistocene–Holocene (<13 ka)
G4–G1	11.6	3	3.9	post-Provo shoreline (<14 ka)
G5–G1	14.3	4	3.6	post-Bonneville highstand (<18 ka)

¹ Earthquake time based on single limiting age (see discussion in text, and appendix H). See figure 4 for site location.

² Mean earthquake time and 2σ range; see appendices G and H for OxCal modeling.

³ Recurrence interval (RI) calculated from mean earthquake times (bold), with minimum and maximum recurrence intervals calculated from 2σ ranges of earthquake times; RI = 0 results from overlapping 2σ ranges.

⁴ Earthquake time poorly constrained; see appendix H.

⁵ Recurrence interval calculated from elapsed time between earthquakes (based on mean earthquake times) divided by number of inter-event time intervals.

Table 4. Preliminary chronology and recurrence of surface-faulting earthquakes on the West Valley fault zone.

WVFZ Earthquake	Granger Fault (ka)	Taylorsville Fault (ka)	Preliminary Chronology ¹ (ka)	Inter-event RI ² (kyr)
W1³	1.4 ± 0.7 (Terracon)	–	1.4 (0.7–2.1)	–
W2³	–	2.2 ± 0.2 (AGRA) ⁴	2.2 (2.0–2.4)	W2–W1: 0.8 (0–1.7)
W3	5.5 ± 0.8 (BL1)	–	5.5 (4.7–6.3)	W3–W2: 3.3 (2.3–4.4)
W4	12.3 ± 1.1 (BL2)	–	12.3 (11.2–13.4)	W4–W3: 6.8 (4.9–8.7)
W5	13.0 ± 1.1 (BL3)	–	13.0 (11.9–14.1)	W5–W4: 0.7 (0–2.9)
W6	15.7 ± 3.4 (BL4)	–	15.7 (12.3–19.1)	W6–W5: 2.7 (0–7.2)
Interval	Elapsed Time (kyr)	No. Intervals	Mean RI ⁵ (kyr)	Notes
W3–W1	4.1	2	2.0	mid-Holocene (<6 ka)
W4–W1	10.9	3	3.6	latest Pleistocene–Holocene (<13 ka)
W5–W1	11.6	4	2.9	post-Provo shoreline (<14 ka)
W6–W1	14.3	5	2.9	post-Bonneville highstand (<18 ka)

¹ Mean earthquake time and 2σ range; see appendices G and H for OxCal modeling.

² Recurrence interval (RI) calculated from mean earthquake times (bold), with minimum and maximum recurrence intervals calculated from 2σ ranges of earthquake times; RI = 0 results from overlapping 2σ ranges.

³ Earthquake time poorly constrained; see appendix H.

⁴ Earthquake time from Solomon (1998) and unpublished Utah Geological Survey files (see discussion in text, and appendix H). See figure 4 for site location.

⁵ Recurrence interval calculated from elapsed time between earthquakes (based on mean earthquake times) divided by number of inter-event time intervals.

The range of inter-event recurrence intervals for the WVFZ as a whole is the same as for the Granger fault (0.7–6.8 kyr), but the mean recurrence intervals range from 2.0 to 3.6 kyr (tables 3 and 4). Again, the variability reflects differences in surface-faulting activity on different strands of the fault zone combined with an incomplete earthquake chronology, and actual mean recurrence intervals are likely shorter. Keaton and others (1987) and Keaton and Currey (1989) reported average recurrence estimates of 1.8–2.2 kyr for the WVFZ as a whole, but these estimates are subject to large uncertainty as discussed above. When the UQFPWG evaluated existing paleoseismic data for the WVFZ in the early 2000s, they considered the available data to be insufficient to estimate preferred and 5th–95th percentile recurrence intervals for the WVFZ (Lund, 2005).

Slip Rate

The cumulative displacement data obtained by Keaton and others (1987) and Keaton and Currey (1989), combined with the well-documented late Quaternary stratigraphic record of pluvial-lake-cycle and interpluvial sedimentation, allowed them to calculate average slip rates for different time intervals. Their slip rates include 0.03–0.5 mm/yr for the Granger fault over various time intervals within the past 140 kyr, 0.1–0.2 mm/yr for the Taylorsville fault since 12 ka, and 0.5–0.6 mm/yr for the entire WVFZ since 13 ka (table 5). Using these data, the UQFPWG estimated 5th percentile, preferred, and 95th percentile slip rates of 0.1–0.4–0.6 mm/yr for the WVFZ (Lund, 2005). Our calculated slip rates for the Granger fault of 0.09–0.12 mm/yr (post-Bonneville highstand) and 0.06–0.09 mm/yr (Holocene), based on data from the Baileys Lake site, fall within the previously determined range for the fault. Given the small number of events documented in paleoseismic trenching studies and the likelihood of an incomplete paleoseismic record for the WVFZ, we do not attempt to evaluate changes in slip rate over time based on inter-event times and per-event displacements.

Discussion

Our investigation at the Baileys Lake site improves the late Quaternary earthquake history of the Granger fault, and of the WVFZ as a whole, by providing per-event timing and displacement data for four earthquakes since the Bonneville highstand around 18 ka. Our data, combined with earthquake-timing data from consultants' trenches, provide evidence for six earthquakes on the WVFZ: five on the Granger fault and one on the Taylorsville fault. Inter-event recurrence intervals range from 0.7 to 6.8 kyr for both the Granger fault and the entire WVFZ, and mean recurrence over different time intervals ranges from 3.6 to 5.4 kyr for the Granger fault and 2.0 to 3.6 kyr for the entire WVFZ. The variability in recurrence intervals, similar to that documented by Keaton and others (1987) and Keaton and Currey (1989), likely results from differences in surface-faulting activity on different strands of the fault zone combined with an incomplete earthquake chronology, and actual mean recurrence intervals are likely shorter than those that we report here.

We found evidence at the Baileys Lake site for two earthquakes that occurred during the Bonneville lake cycle: one (BL4) during the early part of the regressive phase of the lake and one (BL3) near the end of the regression. This differs from the findings of Keaton and others (1987), who found no evidence of differential displacements within Bonneville lake-cycle sediments in their boreholes near the south end of the Granger fault. As a result, they interpreted a period of tectonic quiescence on that part of the fault during Lake Bonneville time. Additionally, the timing of the most recent surface-faulting earthquake documented at the Baileys Lake site (BL1) differs substantially from the timing of the most-recent earthquakes documented in consultants' trenches elsewhere on the WVFZ (one on the Granger fault and one on the Taylorsville fault). These differences underscore the spatial and temporal variability of surface faulting across a distributed fault system like the WVFZ, where some strands may rupture in one earthquake and different strands rupture in another earthquake.

Average per-event vertical displacement for the Granger fault at the Baileys Lake site is 0.5 ± 0.1 m. This is similar to the 0.5–0.7 m of displacement measured for a single surface-faulting earthquake documented in a consultant's trench near the north end of the Taylorsville fault (Solomon, 1998; unpublished UGS data; appendix H), and is also similar to the displacement range of 0.2–0.7 m predicted by a master–antithetic fault relation determined by two-dimensional boundary-element modeling (Bruhn and Schultz, 1996). By comparison, Keaton and others (1987) estimated an average per-event vertical displacement of 1.2–1.5 m for the WVFZ, but this estimate was based on cross-cutting geomorphic relations and a single vertical displacement measurement from a trench exposure. Also, the displacement data of Keaton and others are from near the middle of the WVFZ, whereas the Baileys Lake site and the consultant's trench site on the Taylorsville fault are near the northern end of the mapped traces of those faults. Displacement may increase toward the middle of the fault zone if the along-strike distribution of slip on the WVFZ has an ellipsoidal shape, and a displacement of 1.2–1.5 m may be more representative of maximum displacement than average displacement.

COMPARISON OF SURFACE-FAULTING CHRONOLOGIES FOR THE WEST VALLEY FAULT ZONE AND SALT LAKE CITY SEGMENT OF THE WASATCH FAULT ZONE

A major goal of this study was to compare surface-faulting chronologies of the WVFZ and SLCS and thus clarify the seismogenic relation between the two fault zones (i.e., to what extent the WVFZ is seismically independent of, or moves coseismically with, the SLCS). Kinematic modeling of a normal fault system comprising a master fault and antithetic fault that intersect in a weak, partly ductile zone at a depth of about

Table 5. Summary of displacement, recurrence, and slip-rate data for the West Valley fault zone.

Time Interval ¹	Vertical Displacement	Number of Events ²	Site and Reference	Evidence/Comments	Ave. RI (kyr)	Ave. SR ³ (mm/yr)
Granger fault:						
11–0 ka	1.4–1.5 m	1	Goggin Drain (Keaton and Currey, 1989)	Boreholes; offset of post-Bonneville red beds calculated from horizontal projection and first-order trend surfaces	NA	0.1
12–0 ka	0.7–1.1 m	2	Baileys Lake (this study)	Trenches; faulted post-Bonneville sediments	6.0	0.06–0.09
12.5–9 – 0 ka	0.7 m	1	Three Flags (Keaton and Currey, 1989)	Boreholes; offset of post-Bonneville red beds calculated from horizontal projection	NA	0.06–0.08
12.5–11.5 – 0 ka	≤ 3 m	2	1300 South (Keaton and Currey, 1989)	Boreholes; offset of post-Bonneville red beds calculated from horizontal projection and first-order trend surfaces	5.8–6.3	0.3
13–0 ka	5.2–6.7 m	2	UDOT (Keaton and others, 1987)	Boreholes; playa formation (event 1), burial by scarp-derived colluvium (event 2)	6.5	0.4–0.5
13–0 ka	—	3	Central part of Granger fault traces (Keaton and others, 1987)	Geomorphic; depositional features and paleochannels	—	—
13–0 ka	—	5	Central to southern Granger fault (Keaton and others, 1987)	Combined borehole and geomorphic	2.6	0.4–0.5
18–0 ka	1.7–2.1 m	4	Baileys Lake (this study)	Trenches; faulted Bonneville and post-Bonneville sediments	3.4	0.1
28–22 – 0 ka	3–4 m	2	Goggin Drain (Keaton and Currey, 1989)	Boreholes; offset of Fielding Geosol calculated from horizontal projection and first-order trend surfaces	11.0–14.0	0.1–0.2
28–22 – 0 ka	4.5 m	3	1300 South (Keaton and Currey, 1989)	Boreholes; offset of Fielding Geosol calculated from horizontal projection and first-order trend surfaces	7.3–9.3	[0.2]
26–13 ka	0 m	0	UDOT (Keaton and others, 1987)	Boreholes; top and bottom of Bonneville Alloformation displaced same amount	NA	0
60–26 ka	≥ 7.6 m	>2 (est. 5–6)	UDOT (Keaton and others, 1987)	Boreholes; colluvium underlying and overlying Cutler Dam Alloformation in hanging wall	[5.7–6.8]	[≥ 0.2]
60–0 ka	≥ 12.8–14.3 m	—	UDOT (Keaton and others, 1987)	Boreholes; cumulative post-Cutler Dam (60 ± 20 ka) displacement	—	≥ 0.2–0.4
140–60 ka	3.1–6.1 m	(est. 3–4)	UDOT (Keaton and others, 1987)	Boreholes; colluvium between Cutler Dam and Little Valley Alloformations in hanging wall	[20.0–27.0]	0.03–0.1
140–0 ka	17.4–18.9 m	(est. 11–16)	UDOT (Keaton and others, 1987)	Boreholes; cumulative post-Little Valley (140 ± 10 ka) displacement	[8.8–12.7]	0.1
Taylorville fault:						
~6–0 ka	0.5–0.7 m	1	AGRA site (1300 N 2200 W) (Solomon, 1998; unpublished UGS data)	Trench; faulted post-Bonneville sediments	NA	0.1
12–0 ka	>1.2–1.5 m	2	Pioneer Industrial Park (Keaton and others, 1987)	Trench; deformed Bonneville sediments	6.0	>0.1
Entire West Valley fault zone:						
13–0 ka	>6.4–8.2 m	6–7	NA (Keaton and others, 1987)	Combined data for Granger and Taylorville faults	1.8–2.2	0.5–0.6
18–0 ka	>2.3–2.8 m	6	NA (this study)	Combined data for Granger and Taylorville faults	2.0–3.6	—

¹ Time intervals based on correlation of marker beds with the time of pluvial lake-cycle events.² For Keaton and others (1987) and Keaton and Currey (1989) data, number of events is estimated based on assumption of 1.2–1.5 m vertical offset per event.³ Reported values rounded to one significant figure.

NA, not applicable; RI, recurrence interval; SR, slip rate; UDOT, Utah Department of Transportation; est. = estimate.

Brackets indicate value derived from data in Keaton and others (1987) or Keaton and Currey (1989) but not given in the original report.

15 km (Bruhn and Schultz, 1996) has shown that movement on the master fault can trigger slip on the antithetic fault, and in the case of a listric master fault, produce antithetic-fault surface rupture. Applying this model to the SLCS (master fault)–WVFZ (antithetic fault) pair, we used our comparison of the timing of surface-faulting earthquakes on the two fault zones to test the hypothesis of seismogenic dependence of the WVFZ on the SLCS.

In this discussion, *independent* refers to antithetic fault rupture that does not contribute seismic moment to an earthquake initiated by slip on a master fault, but has its own moment release in a distinct, separate earthquake. Independent ruptures include triggered events related to but occurring sometime after slip on the master fault (e.g., as part of an aftershock sequence) as well as events that lack a clear relation to slip on the master fault. In contrast, *coseismic* refers to the synchronous rupture of both the master and antithetic faults, where both ruptures contribute seismic moment to a single earthquake. The M_s 6.9 Campania–Basilicata (Italy) earthquake in 1980 is an example of coseismic faulting, where an antithetic fault ruptured 40 s after an earthquake nucleated on the master fault but before the end of the overall rupture episode (Bernard and Zollo, 1989; Westaway, 1992). In contrast, the 1984 Devil Canyon (Idaho) earthquake is an example of independent, triggered rupture, where antithetic faulting on the Lone Pine fault produced an M_L 5.0 aftershock two and a half weeks after the M_L 5.8 main shock on the master Challis fault (Payne and others, 2004). We do not know of a clear example of completely independent rupture of an antithetic fault paired with a major, range-bounding master normal fault. The M_L 6.6 Hansel Valley (Utah) earthquake in 1934 (Walter, 1934; Shenon, 1936; dePolo and others, 1989) may be an example of this, where surface faulting occurred on possible antithetic intrabasin faults but no rupture occurred on the nearby range-bounding North Promontory fault, which may be a master fault. However, a strike-slip focal mechanism has been determined for this earthquake (Doser, 1989), and the vertical offsets on the floor of Hansel Valley could have a non-tectonic origin (e.g., lateral spread), so whether this earthquake is really an example of an independent antithetic faulting event is unclear.

The inherent limitations of paleoseismic earthquake chronologies—primarily related to the uncertainty in earthquake times—make confident determinations of prehistoric coseismic (i.e., synchronous) rupture on a master-antithetic fault pair virtually impossible. Also, the incomplete chronology for the WVFZ complicates direct comparison with the more complete record of the SLCS. Still, a comparison of WVFZ and SLCS chronologies can provide insight into whether an earthquake on the WVFZ may have been, or clearly was not, coseismic with an earthquake on the SLCS. Such a comparison can also show to what degree earthquakes on the WVFZ may be linked to fault activity on the SLCS.

Table 6 and figure 15 show several significant similarities in the times of specific earthquakes on the WVFZ and SLCS (see DuRoss and others [2014] for discussion of the SLCS chronology based on correlation of earthquakes documented at different sites). In particular, the mean times and two-sigma ranges for WVFZ earthquakes W1, W2, W3, and W4 are very similar to those for SLCS earthquakes S1, S2, S4, and S8, respectively (although the earthquake times of W1 and W2 are somewhat less robust given the caveats discussed above in the “Earthquake Timing and Recurrence” section). As figure 15 shows, the mean time of W2 is identical to that of SLCS earthquake S2 as documented at South Fork Dry Creek/Dry Gulch, and differs from the S2 mean time documented at Little Cottonwood Canyon by only 100 yr (~5%). Likewise, the mean time of W3 is identical to that of SLCS earthquake S4 as documented at Little Cottonwood Canyon, and differs from the S4 mean times documented at Penrose Drive and South Fork Dry Creek by ≤ 500 yr ($\leq 10\%$). SLCS earthquake S8 has been documented at only one site (Penrose Drive), but its mean time differs from that of W4 by only 200 yr (2%). The mean time and two-sigma range for W5 do not indicate a clear temporal association with a SLCS earthquake; perhaps the relatively short W5–W4 inter-event recurrence interval (0.7 kyr) indicates two WVFZ earthquakes associated with a single SLCS earthquake (S8), or one associated earthquake and one independent earthquake (unlikely, in our opinion). Alternatively, evidence for an SLCS earthquake around the time of W5 may have been removed by erosion or otherwise not documented in the SLCS trench exposures (DuRoss and others, 2014). Finally, the mean time of W6 is similar to that of

Table 6. Comparison of earthquake times on the West Valley fault zone and Salt Lake City segment.

Preliminary WVFZ Chronology			Preliminary SLCS Chronology	
Earthquake	Mean Time (ka)	2 σ Range (ka)	Earthquake	Min–Max Range ¹ (ka)
W1 ²	1.4	0.7–2.1	S1	1.1–1.5
W2 ²	2.2	2.0–2.4	S2	1.8–2.6
–	–	–	S3	3.2–4.9
W3	5.5	4.7–6.3	S4	4.5–6.6
–	–	–	S5	6.7–8.5
–	–	–	S6	8.6–10.8
–	–	–	S7	10.7–11.1
W4	12.3	11.2–13.4	S8	10.5–13.7
W5	13.0	11.9–14.1	–	–
W6	15.7	12.3–19.1	S9	13.8–19.2

¹ Salt Lake City segment chronology represented by minimum and maximum earthquake times derived generally from 2 σ ranges for earthquakes at different sites that are considered to correlate with each other based on OxCal modeling (DuRoss and others, 2014). See figure 15 for a graphical representation of mean times and 2 σ ranges for earthquakes at the different sites on the West Valley fault zone and Salt Lake City segment.

² Earthquake time poorly constrained; see appendix H.

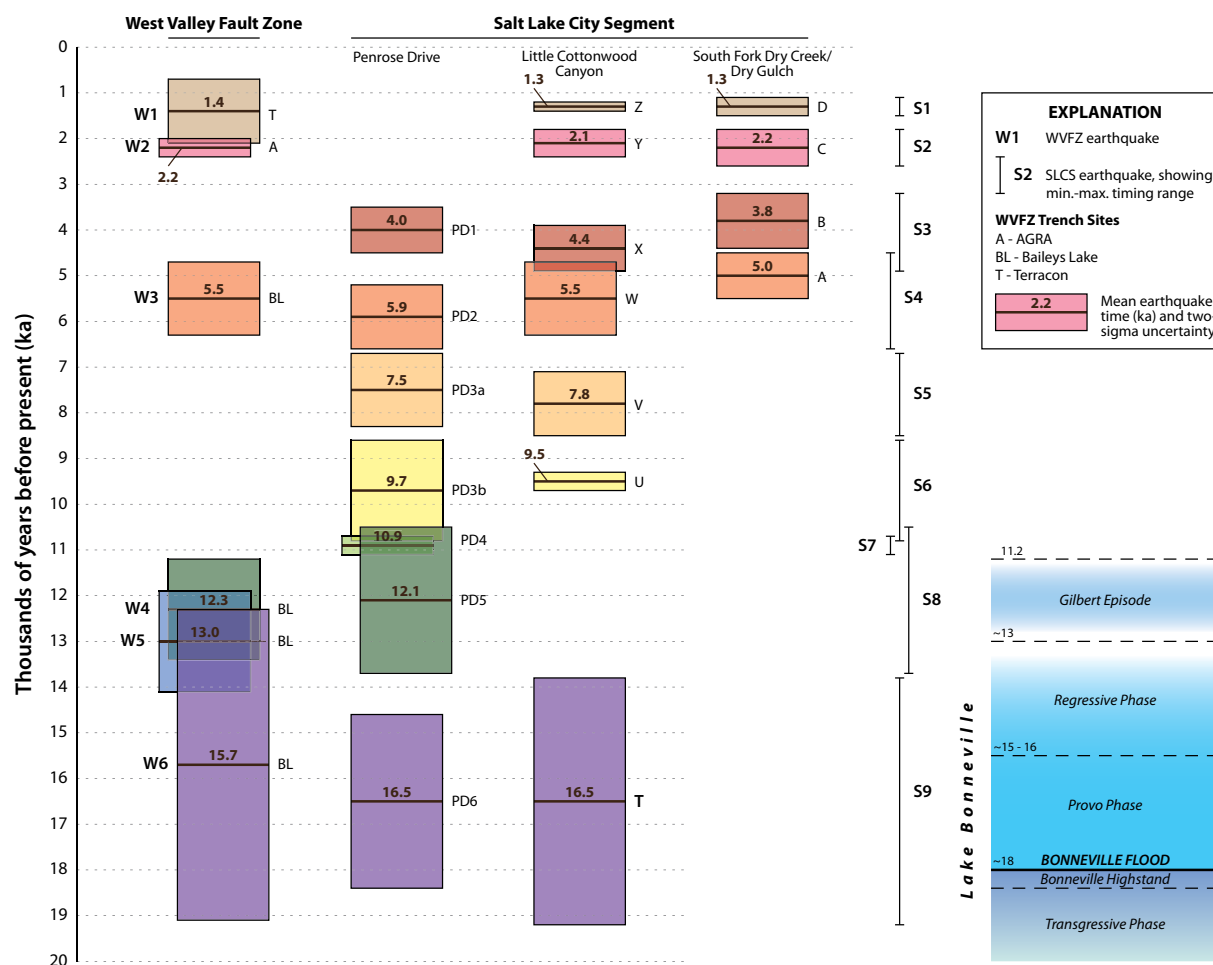


Figure 15. Comparison of surface-faulting chronologies for the West Valley fault zone and Salt Lake City segment (modified from DuRoss and others, 2014). Note that the time of earthquake W1 is based on a single limiting age (see discussion in text, and appendix H). Schematic Lake Bonneville and Gilbert-episode chronologies shown at the same temporal scale for comparison with late Pleistocene earthquake times. Sources of earthquake timing information: West Valley fault zone—this study; Penrose Drive site—DuRoss and others (2014); Little Cottonwood Canyon site—McCalpin (2002), modified by OxCal modeling (DuRoss and others, 2014); South Fork Dry Creek/Dry Gulch site—Black and others (1996), modified by OxCal modeling (DuRoss and others, 2014).

SLCS earthquake S9 as documented at Penrose Drive and Little Cottonwood Canyon; the 800-yr difference in mean times between these late Pleistocene (~15–16 ka) events represents a difference of only ~5%.

The paleoseismic timing data are consistent with displacement modeling and a general structural model that suggests seismogenic dependence of the WVFZ on SLCS activity. Five of six paleoearthquakes documented on the WVFZ have mean earthquake times and two-sigma ranges that are similar to those of SLCS earthquakes; the one WVFZ earthquake that does not have a clear temporal association with a SLCS earthquake (W5) occurred in the latest Pleistocene (~13 ka), a period in which the SLCS record may be incomplete (DuRoss and others, 2014). Additionally, per-event vertical displacements on the WVFZ (generally 0.4–0.7 m, but perhaps as large as 1.5 m) are similar to those predicted by two-dimensional boundary-element modeling of antithetic faulting triggered by slip on a listric master fault (0.2–0.7 m;

after Bruhn and Schultz, 1996). Finally, although the precise subsurface geometry of the WVFZ–SLCS fault system is unknown, the modeling of Bruhn and Schultz (1996) and seismic reflection profiles across the SLCS and elsewhere across the Wasatch fault zone (Bashore and others, 1981; Bashore, 1982; Smith and Bruhn, 1984; Velasco and others, 2010) indicate the potential for a listric geometry for the SLCS, or at least a flattening of dip at some depth within the seismogenic crust. This structural geometry suggests that the antithetic WVFZ has formed in response to rollover and collapse in the SLCS hanging wall (after the model of Xiao and Suppe, 1992; see also Withjack and others, 1995), and therefore WVFZ movement is likely coseismic (i.e., synchronous) with SLCS movement. Based on comparison of WVFZ and SLCS paleoearthquake timing and displacement data, we infer that large earthquakes on the WVFZ are more likely to be synchronous with or triggered by fault movement on the SLCS than occurring independently of movement on the SLCS. Kinematic and geometric model-

ing of the fault system also indicates a high likelihood for synchronous rupture.

SUMMARY AND CONCLUSIONS

We conducted a fault-trench investigation at the Baileys Lake site on the WVFZ to answer significant questions regarding the timing, displacement, and recurrence of large ($M \sim 6.5$) surface-faulting earthquakes on the WVFZ. We also compared WVFZ earthquake timing and displacement data with data from the SLCS, including new data from the Penrose Drive site on the northern SLCS, to determine whether the WVFZ is seismically independent of, or moves coseismically with, the SLCS.

At the Baileys Lake site, we excavated three trenches across two small (<1 -m-high) east-facing fault scarps near the northern end of the Granger fault, which comprises the westernmost traces of the WVFZ. Our trenches exposed late Quaternary geologic deposits consisting of Holocene loess, a nearly complete Lake Bonneville section, and pre-Bonneville wetland/alluvial-marsh sediments dated at 35.8 ± 0.8 ka. Fault-zone deformation exposed at the western scarp includes monoclinial warping and discrete shear offset, whereas we observed only broad, monoclinial warping at the eastern scarp. Stratigraphic and structural relations provide evidence for four surface-faulting earthquakes on the western fault trace, and at least one folding event on the eastern fault trace that may or may not correlate with the most recent surface faulting on the western trace. Seven radiocarbon ages, 14 OSL ages, and 13 ostracode samples provide temporal constraints on earthquake times, which we modeled using OxCal calibration and analysis software. The earliest earthquake, BL4, has a clear event horizon and associated seismite, and occurred at 15.7 ± 3.4 ka (2σ); BL4 was a sublacustrine event (Provo phase of Lake Bonneville). Earthquake BL3, evidenced by fault terminations and timing constraints on deformation of lacustrine strata in the fault zone, occurred at 13.0 ± 1.1 ka, after Lake Bonneville's regression to very low levels and before transgression of the Gilbert lake across the site. Earthquakes BL2 and BL1, the only earthquakes at the Baileys Lake site for which scarp-derived colluvium has been preserved, occurred at 12.3 ± 1.1 ka (during the Gilbert episode) and 5.5 ± 0.8 ka (post-Gilbert), respectively. Average per-event vertical displacement for the Granger fault at the Baileys Lake site is 0.5 ± 0.1 m.

Combining the Baileys Lake data with previous paleoseismic data yields a paleoearthquake chronology comprising six earthquakes for the WVFZ as a whole: five on the Granger fault and one on the Taylorsville fault. Mean recurrence over different time intervals ranges from 3.6 to 5.4 kyr for the Granger fault, and from 2.0 to 3.6 kyr for the WVFZ as a whole. Given the distributed nature of surface faulting on the WVFZ, the variability in recurrence intervals likely results from differences in surface-faulting activity on different fault

strands, as well as from an incomplete earthquake chronology for the fault zone as a whole.

Our calculated slip rates for the Granger fault of 0.09–0.12 mm/yr (post-Bonneville highstand) and 0.06–0.09 mm/yr (Holocene), based on data from the Baileys Lake site, fall within the previously determined range for the fault of 0.03–0.5 mm/yr (Keaton and others, 1987; Keaton and Currey, 1989). Because of the small number of earthquakes documented in paleoseismic trenching studies and the likelihood of an incomplete paleoseismic record for the WVFZ, we do not attempt to evaluate changes in slip rate over time for the WVFZ as a whole based on inter-event times and per-event displacements.

All but one of the earthquakes documented on the WVFZ have mean times and two-sigma ranges that are very similar to those of SLCS earthquakes. The one WVFZ earthquake that does not have a clear temporal association with a SLCS earthquake occurred in the latest Pleistocene (~ 13 ka), a period in which the SLCS record may be incomplete. Also, per-event vertical displacements on the WVFZ (generally 0.4–0.7 m from trench data) are similar to those predicted by two-dimensional boundary-element modeling of antithetic faulting triggered by slip on a listric master fault (0.2–0.7 m; after Bruhn and Schultz, 1996). Based on comparison of WVFZ and SLCS earthquake timing and displacement data, large earthquakes on the WVFZ that are coseismic with or triggered by fault movement on the SLCS have a higher likelihood than WVFZ earthquakes that occur independently of movement on the SLCS. When considered together with mechanical and geometric models of the fault system, the paleoseismic data support a high likelihood for synchronous rupture of the WVFZ with the SLCS.

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APPENDIX A

DESCRIPTION OF STRATIGRAPHIC UNITS IN TRENCHES AT THE BAILEYS LAKE SITE

Unit ¹	USCS ²	Texture (wt. %) ³	Plast. ⁴	Dens./ Consist. ⁵	Carb. Morph. ⁶	Rxn w/HCl ⁷	Clast Ang. ⁸	Bedding ⁹	Lower Bound. ¹⁰	Color, dry (moist) ¹¹	Soil Development	Comments and Genesis
11	ML	99/1/0	M-H	VSt	none	M	—	NS	Ab-Cl	10YR 6/2 (10YR 4/2)	Modern platy A horizon (soil unit S2); burrowed/root-mixed; pinhole structure, root pores	Organic-rich clayey silt; discontinuous, locally filling in topographic depressions; massive, overprinted by modern A horizon; Loess
10	ML, OL	95/5/0	M	VSt	none	M-S	—	NS	Cl	10YR 6/2 (10YR 4/2)	Organics throughout deposit; locally root-penetrated and burrowed	Disaggregated soil with silt; colluvium composed of small granular soil blocks eroded from prismatic soil (soil unit S1); massive; may be in part contemporaneous with unit 11; Scarp-Derived Colluvium (BL1 wedge)
9	ML	99/1/0	M	VSt	none-II	S	—	NS	Ab-Cl	10YR 8/1 (10YR 7/2)	Prismatic soil (buried; soil unit S1); abundant carbonate (both primary and pedogenic); minor Fe staining; abundant root pores, heavily burrowed	Massive silt with clay; Loess
8	CL	98/2/0	L-M	VSt	none-II	S	—	WS	Ab-Cl	5Y 7/1 (2.5Y 6/2)	Vertical jointing; root pores, locally burrowed	Finely laminated clay, silt, and carbonate (marl); bedding locally wavy; locally cemented with carbonate (depositional); Lacustrine (Gilbert episode)
7	SP	2/98/0	NP	H	none	S	SA	WS	Ab	10YR 5/1 (10YR 3/2)	No soil development; minor burrowing	Dark gray, medium to coarse sand and minor silt; clast-supported texture; locally thinly bedded, fining upward, and cemented with carbonate (likely depositional); thins westward; Lacustrine (Gilbert episode [shorezone sand])

Unit ¹	USCS ²	Texture (wt. %) ³	Plast. ⁴	Dens./ Consist. ⁵	Carb. Morph. ⁶	Rxn w/HCl ⁷	Clast Ang. ⁸	Bedding ⁹	Lower Bound. ¹⁰	Color, dry (moist) ¹¹	Soil Development	Genesis and Comments
6	ML	99/1/0	M	VSt	none-II	M-S	—	V	Ab-CI	10YR 6/2 (10YR 5/3) to 10YR 8/1 (10YR 6/2)	Organics throughout fine-grained "soil stringers"; some organics mixed with fine- grained colluvium; burrowed; local carbonate cementation	Colluvium comprising disaggregated fragments (fine gravel size) of clay, silt, and sand eroded from scarp, interbedded with 0.5–3 cm thick, organic-rich, fine grained "soil stringers" that thicken to the east and have slope-parallel geometry; Scarp-Derived Colluvium (BL2 wedge)
5	CL	99/1/0	L	VSt	none	S	—	WS	CI	10YR 7/1 (2.5Y 6/3)	Vertical jointing; root pores with minor Fe staining; minor burrowing	Laminated clay and silt with carbonate (marl); conformably drapes pre-existing topography; locally differentiated as 5a and 5b; upper unit (5b)— finely laminated; lower unit (5a)— laminated to thin bedded, locally massive; few ostracodes, mostly unidentifiable fragments; Lacustrine (Gilbert episode)
4	SW, CH	10/80/10	NP, H	M, VSt	none	S	A-SA	WS-V	Ab	10YR 8/1 (10YR 8/2)	No soil development	Primarily carbonate fragments (reworked "hash") with local in situ precipitated carbonate (locally well-cemented, wavy tufa mats); locally includes clay, silt, and fine to coarse sand; clast-supported texture; Lacustrine (Gilbert episode, transgressive [shorezone tufa])
3	CH	90/10/0	H	VSt	none	W-M	—	WS	Ab	2.5Y 7/2 (5Y 5/2)	Root pores; Fe and Mn staining; pervasive vertical jointing	Finely laminated greenish clay and silt; blocky weathering due to joints and silt partings; prominent parting observed locally 25–30 cm above base; few ostracodes, most broken; Lacustrine (Bonneville, regressive phase)

Unit ¹	USCS ²	Texture (wt. %) ³	Plast. ⁴	Dens./ Consist. ⁵	Carb. Morph. ⁶	Rxn w/HCl ⁷	Clast Ang. ⁸	Bedding ⁹	Lower Bound. ¹⁰	Color, dry (moist) ¹¹	Soil Development	Genesis and Comments
2e	CH, ML	99/1/0	H	VSt	none	W, S	—	WS	Ab	7.5YR 7/3 (7.5YR 5/4)	Root pores and Fe staining; vertical jointing	Massive red clay with 2–3-cm-thick silty clay (upper) and sandy silt (lower) interbeds exhibiting open, upright folds; red color grades to gray in uppermost 10–18 cm; few to abundant ostracodes; Lacustrine (Bonneville, mid- to late transgressive phase)
2d	CL–SP	50/50/0	M–NP	VSt–H	none	M	—	WS	Ab	2.5Y 6/2 (2.5Y 5/3)	No soil development; local Fe staining	Upper part: ~10-cm-thick clay with silt and fine sand; Lower part: ~10-cm-thick fine sand with thin, red and green clay fragments (rip-up clasts); Turbidite Marker Bed (Bonneville, mid- to late transgressive phase)
2c	CH ML–SP	99/1/0 50/50/0	H NP	St M–H	none none	W W	— —	WS WS	Ab Ab	7.5YR 7/2 (7.5YR 5/3) 2.5Y 7/3 (2.5Y 5/3)	Root pores and minor filaments; minor Fe staining	Red clay with gray, 2–10-cm-thick silt and fine sand interbeds; clay beds contain ostracodes, some broken; Lacustrine (Bonneville, transgressive phase with turbidites)
2b	CH	99/1/0	H	St	none	W–S	—	PS	Ab	U: 5YR 8/2 (5YR 4/3) L: 2.5Y 8/2 (2.5Y 7/2)	Root pores, decayed filaments, and considerable oxidation (Fe and Mn) in upper ~0.5 m, where red clay grades to gray with depth; minor carbonate nodules	Massive light gray clay (red in upper ~0.5 m) with few laterally continuous silt partings; prominent parting 15 cm below top; few to abundant ostracodes; Lacustrine (Bonneville, transgressive phase)

Unit ¹	USCS ²	Texture (wt. %) ³	Plast. ⁴	Dens./ Consist. ⁵	Carb. Morph. ⁶	Rxn w/HCl ⁷	Clast Ang. ⁸	Bedding ⁹	Lower Bound. ¹⁰	Color, dry (moist) ¹¹	Soil Development	Genesis and Comments
2a	SM	40/60/0	NP-H	M	none	M	—	WS	Ab	10YR 6/3 (10YR 4/2)	No soil development; local weak to moderate Fe staining; locally cemented with nodular carbonate, especially near fault zone	Ripple-laminated, locally cross-bedded (westerly apparent dip) silty sand with clay interbeds; generally fining upward; gastropod shells and shell fragments and few ostracodes in clay; Lacustrine (Bonneville, early transgressive phase)
1	CH	99/1/0	H	St	none	W-M	—	V	NE	5Y 6/2 (5Y 4/2) to 2.5Y 7/0 (2.5Y 5/0)	Root pores with minor oxidation (mottling), decayed filaments; ≥30- cm-thick oxidized zone; weak vertical structure (fractures); local burrowing	Gray to brown clay thinly interbedded with white fine sand; Pre-Bonneville Wetland/Alluvial Marsh

¹ Units as shown on plate 1, listed in stratigraphic order (top to bottom).

² Unified Soil Classification System (ASTM D2488).

³ Percentages of fines/sand/gravel fractions are field estimates.

⁴ Plasticity: NP – nonplastic, L – low, M – medium, H – high.

⁵ Density: Ls – loose, L – low, M – medium, H – high; Consistency: Vsf – very soft, S – soft, St – stiff, VSt, very stiff.

⁶ Pedogenic carbonate morphology; stage designations after Machette (1985) and Birkeland and others (1991).

⁷ Reaction with HCl: W – weak, M – moderate, S – strong.

⁸ Clast angularity: A – angular, SA – subangular, SR – subrounded, R – rounded.

⁹ Bedding: NS – nonstratified, PS – poorly stratified, WS – well stratified, V – variable.

¹⁰ Lower boundary: Ab – abrupt, Cl – clear, Gr – gradual, NE – not exposed.

¹¹ Munsell color of matrix. L, lower part of unit; U, upper part of unit.

APPENDIX B

DESCRIPTION OF PEDOGENIC SOIL UNITS IN TRENCHES AT THE BAILEYS LAKE SITE

Unit ¹	Horizon	Depth (cm)	Color, dry (moist) ²	Structure (type, grade, size) ³	Gravel (%)	Consistence, dry (wet) ⁴	Texture	Clay Films (amount, distinctness, location)	Lower Boundary ⁵	Comments
Site 1: West(N) trench, south wall, horizontal meter mark 34.0										
S2	A	0–13	10YR 6/2 (10YR 4/2)	gr–pl, moderate, fine to medium	0	sh (ss, ps)	Silty clay loam	None	a, w	Root penetrated, abundant pores; no visible carbonate.
S2	AB	13–20	10YR 6/2 (10YR 4/2)	massive	0	h (ss, ps)	Silty clay loam	None	a–c, w	Soil developed on loess; abundant roots, root pores, burrowing; no visible carbonate.
S1	Bt	20–40	10YR 6/2 (10YR 4/2)	pr–abk, moderate, fine	0	h (ss, ps)	Silty clay loam to silty clay	Few, faint, clay films line tubular or interstitial pores	c–g, w	Abundant roots, root pores, minor burrowing; minor carbonate, likely inherited from parent material (loess and playa clays).
Site 2: West(N) trench, south wall, horizontal meter mark 15.8										
S2	A	0–20	10YR 6/2 (10YR 4/2)	gr–pl, moderate, fine to medium	0	sh (ss, ps)	Silty clay loam	None	a, w	Root penetrated, abundant pores, burrowed; no visible carbonate.
S2	AB	20–32	10YR 6/2 (10YR 4/2)	massive	0	h (ss, ps)	Silty clay loam	None	a–c, w	Soil developed on loess; abundant roots, root pores, burrowing; no visible carbonate.
S1	Bt	32–47	10YR 6/2 (10YR 4/2)	pr–abk, moderate, fine	0	h (ss, ps)	Silty clay loam to silty clay	Few, faint, clay films line tubular or interstitial pores	c–g, w	Abundant roots, root pores, minor burrowing; minor carbonate, likely inherited from parent material (loess and playa clays).

Note: Abbreviations and symbols used to describe soil properties after Birkeland and others (1991).

¹ Units as shown on plate 1.

² Munsell color of matrix.

³ Structure type: gr – granular, abk – angular blocky, sbk – subangular blocky, pr – prismatic, cpr – columnar, pl – platy.

⁴ Dry consistence: lo – loose, so – weakly coherent, sh – slightly hard, h – hard, vh – very hard, eh – extremely hard. Wet consistence (stickiness): so – nonsticky, ss – slightly sticky, s – sticky, vs – very sticky. Wet consistence (plasticity): po – nonplastic, ps – slightly plastic, p – plastic, vp – very plastic.

⁵ Boundary distinctness: a – abrupt (<2 cm), c – clear (2–5 cm), g – gradual (5–15 cm), d – diffuse (>15 cm). Topography: s – smooth, w – wavy, i – irregular, b – broken.

APPENDIX C

PROCESSING AND ANALYSIS OF RADIOCARBON SAMPLE MATERIAL FROM THE BAILEYS LAKE SITE BY PALEORESEARCH INSTITUTE

Table C.1. Correlation of original and final sample identification numbers.

Original Field ID ¹	Final ID ²	Comments
BL-R1	BL-R1	–
BL-R2a	BL-R2-1	–
BL-R2b	BL-R2-2	–
BL-R3a	–	Possible contamination from burrowing; not submitted for processing
BL-R3b	BL-R3-1	7 fragments unidentified hardwood (PRI)
	BL-R3-2	45 fragments unidentifiable charcoal and stems (PRI)
BL-R4	BL-R4	–
BL-R5	BL-R5	–

¹ Sample identification used in PaleoResearch Institute (PRI) report (this appendix).

² Sample identification used in this report.

EXAMINATION OF BULK SEDIMENT AND MICROCHARCOAL EXTRACTION FOR
SAMPLES FROM THE BAILEYS LAKE TRENCH SITE,
SALT LAKE CITY, UTAH

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INTRODUCTION

Six bulk soil samples from two paleoseismic trenches were floated to recover organic fragments suitable for radiocarbon analysis. These samples were collected from the Baileys Lake trench site on the Granger fault in Salt Lake City, Utah, as part of the Utah Geological Survey's efforts to develop detailed information on the timing and recurrence of paleoearthquakes in the West Valley fault zone. Botanic components and detrital charcoal were identified, and potentially radiocarbon datable material was separated. Four of the samples yielded sufficient charred material that can be submitted for AMS radiocarbon analysis. In the absence of larger-sized charred remains, one of the samples was extracted to recover microscopic charcoal/particulate soil organics for dating. Samples for AMS radiocarbon dating will be submitted to Woods Hole Institute.

METHODS

Flotation and Charcoal Identification

The samples were water-screened a 150 micron mesh sieve, taking care to retain all material that passed through the screen for possible microcharcoal and/or humate extraction. The water-screened portion was floated using a modification of the procedures outlined by Matthews (1979). Each sample was added to approximately 3 gallons of water, then stirred until a strong vortex formed. The floating material (light fraction) was poured through a 150 micron mesh sieve. Additional water was added and the process repeated until all floating material was removed from the sample (a minimum of five times). The material that remained in the bottom (heavy fraction) was poured through a 0.5-mm mesh screen. The floated portions were allowed to dry. The light fractions were weighed, then passed through a series of graduated screens (US Standard Sieves with 2-mm, 1-mm, 0.5-mm and 0.25-mm openings) to separate charcoal debris and to initially sort the remains. The contents of each screen then were examined.

Charcoal fragments, when present, were separated and broken to expose fresh cross, radial, and tangential sections, then examined under a binocular microscope at a magnification of 70x and under a Nikon Optiphot 66 microscope at magnifications of 320-800x. The weights of each charcoal type were recorded. The material that remained in the 2-mm, 1-mm, 0.5-mm, and 0.25-mm sieves was scanned under a binocular stereo microscope at a magnification of 10x, with some identifications requiring magnifications of up to 70x. The material that passed through the 0.25-mm screen was not examined. Remains were recorded as charred and/or uncharred, whole and/or fragments. The term "seed" is used to represent seeds, achenes, caryopses, and other disseminules. Macrofloral remains, including charcoal, are identified using manuals (Carlquist 2001; Hoadley 1990; Martin and Barkley 1961; Musil 1963; Panshin and de Zeeuw 1980; Schopmeyer 1974) and by comparison with modern and archaeological references. Because charcoal and possibly other botanic remains were to be submitted for radiocarbon dating, clean laboratory conditions were used during flotation and identification to avoid contamination. All instruments were washed between samples, and samples were protected from contact with modern charcoal.

Microcharcoal Recovery

Now it is possible to recover microscopic charcoal (microcharcoal) from sediments for the purpose of obtaining an AMS radiocarbon age. Microscopic charcoal fragments are far superior to humates because they provide dates with the same precision as those obtained from larger pieces of charcoal, with the single exception that the individual pieces of microscopic charcoal are not identified to taxon.

A chemical extraction technique based on that used for pollen, and relying upon heavy liquid extraction, has been modified to recover microcharcoal for the purpose of obtaining an AMS radiocarbon age. After removing calcium carbonates and iron with hydrochloric acid (10%), the sample was screened through 150 micron mesh. The material remaining in the screen was examined for the presence of macroscopic charcoal. Since no macroscopic charcoal was found, the screened sample then was rinsed until neutral, and a small quantity of sodium hexametaphosphate was added. The sample then was filled with reverse osmosis, deionized (RODI) water and allowed to settle according to Stoke's Law. After two hours the supernatant, containing clay, was poured off and the sample was rinsed with RODI water three more times, being allowed to settle according to Stoke's Law after each rinse to remove more clays. This settling process was repeated until the supernatant was clear of clays. Once the clays had been removed, the sample was freeze-dried using a vacuum system, freezing out all moisture at -107 °C. Sodium polytungstate (SPT), with a density of 1.8, was used for the flotation process. The sample was mixed with SPT and centrifuged at 1500 rpm for 10 minutes to separate organic from inorganic remains. The supernatant containing pollen, organic remains, and microcharcoal was decanted. Sodium polytungstate again was added to the inorganic fraction to repeat the separation process until all visible microcharcoal had been recovered. The microcharcoal was recovered from the sodium polytungstate and rinsed thoroughly with RODI water. Following this step, the sample was examined using a binocular microscope at a magnification of up to 30x to check the matrix for microscopic charcoal and other debris. Each sample received a treatment with hot hydrofluoric acid (40%) to remove all visible silica. RODI water rinses followed, with another examination with the binocular microscope. The hydrofluoric acid treatments were repeated, but it still was not possible to remove all of the inorganic remains.

DISCUSSION

The Bailey's Lake Site consists of three trenches excavated across two parallel strands of the Granger Fault, located within Salt Lake City in Utah's West Valley fault zone. The West Valley fault zone (WVFZ), previously termed the Jordan Valley fault zone, trends north-northeast through an urbanized area three miles southwest of downtown Salt Lake City. The Granger Fault in the southern WVFZ presents as an east-facing scarp with heights of as great as 6.1 meters. The site lies at the approximate elevation of the Late Holocene highstand of Great Salt Lake and below the elevation of the Gilbert shoreline of Lake Bonneville.

Modern surface vegetation in this area includes saltbush (*Atriplex*), rabbitbrush, (*Chrysothamnus*), and grasses (Poaceae) (Michael Hylland, personal communication, November 2010). This area has experienced modifications from the excavation of canals,

ditches, and pipeline trenches, as well as introduction of fill for roadside embankments and footings for powerline towers. The site also has been intermittently grazed by livestock. Excavations at the Bailey's Lake trench site exposed possible pre-Bonneville marsh deposits, sandy to clayey Bonneville lake-cycle deposits, fine-grained wetland and/or Gilbert lake-cycle deposits, sandy fluvial sediment, loess, and fault-scarp-derived colluvium. Six bulk soil samples from these excavations were submitted for macrofloral analysis prior to radiocarbon dating.

West(N) Trench

Sample BL-R1 was collected from the north wall of the northern-most of the two western trenches from soil S3 and was buried by P1 colluvium (Table 1). This sample will provide a broad minimum date for P2. Several fragments of charcoal too small and vitrified for identification were present in this sample, as well as several small, unidentified charred stem fragments (Table 2, Table 3). Vitrified charcoal has a shiny, glassy appearance due to fusion by heat. The charred stem fragments and the charcoal fragments were noted only in the 0.25 mm screen and were so small that it was difficult and time consuming to try and separate these remains; therefore the charred material was left combined and yielded a total weight of 0.0112 g. Four charred *Scirpus*-type seeds also were noted and suggest the presence of bulrush growing along the lake margin. Uncharred bark scale fragments, an uncharred *Erodium* seed, and uncharred roots and rootlets reflect modern plants in the area. The sample also yielded a few, small uncharred bone fragments, two insect chitin fragments, a few snail shell fragments, and a small amount of muscovite.

Sample BL-R2 was processed as two separate samples, designated BL-R2a and BL-R2b. Sample BL-R2a is a fragmented bulk soil sample collected from dark, inclined beds in P2 colluvium in the north wall of the northern West trench. This sample will provide a possible minimum age for P2 and a broad maximum age for P1. A charred Cheno-am perisperm and six charred *Scirpus*-type seed fragments were noted in sample BL-R2a, each weighing less than 0.0001 g. Cheno-am seed perisperm (similar to endosperm) consists of the nutritive tissue of the seed, surrounding and absorbed by the embryo. It represents a mature seed that has lost the outer seed coat (testa). Charred unidentified stem fragments and charcoal fragments too small and vitrified for identification from the 0.25 mm screen weighed a total of 0.0052 g. In addition, the sample contained a few root fragments, numerous rootlets, a few small bone fragments, an insect chitin fragment, and a moderate amount of snail shells.

Sample BL-R2b was recovered from dark, inclined beds in P2 colluvium as an intact block and will provide a possible minimum age for P2 and a broad maximum age for P1. Charred unidentified stem fragments and small, vitrified charcoal fragments from the 0.25 mm screen of sample BL-R2b yielded a total weight of 0.0043 g. A charred unidentified fruit fragment weighing less than 0.0001 g, a few uncharred rootlets, a few snail shells, and a small amount of muscovite also were noted.

Sample BL-R3b was taken from P1 colluvium in the north wall of the northern-most of the two western trenches and will provide a possible minimum age for P1. This sample yielded seven fragments of hardwood charcoal too small for further identification weighing 0.0055 g. Charcoal too small for identification and several charred unidentified stem fragments from the 0.25 mm screen weighed a total weight of 0.0077 g.

West(S) Trench

Sample BL-R4 was collected from the upper part of Unit 1a, a possible pre-Bonneville marsh deposit, in the south wall of the southern-most of the two western trenches. This sample will act as an age control for the lacustrine sequence and will provide a broad maximum age for P4. Recovery of three charred *Scirpus*-type seed fragments weighing less than 0.0001 g again note the presence of bulrush. A single piece of charcoal noted in the 0.25 mm screen weighing less than 0.0001 g was too small and vitrified for identification and too small for radiocarbon dating. As a result, the sediment that passed through the 150 micron mesh sieve during water-screening was processed to recover microcharcoal or particulate soil organics. Microcharcoal extraction resulted in a total weight of 0.0025 g, approximately 25-30% of which is insoluble microminerals. This microcharcoal sample is sufficient for AMS radiocarbon dating.

Sample BL-R5 is a bulk soil sample collected from Unit 3, a late Pleistocene-early Holocene wetland or shallow lacustrine deposit, in the south wall of the southern-most of the two western trenches to provide the maximum age for P3 and a broad minimum age for P4. No organic material was noted in this sample, which contained only clay and muscovite.

SUMMARY AND CONCLUSIONS

Macrofloral analysis of sediment samples from paleoseismic trenches at the Baileys Lake trench site on the Granger fault in Salt Lake City, Utah, yielded charred organic remains that can be submitted for AMS radiocarbon dating. All four samples from the West(N) trench contained small charred stem fragments and charcoal too small and vitrified for identification in sufficient quantities for dating. Sample BL-R4 from the West(S) trench did not yield sufficient macroscopic charred remains; however, a sufficient quantity of microscopic charcoal fragments were recovered for dating. Sample BL-R5 yielded no organic remains.

TABLE 1
PROVENIENCE DATA FOR SAMPLES FROM THE BAILEYS LAKE SITE, SALT LAKE CITY, UTAH

Sample Number	Trench	Wall	Sample location (horiz., vert.)	Provenience/ Description	Analysis
BL-R1	West(N)	North	22.1-22.4m, 3.3m	Bulk sample from soil S3 buried by P1 colluvium; maximum age for P1, broad minimum for P2	Macrofloral
BL-R2a			22.1m, 3.1-3.2m	Bulk sample from dark, inclined beds in P2 colluvium; minimum(?) age for P2, broad maximum for P1	Macrofloral
BL-R2b			22.1m, 3.1-3.2m	Bulk sample from dark, inclined beds in P2 colluvium; minimum(?) age for P2, broad maximum for P1	Macrofloral
BL-R3b			22.2m, 3.5m	Bulk sample from P1 colluvium; minimum (?) age for P1	Macrofloral
BL-R4	West(S)	South	25.8m, 1.1m	Bulk sample from upper part of unit 1a (possible pre-Bonneville marsh deposits); age control for lacustrine sequence, broad maximum age for P4	Macrofloral Microcharcoal
BL-R5			17.4m, 2.2m	Bulk sample from unit 3 (latest Pleistocene-early Holocene wetland or shallow lacustrine deposits); maximum age for P3, broad minimum for P4	Macrofloral

TABLE 2
MACROFLORAL REMAINS FROM THE BAILEYS LAKE SITE, SALT LAKE CITY, UTAH

Sample No.	Identification	Part	Charred		Uncharred		Weights/ Comments
			W	F	W	F	
BL-R1	Liters Floated						1.00 L
West(N) trench North wall	Light Fraction Weight						0.445 g
	FLORAL REMAINS:						
	<i>Scirpus</i> -type	Seed		4			< 0.0001 g
	Unidentified	Bark scale			2		
	<i>Erodium</i>	Seed			1		
	Roots					X	Few
	Rootlets					X	Numerous
	CHARCOAL/WOOD:						
	Total charcoal \geq 0.25 mm						0.0112 g
	Unidentifiable charcoal - vitrified, small + Unidentified charred stem fragments	Charcoal/ Stem		X			0.0112 g
	NON-FLORAL REMAINS:						
	Bone < 2 mm					X	Few
	Gravel					X	Few
	Insect	Chitin				2	
Muscovite					X	Few	
Snail shell < 2 mm					X	Few	
BL-R2a	Liters Floated						0.40 L
West(N) trench North wall	Light Fraction Weight						0.468 g
	FLORAL REMAINS:						
	Cheno-am	Perisperm	1				< 0.0001 g
	<i>Scirpus</i> -type	Seed		6			< 0.0001 g
	Roots					X	Few
	Rootlets					X	Numerous
	CHARCOAL/WOOD:						
	Total charcoal \geq 0.25 mm						0.0052 g
	Unidentifiable charcoal - vitrified, small + Unidentified charred stem fragments	Charcoal/ Stem		X			0.0052 g

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred		Uncharred		Weights/ Comments
			W	F	W	F	
BL-R2a	NON-FLORAL REMAINS:						
West(N) trench North wall	Bone < 2 mm	Chitin				X	Few
	Gravel					X	Few
	Insect					1	
	Muscovite					X	Few
	Snail shell \geq 2 mm					1	0.003 g
	Snail shell < 2 mm				10	X	Moderate
BL-R2b	Liters Floated						0.10 L
West(N) trench North wall	Light Fraction Weight						0.788 g
	FLORAL REMAINS:						
	Unidentified	Fruit		1			< 0.0001
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Total charcoal \geq 0.25 mm						0.0043 g
	Unidentifiable charcoal - vitrified, small + Unidentified charred stem fragments	Charcoal/ Stem		X			0.0043 g
	NON-FLORAL REMAINS:						
	Gravel					X	Few
	Muscovite					X	Few
	Snail shell < 2 mm					X	Few
BL-R3b	Liters Floated						0.90 L
West(N) trench North wall	Light Fraction Weight						3.073 g
	FLORAL REMAINS:						
	Unidentified	Bark scale			3		
	Rootlets					X	Few
	CHARCOAL/WOOD:						
	Total charcoal \geq 0.5 mm						0.0132 g
	Unidentified hardwood	Charcoal		7			0.0055 g
	Unidentifiable charcoal - vitrified, small + Unidentified charred stem fragments	Charcoal/ Stem		45			0.0077 g

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred		Uncharred		Weights/ Comments
			W	F	W	F	
BL-R3b	NON-FLORAL REMAINS:						
West(N) trench North wall	Bone \geq 2 mm	Vertebra				2	0.035 g
	Bone < 2 mm					X	Few
	Bone				1		< 0.001 g
	Gravel	Chitin				X	Few
	Insect					2	
	Snail shell < 2 mm				2	X	Moderate
BL-R4	Liters Floated						1.10 L
West(S) trench South wall	Light Fraction Weight						0.787 g
	FLORAL REMAINS:						
	<i>Scirpus</i> -type	Seed		3			< 0.0001 g
	CHARCOAL/WOOD:						
	Total charcoal \geq 0.25 mm						< 0.0001 g
	Unidentifiable - small, vitrified	Charcoal		1			< 0.0001 g
	NON-FLORAL REMAINS:						
	Insect	Chitin				5	
	Light orange clay clumps					X	Few
	Muscovite					X	Moderate
BL-R5	Volume Water-screened						0.10 L
West(S) trench South wall	Water-screened Sample Weight						0.853 g
	NON-FLORAL REMAINS:						
	Clay					X	Few
	Muscovite					X	Few

W = Whole

F = Fragment

X = Presence noted in sample

L = Liter

g = grams

mm = millimeters

L = liters

TABLE 3
INDEX OF MACROFLORAL REMAINS RECOVERED FROM THE BAILEYS LAKE SITE, SALT LAKE CITY, UTAH

Scientific Name	Common Name
FLORAL REMAINS:	
Cheno-am	Includes goosefoot and amaranth families
<i>Erodium</i>	Storksbill, Filaree
<i>Scirpus</i> -type (includes <i>Amphiscirpus</i> , <i>Bolboschoenus</i> , <i>Isolepis</i> , <i>Shoenoplectus</i> , and <i>Scirpus</i>)	Bulrush
CHARCOAL/WOOD:	
Unidentified hardwood	Wood from a broad-leaved flowering tree or shrub
Unidentifiable - vitrified	Charcoal exhibiting a shiny, glassy appearance due to fusion by heat
NON-FLORAL REMAINS:	
Muscovite	The most common mica, found in granites, pegmatites, gneisses and schists, with a layered structure of aluminum silicate sheets weakly bonded together by layers of potassium ions

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APPENDIX D

SUMMARY OF RADIOCARBON DATING, BAILEYS LAKE SITE

Sample No.	NOSAMS ¹ Accession No.	Trench, wall	Station ² (m)	Depth ³ (m)	Unit Sampled ⁴	Material Sampled	Organic Material Dated ⁵	Pre-Treatment Method	$\delta^{13}\text{C}$ ⁶	Relation to Earthquake ⁷	Age ⁸ (¹⁴ C yr B.P.)	Age ⁹ (cal yr B.P.)
BL-R1	OS-86493	West(N), north	21.8, 3.3	0.48	S1 (top)	Paleosol	Unidentifiable charcoal (vitrified, small) and unidentified stem fragments (charred) (11.2 mg)	Acid-base-acid	-25	Max – BL1	5400 ± 30	6220 ± 100
BL-R2-1	OS-86491	West(N), north	22.1, 3.1	0.82	6	Scarp-derived colluvium (organic interbed) (BL2)	Unidentifiable charcoal (vitrified, small) and unidentified stem fragments (charred) (5.2 mg)	Acid-base-acid	-25	Min – BL2	675 ± 30	620 ± 80
BL-R2-2	OS-86573	West(N), north	22.1, 3.1	0.82	6	Scarp-derived colluvium (organic interbed) (BL2)	Unidentifiable charcoal (vitrified, small) and unidentified stem fragments (charred) (4.3 mg)	Acid-base-acid	-25	Min – BL2	1800 ± 25	1740 ± 100
BL-R3-1	OS-86492	West(N), north	22.3, 3.5	0.40	10	Scarp-derived colluvium (BL1)	7 fragments unidentified hardwood charcoal (5.5 mg)	Acid-base-acid	-25	Min – BL1	3890 ± 30	4330 ± 100
BL-R3-2	OS-86494	West(N), north	22.3, 3.5	0.40	10	Scarp-derived colluvium (BL1)	45 fragments unidentified charcoal (vitrified, small) and unidentified stem fragments (charred) (7.7 mg)	Acid-base-acid	-25	Min – BL1	4280 ± 30	4850 ± 60
BL-R4	OS-86572	West(S), south	25.8, 1.1	2.97	1	Wetland clay	1 fragment unidentified charcoal (vitrified, small) and microcharcoal (1.7 mg)	Acid-base-acid	-25	—	31,400 ± 350	35,780 ± 820
BL-R5	—	West(S), south	17.4, 2.2	1.38	3 (base)	Lacustrine clay and silt	None; sample lacked organic material	—	—	Min – BL4	—	—

¹ National Ocean Sciences Accelerator Mass Spectrometry Facility, Woods Hole Oceanographic Institution (Woods Hole, Massachusetts).

² Station coordinates are horizontal and vertical meter marks along arbitrary reference grid for trench (see plate 1).

³ Depth below ground surface.

⁴ See appendix A for descriptions of stratigraphic units, and appendix B for description of pedogenic soil unit S1.

⁵ Separation and identification by Paleo Research Institute (Golden, Colorado); see appendix C.

⁶ Assumed delta ¹³C value.

⁷ Min (max) indicates minimum (maximum) limiting time constraint for a surface-faulting earthquake (e.g., BL1).

⁸ Laboratory-reported radiocarbon age with one standard deviation uncertainty. B.P. is before present (AD 1950).

⁹ Mean calendar-calibrated age and 2σ uncertainty, rounded to nearest decade, determined using OxCal calibration software (v. 4.1.7; Bronk Ramsey, 2009) and the IntCal09 atmospheric data set (Reimer and others, 2009).

APPENDIX E

SUMMARY OF LUMINESCENCE DATING, BAILEYS LAKE SITE

Sample No. ¹	Trench, wall	Station ² (m)	Depth ³ (m)	Unit Sampled ⁴	Material Sampled	Water Content ⁵ (%)	Water Saturation History ⁶ (%)	K ⁷ (%)	U ⁷ (ppm)	Th ⁷ (ppm)	Cosmic Dose Additions ⁸ (Gy/kyr)	Total Dose Rate OSL ⁹ (IRSL) ¹⁰ (Gy/kyr)	Equivalent Dose OSL ⁹ (IRSL) ¹⁰ (Gy)	n ¹¹	Relation to Earthquake ¹²	Laboratory Age OSL ⁹ (IRSL) ¹⁰ (yr before 2011)
BL-L1	West (S), south	25.7, 1.3	2.65	2a	Fine lacustrine sand	2 (23)	85	1.28 ± 0.03	1.83 ± 0.12	5.18 ± 0.26	0.19 ± 0.02	1.64 ± 0.05 (2.31 ± 0.07)	51.8 ± 2.28 (72.0 ± 3.71)	19 (21)	—	31,590 ± 1670 (31,150 ± 1930)
BL-L2	West (S), south	25.7, 1.6	2.35	2a	Fine lacustrine sand	20 (25)	85	1.49 ± 0.04	1.89 ± 0.14	5.93 ± 0.34	0.20 ± 0.02	1.79 ± 0.06 (2.49 ± 0.09)	55.8 ± 2.85 (68.8 ± 2.22)	20 (20)	—	31,170 ± 1940 (27,620 ± 1310)
BL-L3	West (S), south	19.6, 0.9	2.75	2c	Lacustrine silt	2 (18)	85	2.28 ± 0.04	2.91 ± 0.11	11.3 ± 0.35	0.19 ± 0.02	3.01 ± 0.06 (4.33 ± 0.09)	73.4 ± 7.34 (115 ± 4.54)	13 (30)	—	24,440 ± 2,500 (26,470 ± 1,200)
BL-L4	West (S), south	19.7, 1.2	2.40	2c	Fine lacustrine sand	7 (22)	85	2.14 ± 0.03	3.08 ± 0.11	10.4 ± 0.29	0.20 ± 0.02	2.95 ± 0.05 (4.27 ± 0.08)	131 ± 15.3 (83.0 ± 2.19)	6 (28)	—	43,380 ± 5,140 (19,440 ± 620)
BL-L5	West (S), south	19.6, 1.4	2.20	2d	Fine to medium lacustrine sand	19 (29)	85	2.39 ± 0.04	3.12 ± 0.15	13.2 ± 0.40	0.20 ± 0.02	3.42 ± 0.07 (4.98 ± 0.10)	67.8 ± 8.07 (136 ± 4.65)	5 (24)	—	19,810 ± 2,380 (27,390 ± 1,080)
BL-L7	West (N), south	21.7, 1.9	1.80	2e	Lacustrine silt	15 (39)	85	2.21 ± 0.05	3.15 ± 0.22	10.6 ± 0.55	0.21 ± 0.02	3.20 ± 0.10 (4.64 ± 0.15)	61.8 ± 1.01 (94.6 ± 2.01)	20 (20)	Max – BL4	19,300 ± 380 (20,380 ± 570)
BL-L8	West (N), south	21.4, 2.2	1.55	3	Fine lacustrine sand	19 (46)	70	1.18 ± 0.02	2.49 ± 0.08	8.17 ± 0.28	0.22 ± 0.02	1.93 ± 0.04 (2.89 ± 0.07)	27.2 ± 0.053 (41.1 ± 1.93)	20 (20)	Min – BL4	14,070 ± 820 (14,220 ± 740)
BL-L9	West (N), south	20.7, 2.4	1.25	3	Lacustrine clay, silt, and fine sand	18 (50)	70	1.31 ± 0.02	2.75 ± 0.09	7.89 ± 0.29	0.23 ± 0.02	2.02 ± 0.05 (2.99 ± 0.07)	26.2 ± 1.11 (37.8 ± 2.12)	19 (20)	Max – BL3	12,960 ± 620 (12,660 ± 770)
BL-L10	West (N), south	22.2, 3.5	0.15	11	Loess	6 (29)	90	1.54 ± 0.02	2.82 ± 0.08	8.26 ± 0.27	0.32 ± 0.02	2.51 ± 0.06 (3.66 ± 0.08)	8.05 ± 0.61 (11.9 ± 0.55)	16 (20)	Min – BL1	3210 ± 250 (3240 ± 160)
BL-L11	West (N), north	19.8, 2.8	0.80	9	Loess	9 (37)	70	1.00 ± 0.03	1.65 ± 0.11	3.87 ± 0.36	0.25 ± 0.02	1.57 ± 0.05 (2.21 ± 0.07)	19.6 ± 0.90 (29.2 ± 1.49)	16 (16)	—	12,470 ± 700 (13,200 ± 810)
BL-L12	West (N), north	22.0, 3.3	0.55	S1	Paleosol	7 (34)	70	1.61 ± 0.03	2.48 ± 0.12	8.28 ± 0.28	0.25 ± 0.02	2.89 ± 0.07 (4.25 ± 0.13)	17.4 ± 1.36 (28.5 ± 1.03)	18 (20)	Max – BL1	6020 ± 500 (6710 ± 310)
BL-L13	West (N), north	21.4, 2.8	1.00	5	Lacustrine clay, silt, and fine sand	4 (29)	70	1.01 ± 0.02	1.92 ± 0.07	3.93 ± 0.23	0.24 ± 0.02	1.68 ± 0.09 (2.41 ± 0.12)	21.0 ± 1.10 (29.9 ± 0.75)	19 (20)	Max – BL2 Min – BL3	12,530 ± 910 (12,390 ± 710)
BL-L14	West (N), south	18.7, 2.6	1.00	7	Fine to coarse lacustrine sand	2 (27)	70	1.37 ± 0.03	1.83 ± 0.09	5.41 ± 0.31	0.24 ± 0.02	2.07 ± 0.07 (2.90 ± 0.10)	23.8 ± 5.36 (31.3 ± 1.96)	13 (13)	Min – BL2	11,510 ± 2610 (10,800 ± 770)
BL-L16	West (S), south	27.9, 2.0	2.15	2a	Fine lacustrine sand	6 (34)	85	1.33 ± 0.03	1.86 ± 0.15	6.07 ± 0.35	0.20 ± 0.02	1.94 ± 0.07 (2.76 ± 0.10)	60.2 ± 3.14 (57.4 ± 1.70)	24 (24)	—	31,030 ± 1960 (20,790 ± 970)

¹ Analyses by U.S. Geological Survey Luminescence Dating Laboratory (Denver, Colorado); samples BL-L6 and BL-L15 collected as duplicates (not analyzed) of samples BL-L7 and BL-L10, respectively.

² Station coordinates are horizontal and vertical meter marks along arbitrary reference grid for trench (see plate 1).

³ Depth below ground surface.

⁴ See appendix A for descriptions of stratigraphic units, and appendix B for description of pedogenic soil unit S1.

⁵ Field moisture; complete sample saturation percent in parentheses.

⁶ Estimated water saturation history (i.e., time below water table) of sampled material.

⁷ Analyses obtained using laboratory gamma spectrometry (high-resolution Ge detector), and readings were delayed after 21 days of being sealed in the planchet (used for dose rates).

⁸ Cosmic doses and attenuation with depth were calculated using the methods of Prescott and Hutton (1994); Gy – gray.

⁹ Dose rate and optically stimulated luminescence (OSL) age for fine-grained (90–125 microns) quartz sand; linear + exponential fit used on equivalent dose, single aliquot regeneration; ages rounded to nearest decade, errors to 1σ.

¹⁰ Dose rate and infrared stimulated luminescence (IRSL) age for fine grains (4–11 microns) of polymineral silt; exponential fit used for equivalent dose, multiple aliquot additive dose; ages rounded to nearest decade, errors to 1σ; fade tests indicate no correction.

¹¹ Number of replicated equivalent dose (De) estimates used to calculate the mean; total number of measurements made, including failed runs with unusable data, in parentheses.

¹² Min (max) indicates minimum (maximum) limiting time constraint for a surface-faulting earthquake (e.g., BL1).

APPENDIX F

OSTRACODE IDENTIFICATION AND INTERPRETATION, BAILEYS LAKE SITE

Sample No. ¹	Trench, wall	Station ² (m)	Unit Sampled ³	Ostracodes	Comments ⁴	Interpretation
O-13	West(N), south	19.6, 2.4	5	None identifiable	Few ostracodes, mostly unidentifiable fragments (probably <i>Candona</i> sp.); some ostracode fragments carbonate-coated	Gilbert episode
O-12	West(N), south	18.4, 2.2	3	<i>Limnocythere ceriotuberosa</i> <i>Candona caudata</i> (?) <i>Candona adunca</i> <i>Cytherissa lacustris</i>	Few ostracodes, most broken; sediment lumps, sand	Bonneville, regressive phase
O-11	West(S), south	17.7, 2.1	2e	<i>Limnocythere ceriotuberosa</i> <i>Candona adunca</i>	Abundant clean ostracodes; sand	Bonneville, mid- to late transgressive phase
O-10	West(S), south	17.7, 1.9	2e	<i>Limnocythere ceriotuberosa</i> <i>Candona caudata</i> (?) <i>Candona adunca</i>	Few ostracodes, some clean, some carbonate-coated; sand	
O-9	West(S), south	20.8, 1.7	2e	<i>Limnocythere ceriotuberosa</i> <i>Candona adunca</i>	Abundant clean ostracodes; sand; few redox lumps	
O-8	West(S), south	19.3, 1.3	2c	<i>Limnocythere ceriotuberosa</i> <i>Candona caudata</i> (?) <i>Candona adunca</i>	Clean ostracodes; sand	Bonneville, transgressive phase
O-7	West(S), south	19.4, 1.1	2c	<i>Limnocythere staplini</i> <i>Limnocythere ceriotuberosa</i> <i>Candona caudata</i> (?)	Sand; black sulfide lumps	
O-6	West(S), south	26.4, 2.6	2b	<i>Limnocythere staplini</i> <i>Limnocythere ceriotuberosa</i> <i>Candona caudata</i> (?)	Clean ostracodes; sand; redox lumps	
O-5	West(S), south	26.4, 2.5	2b	<i>Limnocythere staplini</i>	Few ostracodes, some clean, some carbonate-coated; broken <i>Candona</i> sp.; carbonate-coated redox lumps; sand	
O-4	West(S), south	26.0, 1.6	2a	<i>Limnocythere staplini</i> <i>Candona rawsoni</i>	Abundant curved flakes of carbonate, some with linear impressions on smooth concave sides, convex sides are rough (flakes appear to be leaf or stem encrustations); redox lumps; snail-shell fragments and whole shells; hollow tubes of redox-cemented sand	Bonneville, early transgressive phase
O-3	West(S), south	25.6, 1.4	2a	<i>Limnocythere staplini</i> <i>Candona rawsoni</i> <i>Cytherissa lacustris</i>	Few ostracodes; snail-shell fragments; sediment lumps, sand	
O-2	West(S), south	25.6, 1.2	1	<i>Candona rawsoni</i>	Few ostracodes (fragments); charophyte stem encrustations; redox lumps	Pre-Bonneville wetland/alluvial marsh
O-1	West(S), south	25.6, 0.8	1	<i>Candona rawsoni</i>	Few ostracodes, some shells carbonate-coated; charophyte stem encrustations; sulfide lumps, sand	

¹ Samples listed in stratigraphic order (top to bottom).

² Station coordinates are horizontal and vertical meter marks along arbitrary reference grid for trench (see plate 1).

³ See appendix A for descriptions of stratigraphic units.

⁴ Redox lumps = iron minerals, some oxidized (yellow colors), some reduced (black), mostly cementing sand; sulfide lumps = lumps of black iron sulfide minerals.

APPENDIX G

OXCAL MODEL FOR THE GRANGER FAULT AT THE BAILEYS LAKE SITE

An OxCal model for the Granger fault at the Baileys Lake site was created using OxCal calibration and analysis software (version 4.1.7; Bronk Ramsey, 2009; using the IntCal09 calibration curve of Reimer and others, 2009). The models include *C_Date* for luminescence ages, *R_Date* for radiocarbon ages, and *Boundary* for undated events (paleoearthquakes). These components are arranged into ordered sequences based on the relative stratigraphic positions of the samples. The sequences may contain *phases*, or groups where the relative stratigraphic ordering information for the individual radiocarbon ages is unknown. The model is presented here in reverse stratigraphic order, following the order in which the ages and events are evaluated in OxCal.

Model Input

Plot()

```
{
Sequence("Baileys Lake, full chronology")
{
Boundary("Start");
R_Date("BL-R4, C14 31,400 +/-350",31400,350);
C_Date("BL-L1, OSL 31,590 +/-1670",-29580,1670);
C_Date("BL-L2, OSL 31,170 +/-1940",-29160,1940);
C_Date("BL-L16, OSL 31,030 +/-1960",-29020,1960);
C_Date("BL-L3, OSL 24,440 +/-2500",-22430,2500);
C_Date("BL-L5, OSL 19,810 +/-2380",-17800,2380);
C_Date("BL-L7, OSL 19,300 +/-380",-17290,380);
Boundary("BL4");
C_Date("BL-L8, OSL 14,070 +/-820",-12060,820);
C_Date("BL-L9, OSL 12,960 +/-620",-10950,620);
Boundary("BL3");
C_Date("BL-L13, OSL 12,530 +/-910",-10520,910);
Boundary("BL2");
C_Date("BL-L14, OSL 11,510 +/-2610",-9500,2610);
C_Date("BL-L11, OSL 12,470 +/-700",-10460,700);
Phase("Soil S1");
{
C_Date("BL-L12, OSL 6020 +/-500",-4010,500);
R_Date("BL-R1, C14 5400+/-30",5400,30);
};
Boundary("BL1");
Phase("Unit 10, P1 Colluvium");
{
R_Date("BL-R3-2, C14 4280+/-30",4280,30);
R_Date("BL-R3-1, C14 3890+/-30",3890,30);
};
C_Date("BL-L10, OSL 3210 +/-250",-1200,250);
Boundary("Begin historical record",1847 AD);
};
};
```


Model Output

Baileys Lake Full Chronology	Unmodelled (BP)		Modelled (BP)		Agreement
	mean	sigma	mean	sigma	
Boundary Start	38450	3010			
R_Date BL-R4, C14 31,400 ±350	35850	420	35780	410	99.7
C_Date BL-L1, OSL 31,590 ±1670	31530	1670	32660	1250	97.5
C_Date BL-L2, OSL 31,170 ±1940	31110	1940	31090	1240	119
C_Date BL-L16, OSL 31,030 ±1960	30970	1960	29470	1400	95.6
C_Date BL-L3, OSL 24,440 ±2500	24380	2500	24730	1990	109.3
C_Date BL-L5, OSL 19,810 ±2380	19750	2380	21050	1340	112.5
C_Date BL-L7, OSL 19,300 ±380	19240	380	19210	380	100.3
Boundary BL4			15700	1690	
C_Date BL-L8, OSL 14,070 ±820	14010	820	14080	630	112.5
C_Date BL-L9, OSL 12,960 ±620	12900	620	13360	460	95
Boundary BL3			12960	530	
C_Date BL-L13, OSL 12,530 ±910	12470	910	12640	520	121.2
Boundary BL2			12340	570	
C_Date BL-L14, OSL 11,510 ±2610	11450	2610	11890	580	136.2
C_Date BL-L11, OSL 12,470 ±700	12410	700	11450	560	62.6
Phase Soil S1					
C_Date BL-L12, OSL 6020 ±500	5960	500	6540	260	76.8
R_Date BL-R1, C14 5400±30	6220	50	6220	50	98
Boundary BL1			5540	400	
Phase Unit 10, P1 Colluvium					
R_Date BL-R3-2, C14 4280±30	4850	30	4850	30	98.9
R_Date BL-R3-1, C14 3890±30	4330	50	4330	50	99.9
C_Date BL-L10, OSL 3210 ±250	3150	250	3150	250	100
Boundary Begin historical record, 1847	100	0	100	0	100

APPENDIX H

WEST VALLEY FAULT ZONE EARTHQUAKE TIMING CONSTRAINTS FROM CONSULTANTS' TRENCHES

Two trenches excavated by consultants (as part of pre-development fault-setback investigations required by local governments) have yielded useful earthquake timing data for the West Valley fault zone where the Utah Geological Survey was able to sample organic sediment for radiocarbon dating. One trench was near the north end of the Taylorsville fault at about 2100 West and 1300 North (between the Salt Lake City International Airport and Interstate 215), and was excavated by AGRA Earth and Environmental, Inc. in September 1997 (figures H1 through H4). The other trench was on the middle part of the westernmost trace of the Granger fault in the northeastern quadrant of the intersection of 4800 West and California Avenue (1300 South), near the "1300 South" site of Keaton and Currey (1989), and was excavated by Terracon Consultants, Inc. in March 1998 (figures H5 through H7); see figure 4 in the main report for site locations. These trenches were open only briefly, precluding detailed logging, so the geologic context of the samples is not well established. Because of this, as well as the nature of the radiocarbon ages (apparent mean residence time [AMRT] ages from bulk-soil samples, with applied mean residence correction [MRC] and carbon age span [CAS] factors; see discussion in Machette and others, 1992, appendix), relatively large uncertainty exists in the relation between the radiocarbon ages and earthquake timing. Also, we must assume that the soil samples were not contaminated by young organic material. Notwithstanding these caveats, the radiocarbon ages provide constraints on the timing of two surface-faulting earthquakes that are younger than the most recent surface-faulting earthquake documented at the Baileys Lake site.

UGS geologists collected two bulk-soil samples from the AGRA trench on the Taylorsville fault: sample AGRA-RC1 was collected from crack-fill sediment/fault-zone colluvium and yielded an AMRT radiometric age of 2350 ± 80 ^{14}C yr B.P., and sample AGRA-RC2 was collected from sag pond deposits beneath the possible colluvial wedge and yielded an AMRT age of 2520 ± 70 ^{14}C yr B.P. (unpublished UGS data; figure H4). Applying a 200-yr MRC and 200-yr CAS, these radiocarbon ages calendar calibrated to 2110 +210/-200 cal yr B.P. (AGRA-RC1) and 2330 +120/-170 cal yr B.P. (AGRA-RC2) (unpublished UGS data). Solomon (1998) reported the earthquake time as "roughly 2200 years" (the average of the two ages).

UGS geologists collected a single bulk-soil sample from the Terracon site on the Granger fault. Sample GFT-RC1 was interpreted as being from scarp-derived colluvium and yielded an AMRT radiometric age of 1880 ± 80 ^{14}C yr B.P. (unpublished UGS data). Applying a 300-yr MRC and 200-yr CAS, the radiocarbon age calendar calibrated to 1460 +170/-130 cal yr B.P. (unpublished UGS data). If the sample indeed came from the heel of the colluvial wedge as described in unpublished UGS file information, the radiocarbon age may provide a close minimum time constraint for the earthquake, as an age from scarp-derived colluvium can generally be interpreted as a minimum limit on earthquake timing (e.g., McCalpin, 1996; Yeats and others, 1997). However, our review of site photographs (figures H6 and H7) raises the possibility that the sample may have been obtained from a faulted soil A horizon that was buried on the hanging wall by scarp-derived colluvium. Extensive burrowing and soil carbonate and/or

evaporite mineral precipitation (associated with a shallow, fluctuating water table) appear to obscure geologic contacts within the fault zone. If sample GFT-RC1 came from a buried soil beneath the colluvial wedge, it would provide a maximum time constraint for the earthquake.

We used OxCal calibration and analysis software (version 4.1.7; Bronk Ramsey, 2009; using the IntCal09 calibration curve of Reimer and others, 2009) to provide updated calendar calibration of the radiocarbon ages and to model earthquake times. The models include *R_Date* for radiocarbon ages, *Delta_R* for MRC factors, and *Boundary* for undated events (paleoearthquakes). As noted in appendix G, these components are arranged into ordered sequences based on the relative stratigraphic positions of the samples. The models are presented in reverse stratigraphic order (table H1), following the order in which the ages and events are evaluated in OxCal. Because of the uncertainty as to whether sample GFT-RC1 provides a minimum or maximum limiting time constraint, we constructed two models to account for both possibilities (table H1 and figure H8).

The OxCal models indicate two paleoearthquakes. The older earthquake occurred around 2.2 ± 0.2 ka (2σ), consistent with the time estimated by Solomon (1998). The modeled age of the younger earthquake is 1.7 ± 0.3 ka if sample GFT-RC1 is considered to provide a minimum limiting time constraint; if GFT-RC1 provides a maximum limiting time constraint, the modeled age of the younger earthquake is 1.2 ± 0.6 ka (2σ). Lacking a solid basis for interpreting GFT-RC1 as either a minimum or maximum time constraint, we combined the modeled earthquake times to yield a mean time of 1.4 ± 0.7 ka. Both of these earthquakes are younger than the most recent paleoearthquake documented at the Baileys Lake site (see tables 3 and 4, and figure 15 in the main report).



Figure H1. Fault trench on the Taylorsville fault between the Salt Lake City International Airport and Interstate 215, excavated by AGRA Earth and Environmental, Inc. in September 1997; view looking east. Photo by UGS staff.



Figure H2. Fault-zone exposure, north wall of AGRA trench on the Taylorsville fault, September 1997. See figure H4 for interpretation. Photo by UGS staff.



Figure H3. Exposed stratigraphy immediately to the right (east) of the fault zone, north wall of AGRA trench on the Taylorsville fault, September 1997. See figure H4 for interpretation. Photo by UGS staff.

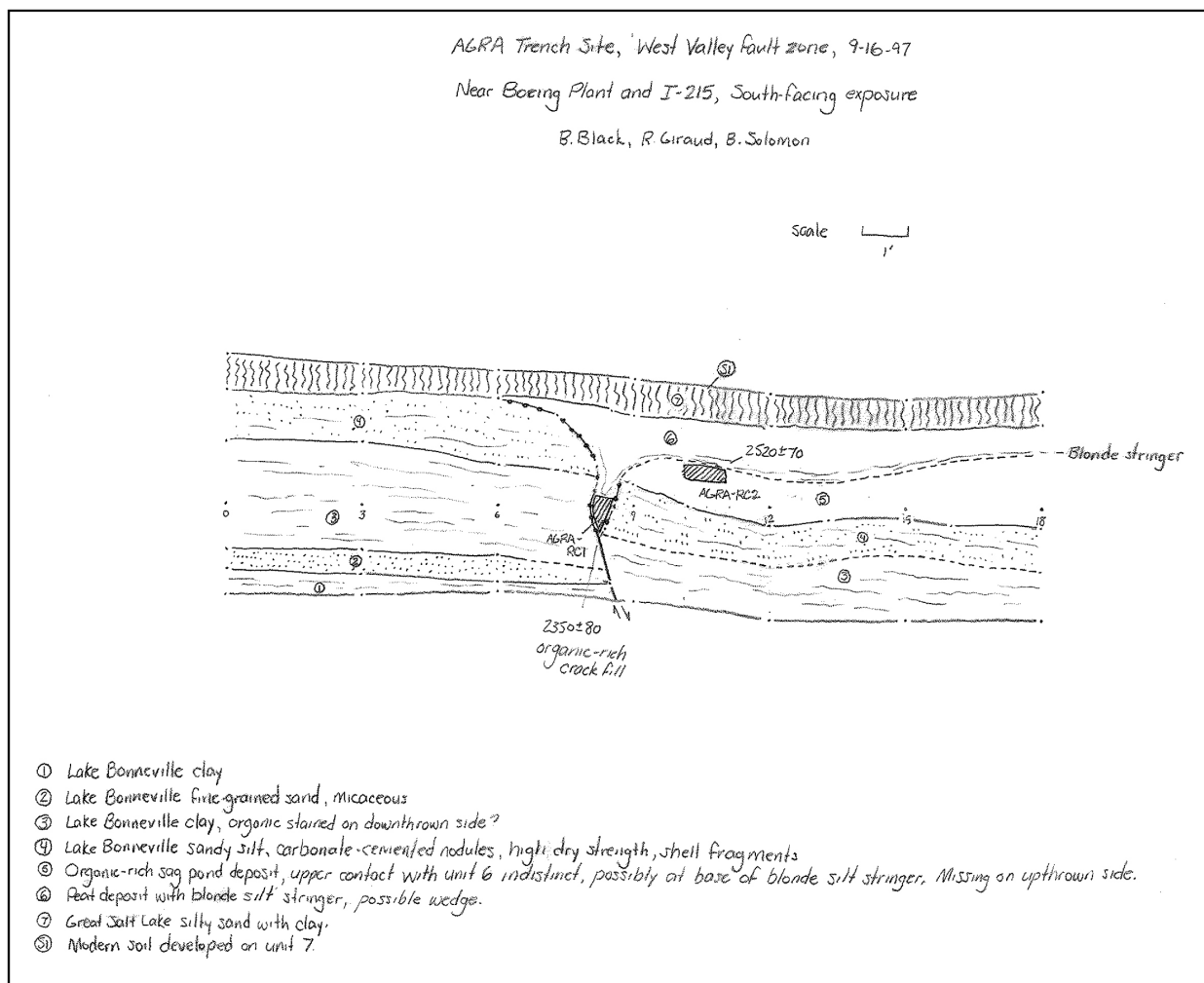


Figure H4. Trench log of north wall of the AGRA trench on the Taylorsville fault (from unpublished UGS files).



Figure H5. Fault trench on the Granger fault at 4800 West and California Avenue (1300 South), excavated by Terracon Consultants, Inc. in March 1998; view looking east. Photo by UGS staff.



Figure H6. Fault-zone exposure, north wall of Terracon trench on the Granger fault, March 1998.
Photo by UGS staff.

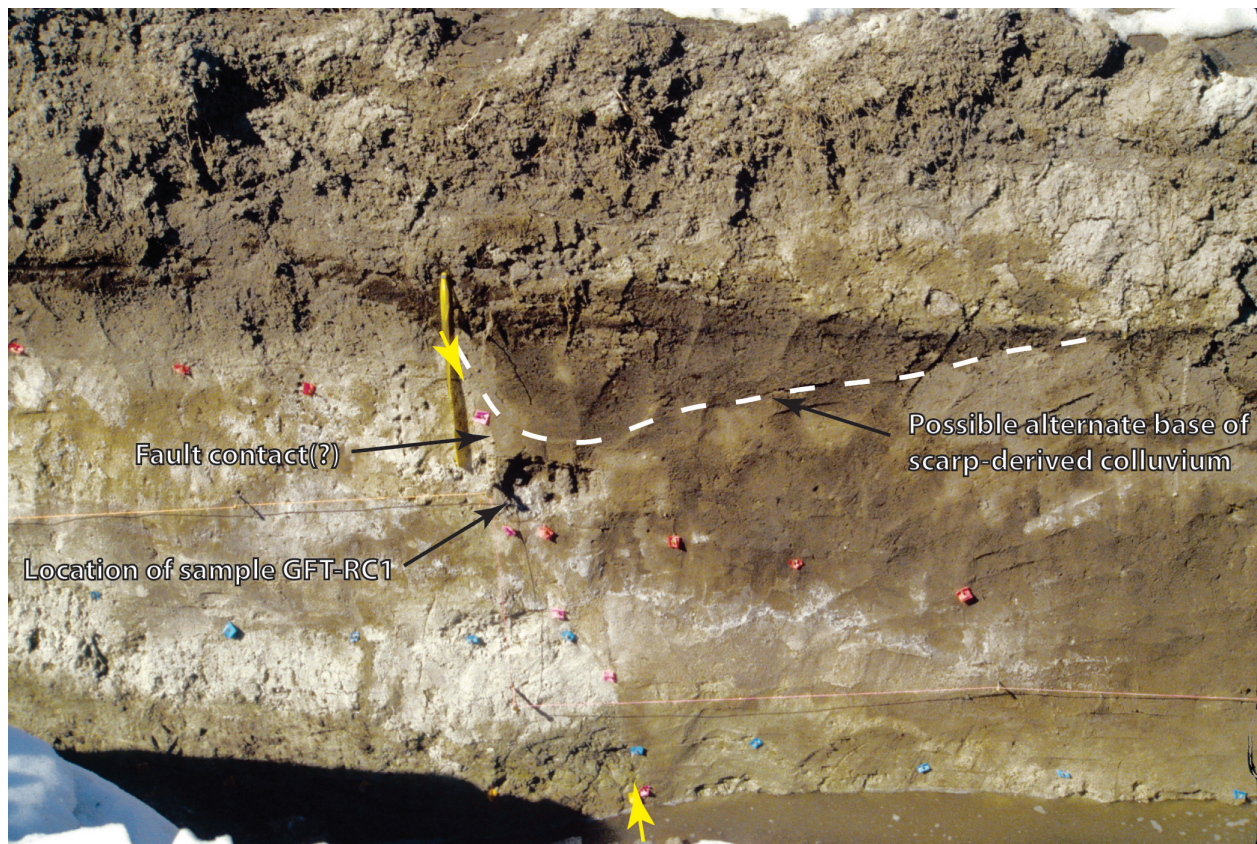
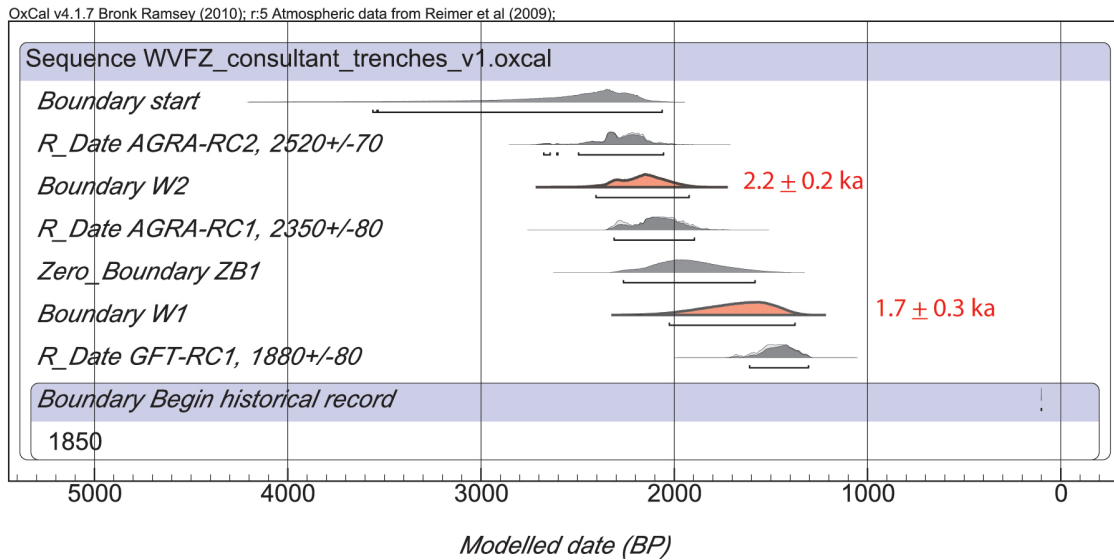


Figure H7. Detail of fault zone exposed in Terracon trench on the Granger fault, March 1998; fault between yellow arrows. Sample GFT-RC1 was originally interpreted as being from the “heel of the MRE [most recent event] colluvial wedge” (unpublished UGS file information), in which case the sampled sediment’s age of 1880 ± 80 ^{14}C yr B.P. may provide a close minimum constraint on earthquake timing. An alternate interpretation is that the sample was from a soil that was faulted and subsequently buried by scarp-derived colluvium, in which case the age may provide a close maximum constraint on earthquake timing. Photo by UGS staff, annotation added for this study.

A.



B.

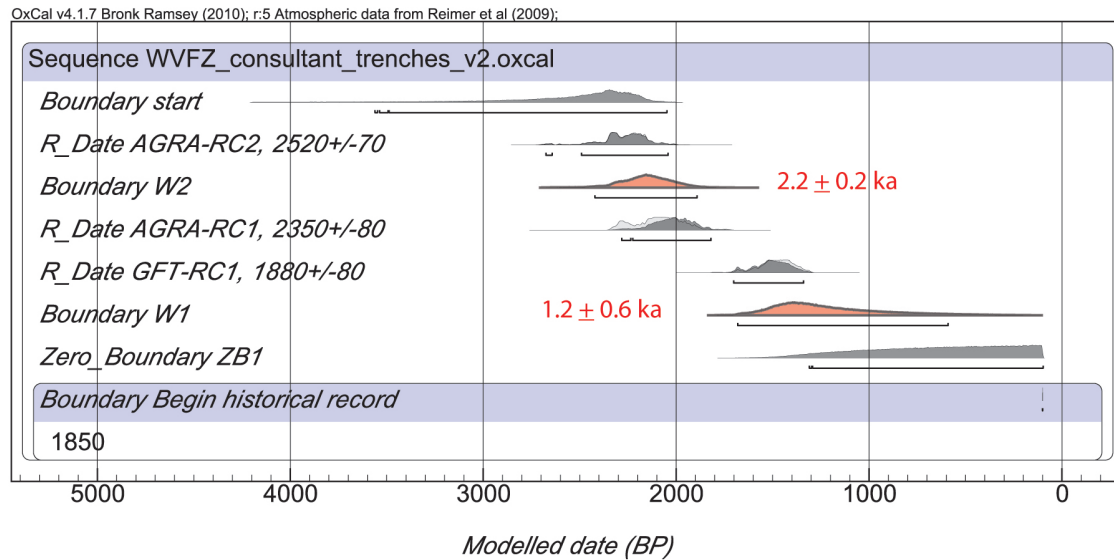


Figure H8. OxCal models for West Valley fault zone earthquake timing based on consultant trench data, showing stratigraphic ordering of ^{14}C ages and probability density functions (PDFs) for the timing of earthquakes W1 and W2 (red). Models constructed using OxCal version 4.1.7 (Bronk Ramsey, 2009) and the IntCal09 radiocarbon calibration curve (Reimer and others, 2009). Brackets below PDFs indicate 2σ time ranges. A and B show sample GFT-RC1 modeled as minimum and maximum age constraint, respectively, for earthquake W1 timing.

Table H1. OxCal model output for West Valley fault zone earthquake timing based on consultant trench data.

WVFZ_consultant_trench_v1.oxcal	Unmodelled (BP)		Modelled (BP)		Agreement
Version 1 ¹	mean	sigma	mean	sigma	
Boundary start			2590	400	
Delta_R MRT-200yr	250	50	251	52	98
R_Date AGRA-RC2, 2520±70	2270	130	2280	120	101
Boundary W2²			2170	120	
R_Date AGRA-RC1, 2350±80	2090	120	2090	110	104
Zero_Boundary ZB1			1920	170	
Boundary W1²			1680	170	
Delta_R MRT-300yr	300	0	300	0	100
R_Date GFT-RC1, 1880±80	1480	90	1460	80	102
Boundary Begin historical record - 1850 AD	100	0	100	0	100

WVFZ_consultant_trench_v2.oxcal	Unmodelled (BP)		Modelled (BP)		Agreement
Version 2 ³	mean	sigma	mean	sigma	
Boundary start			2580	400	
Delta_R MRT-200yr	250	50	266	52	95
R_Date AGRA-RC2, 2520±70	2270	130	2270	120	103
Boundary W2			2150	130	
R_Date AGRA-RC1, 2350±80	2090	120	2020	110	96
Delta_R MRT-300yr	300	0	300	0	100
R_Date GFT-RC1, 1880±80	1480	90	1510	90	94
Boundary W1			1210	290	
Zero_Boundary ZB1			660	360	
Boundary Begin historical record - 1850 AD	100	0	100	0	100

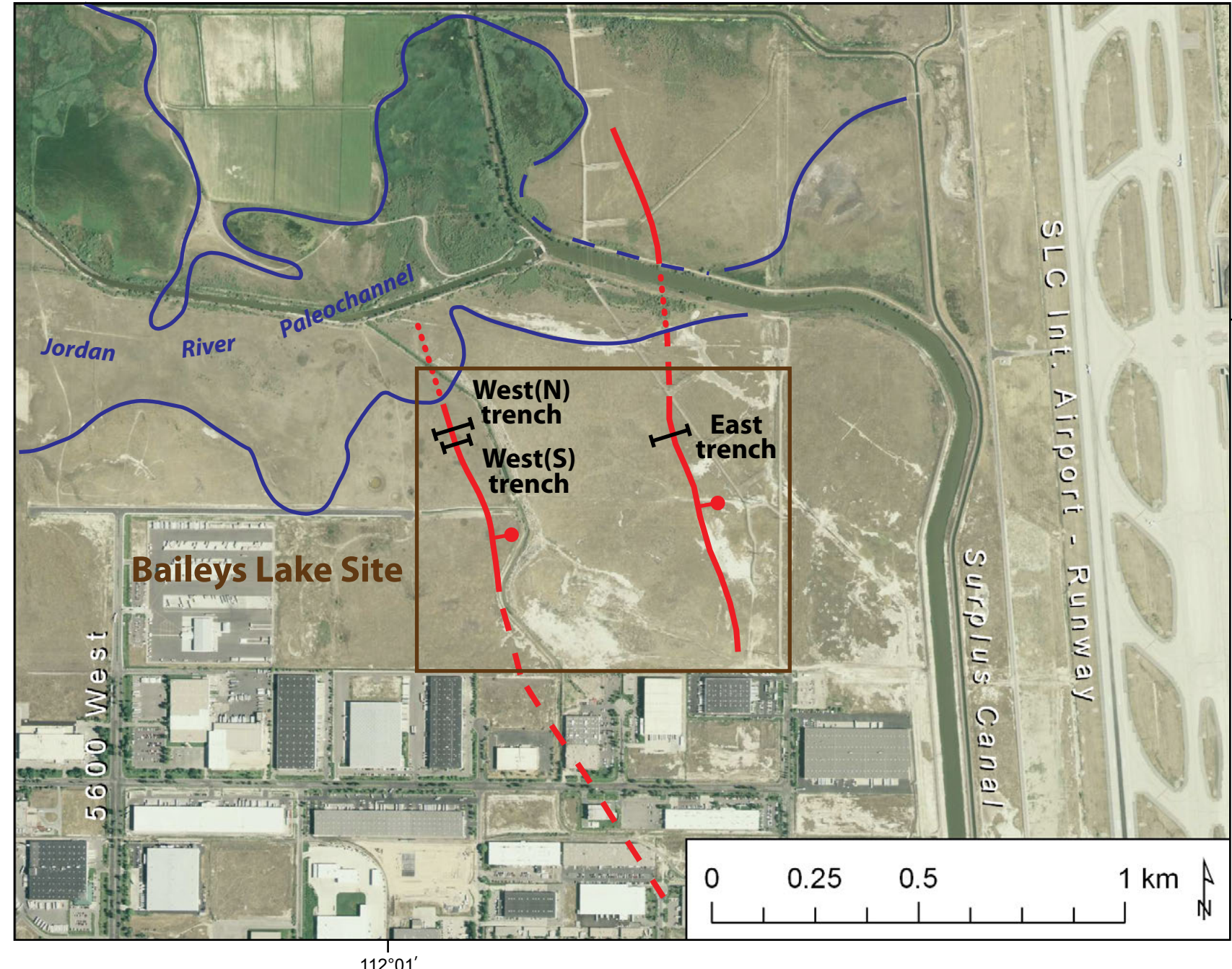
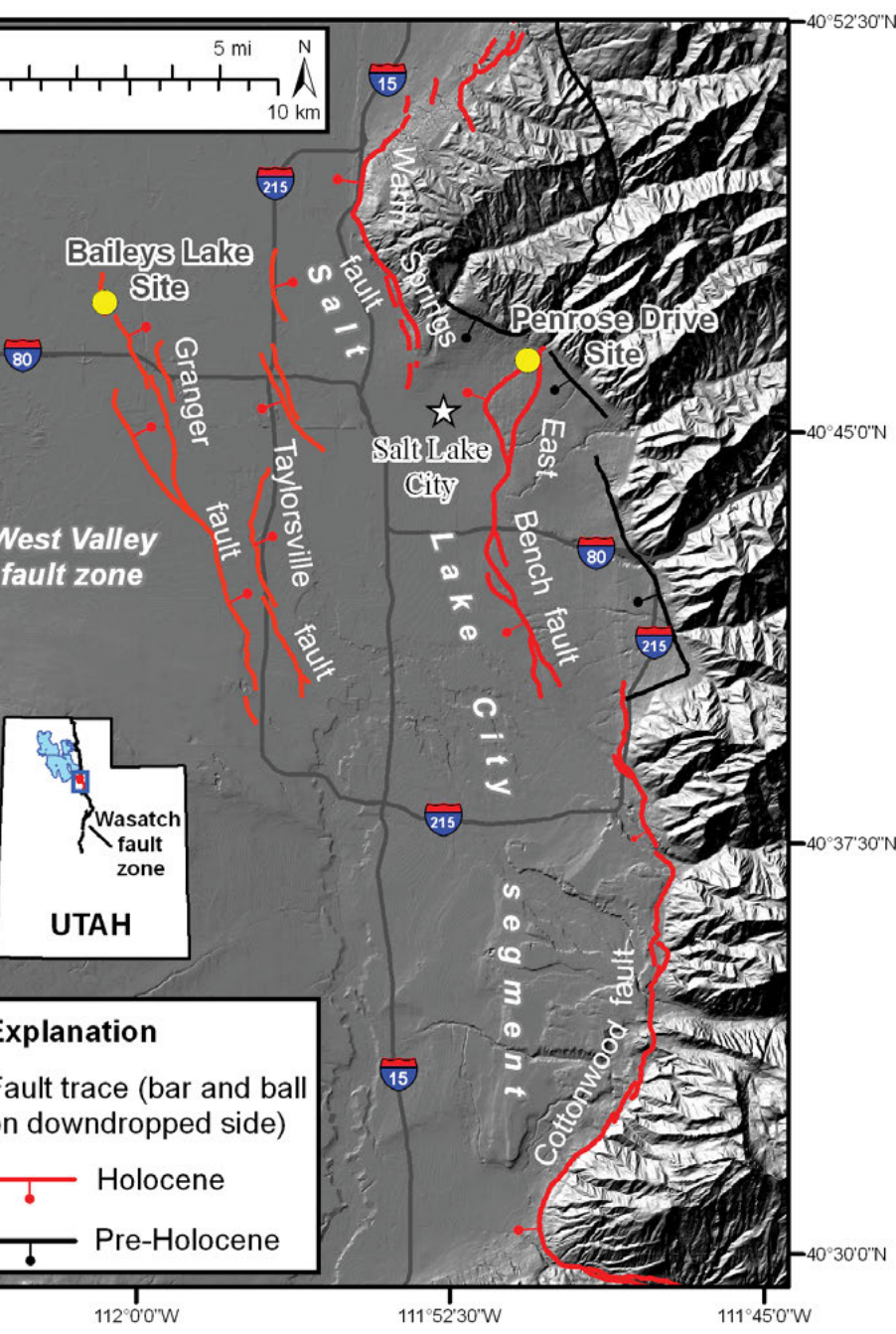
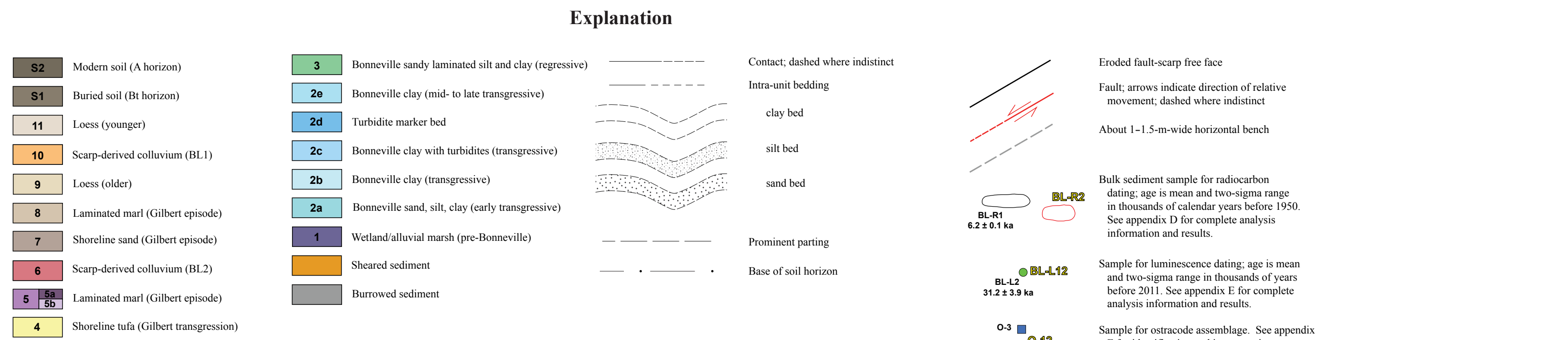
Combined W1 (ver. 1) and W1 (ver. 2)⁴	mean:	1445 cal yr. B.P.
	2 sigma:	659 cal yr. B.P.
	5 th percent:	805 cal yr. B.P.
	50 th percent:	1490 cal yr. B.P.
	95 th percent:	1920 cal yr. B.P.
	mode:	1510 cal yr. B.P.

¹ Sample GFT-RC1 modeled as minimum age constraint for earthquake W1 timing.

² “W1” and “W2” correspond to West Valley fault zone earthquakes W1 and W2 as given in tables 4 and 6, and figure 15 in the main report.

³ Sample GFT-RC1 modeled as maximum age constraint for earthquake W1 timing.

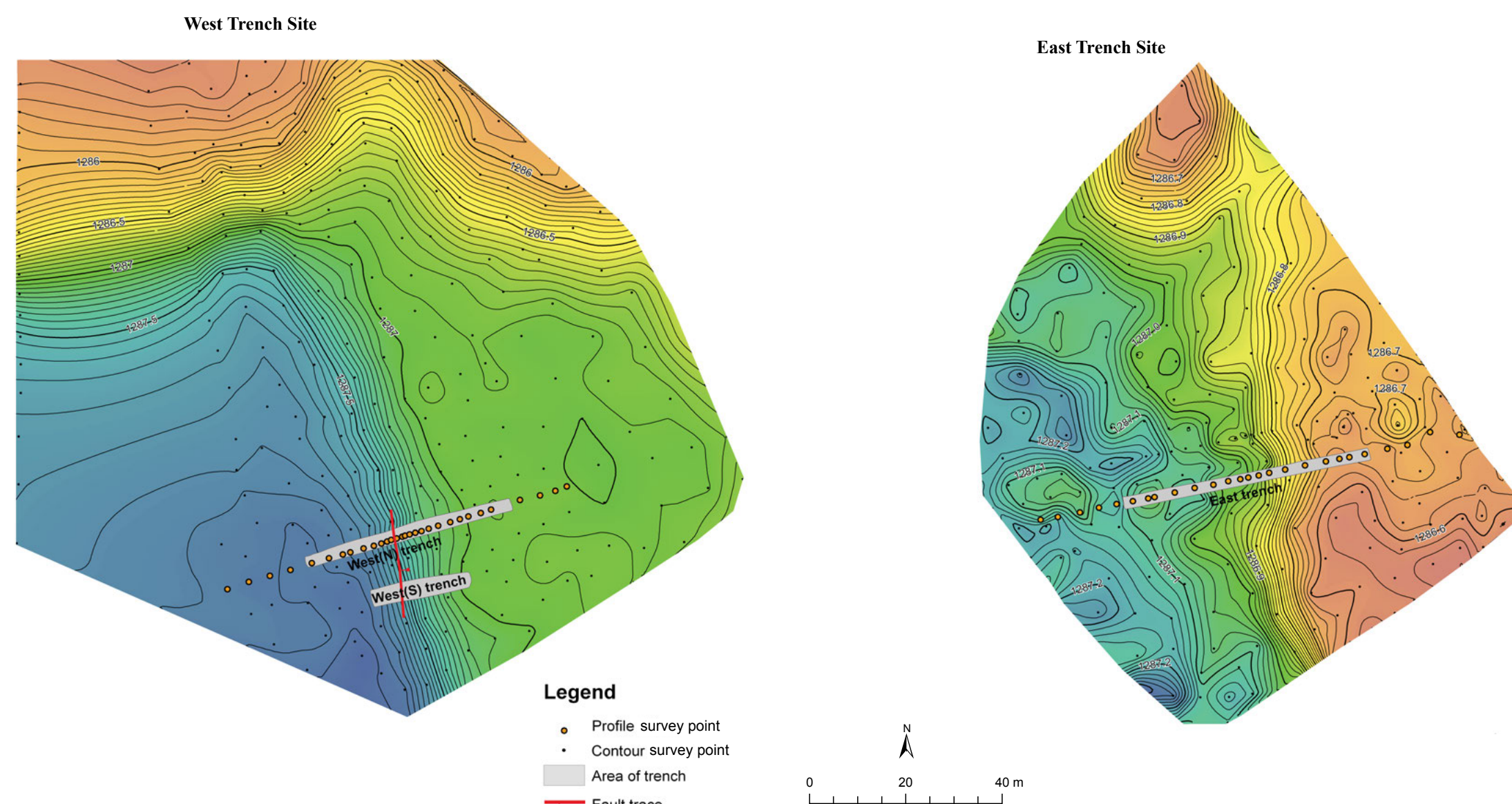
⁴ Mean modeled earthquake time and 2σ uncertainty used for earthquake W1 in preliminary West Valley fault zone chronology (see tables 3, 4, and 6, and figure 15 in the main report).



Summary of dating results for the Baileys Lake site

Sample No.	Trench, wall	Station (m)	Depth (m)	Unit	Material Sampled	Dating Method	Age ¹ (C.Y. B.P.)	Age ² (C.Y. B.P.)
BL-R1	West(N), north	21.8.3.3	0.48	S1	Paleosol	AMS	5400 ± 30	6200 ± 100
BL-R2.1	West(N), north	22.1.3.1	0.82	6	Scarp-derived colluvium (organic interbed) (P2)	AMS	875 ± 30	620 ± 80
BL-R2.2	West(N), north	22.1.3.1	0.82	6	Scarp-derived colluvium (organic interbed) (P2)	AMS	1800 ± 25	1740 ± 100
BL-R3.1	West(N), north	22.3.3.5	0.40	10	Scarp-derived colluvium (organic interbed) (P2)	AMS	3800 ± 30	4300 ± 100
BL-R3.2	West(N), north	22.3.3.5	0.40	10	Scarp-derived colluvium (P1)	AMS	4200 ± 30	4800 ± 60
BL-R4	West(S), south	25.8.1.1	2.87	1	Wetland clay	AMS	31,400 ± 300	35,780 ± 820
BL-R5	West(S), south	17.4.2.2	1.38	3	Lacustrine clay and silt	AMS	—	—
BL-L1	West(S), south	25.7.1.3	2.65	2a	Fine lacustrine sand	OSL	NA	31,590 ± 3340
BL-L2	West(S), south	25.7.1.6	2.35	2a	Fine lacustrine sand	OSL	NA	31,170 ± 3880
BL-L3	West(S), south	19.6.0.9	2.75	2c	Lacustrine silt	OSL	NA	24,440 ± 3000
BL-L4	West(S), south	19.7.1.2	2.40	2c	Fine lacustrine sand	OSL	NA	43,380 ± 10,280
BL-L5	West(S), south	19.6.1.4	2.20	2d	Fine to medium lacustrine silt	OSL	NA	19,810 ± 4760
BL-L7	West(S), south	21.7.1.9	1.80	2a	Lacustrine silt	OSL	NA	19,300 ± 760
BL-L8	West(S), south	21.4.2.2	1.55	3	Fine lacustrine sand	OSL	NA	14,070 ± 1460
BL-L9	West(S), south	20.7.2.4	1.25	3	Lacustrine clay, silt, and fine sand	OSL	NA	12,960 ± 1240
BL-L10	West(N), south	22.2.3.5	0.15	11	Loess	OSL	NA	3270 ± 500
BL-L11	West(N), north	19.8.2.8	0.80	9	Loess	OSL	NA	12,470 ± 1400
BL-L12	West(N), north	22.0.3.3	0.05	S1	Paleosol	OSL	NA	6000 ± 1000
BL-L13	West(N), north	21.4.2.8	1.00	5	Lacustrine clay, silt, and fine sand	OSL	NA	12,030 ± 1930
BL-L14	West(N), south	18.7.2.6	1.00	7	Fine to coarse fluvial sand	OSL	NA	11,510 ± 5220
BL-L16	West(S), south	27.9.2.0	2.15	2a	Fine lacustrine sand	OSL	NA	31,030 ± 3620

Note: See appendices C and D for complete analysis information and results.
¹ Samples BL-L6 and BL-L15 collected as duplicate (not analyzed) of samples BL-L7 and BL-L10, respectively.
² Datum coordinates are horizontal and vertical master results along geodetic reference line for trench.
³ See appendix A for description of stratigraphic units and appendix B for description of paleogeographic and paleoenvironmental data.
⁴ AMS, accelerator mass spectrometry; OSL, optically stimulated luminescence.
⁵ Laboratory reported radiocarbon age with standard deviation uncertainty (σ), 1-sigma present (AD 1950); NA, not applicable.
⁶ Age in calendar years before present (present is taken to be AD 1950 for AMS ages and AD 2011 for OSL ages), rounded to nearest decade; two-sigma uncertainty.

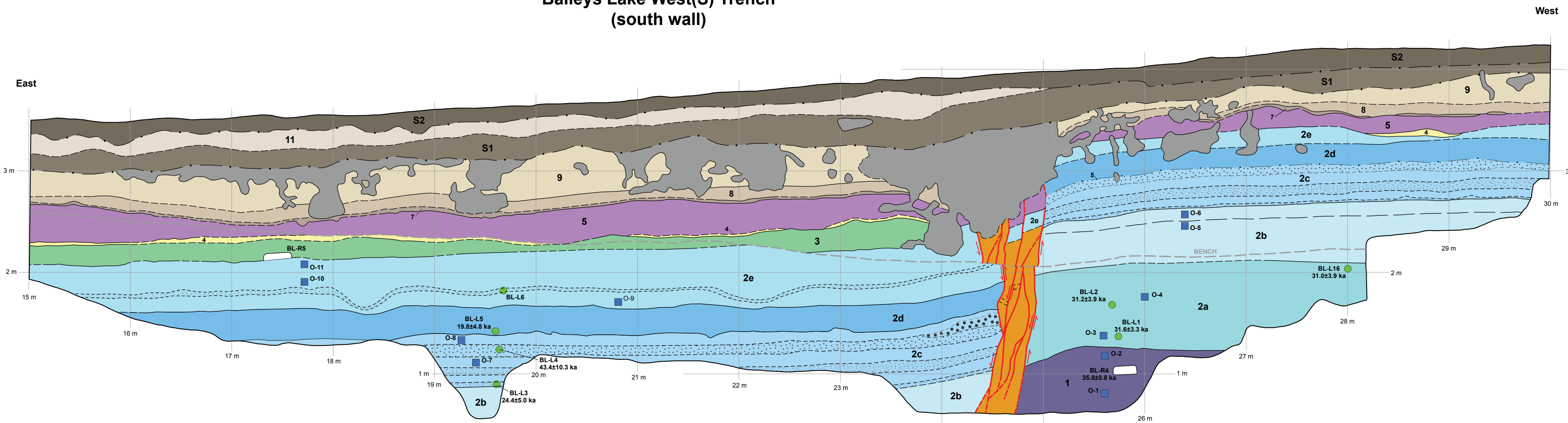


Topographic maps for the trench sites at the Baileys Lake site, showing trench locations and traces of the Granger fault where projected to the surface between the two western trenches. Elevations are relative to mean sea level, based on GPS data measured in 2010; note difference in contour interval between the two maps (west site = 5 m; east site = 2 m). Scarp profiles shown on figure 7.

NOTES

- n1 Well-sorted, non-stratified (liquefied) sand injected horizontally along bedding plane
- n2 Relatively large clay rip-up clast within graded sand interbed (turbidite)
- n3 Angular cobble (9 x 7 x 2 cm) of dark gray micrite (dropstone)

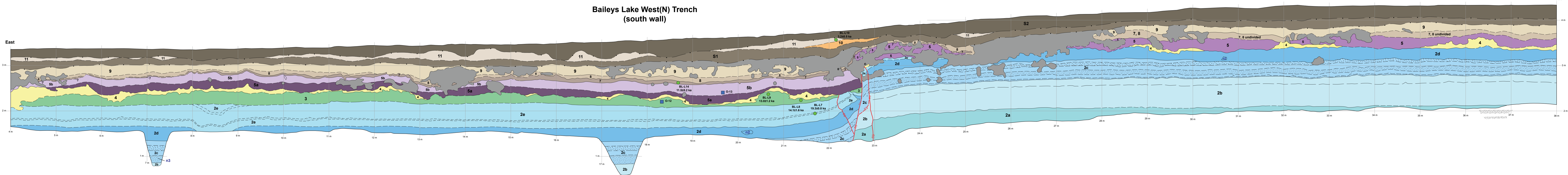
Baileys Lake West(S) Trench (south wall)



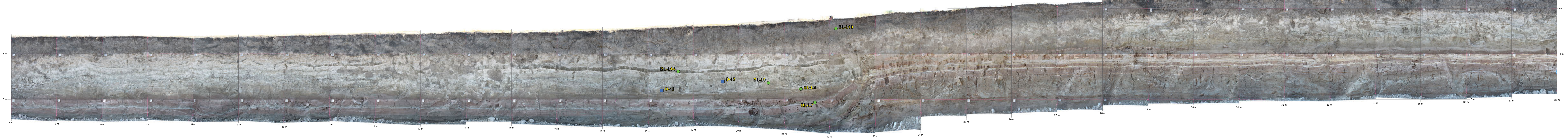
Photomosaic of Baileys Lake West(S) Trench (south wall)



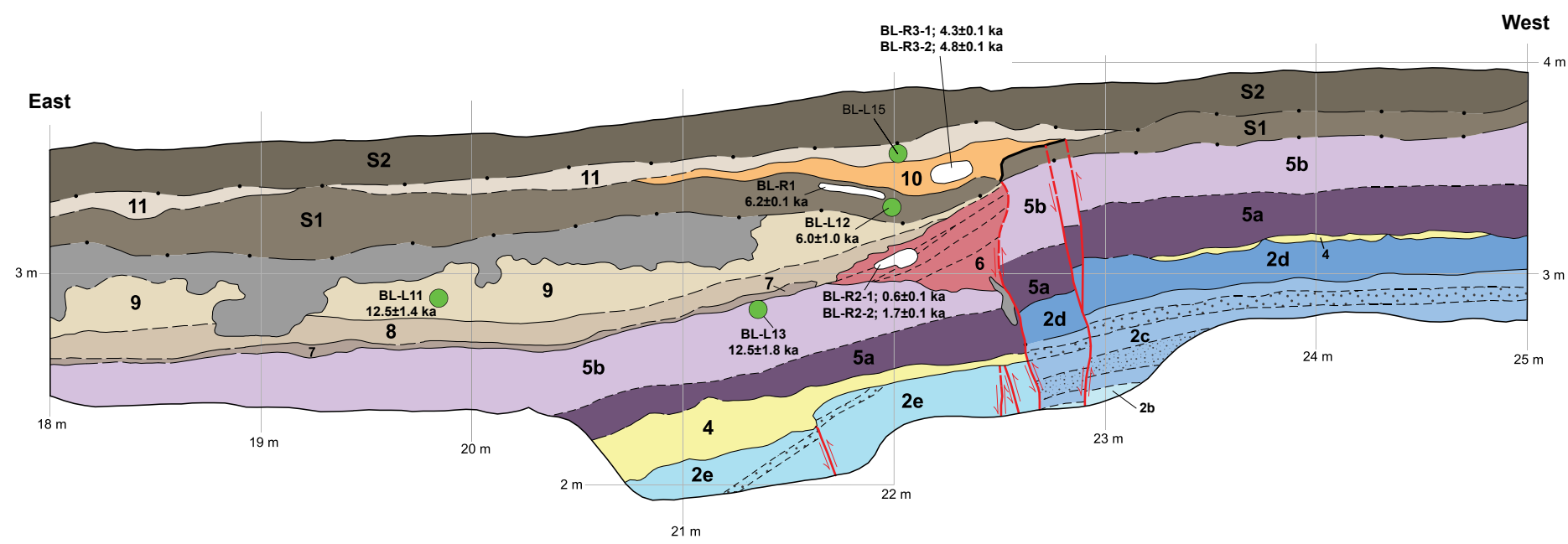
Baileys Lake West(N) Trench (south wall)



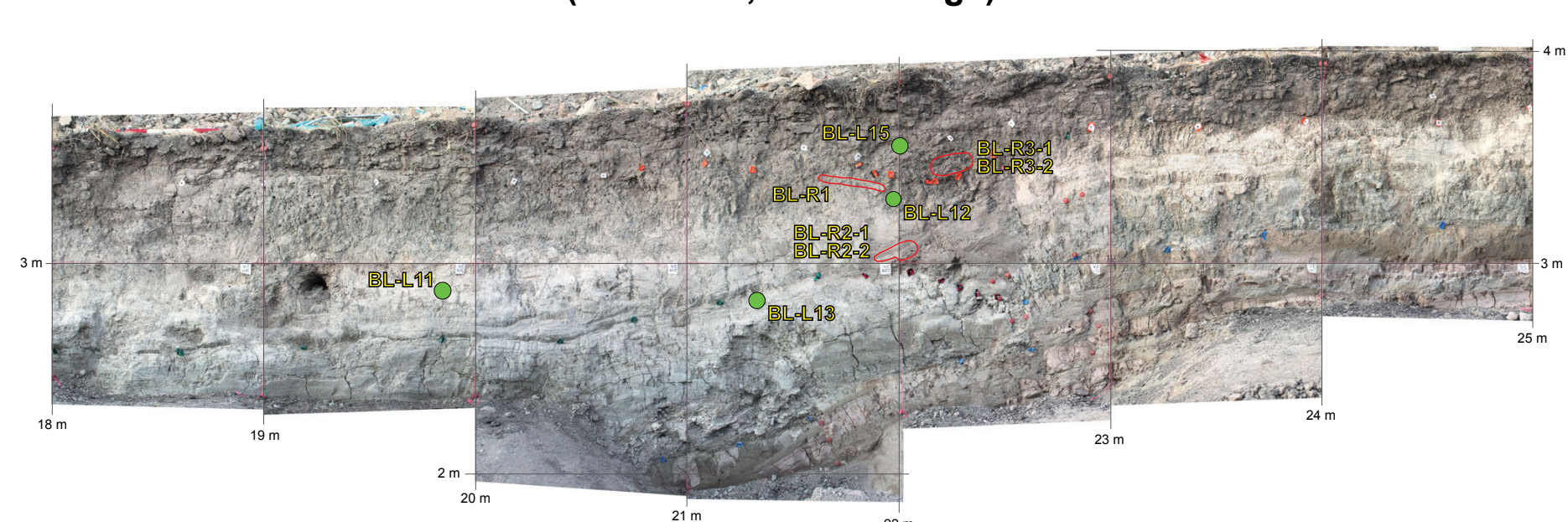
Photomosaic of Baileys Lake West(N) Trench (south wall)



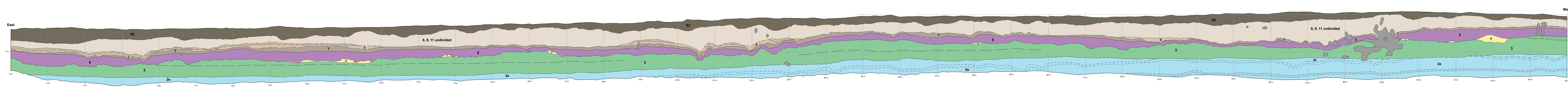
Baileys Lake West(N) Trench (north wall, mirror image)



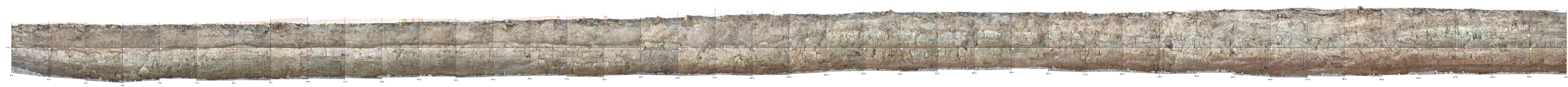
Photomosaic of Baileys Lake West(N) Trench (north wall, mirror image)



Baileys Lake East Trench (south wall)



Photomosaic of Baileys Lake East Trench (south wall)



STRATIGRAPHIC AND STRUCTURAL RELATIONS AT THE BAILEYS LAKE TRENCH SITE, GRANGER FAULT, WEST VALLEY FAULT ZONE

by
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2014