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PALEOSEISMIC INVESTIGATION TO DETERMINE THE MID-HOLOCENE CHRONOLOGY OF SURFACE-FAULTING EARTHQUAKES ON THE NEPHI SEGMENT OF THE WASATCH FAULT ZONE, UTAH AND JUAB COUNTIES, UTAH

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[1] *Download a high-resolution version of this report at* http://geology.utah.gov/ghp/consultants/pdf/NEHRP_G12AP20076/G12AP20076.pdf

ABSTRACT

We excavated trenches on the northern strand (Spring Lake site) and southern strand (North Creek site) of the Nephi segment of the Wasatch fault zone (WFZ) to improve estimates of Holocene surface-faulting earthquake timing, displacement, and rupture extent. Paleoseismic data for the Spring Lake site expand the Holocene record of earthquakes on the northern strand: at least five to seven earthquakes ruptured the Spring Lake site at 0.9 ± 0.2 ka (2σ), 2.9 ± 0.7 ka, 4.0 ± 0.5 ka, 4.8 ± 0.8 ka, 5.7 ± 0.8 ka, 6.6 ± 0.7 ka, and 13.1 ± 4.0 ka, yielding Holocene mean recurrence intervals of ~1.2–1.5 kyr and vertical slip rates of ~0.5–0.8 mm/yr. These data compare well with the results of previous investigations and show that the northern strand has been consistently active during the late Holocene and has a mean recurrence of ~1.0–1.2 kyr. Paleoseismic data for the North Creek site help refine the Holocene earthquake chronology for the southern strand: at least five earthquakes ruptured the North Creek site at 0.2 ± 0.1 ka (2σ), 1.2 ± 0.1 ka, 2.6 ± 0.9 ka (2.2 ka mode), 4.0 ± 0.1 ka, and 4.7 ± 0.7 ka, yielding mean recurrence intervals of 1.1–1.3 kyr and vertical slip rates of ~1.9–2.0 mm/yr. These data compare well with previous paleoseismic data and indicate a mean recurrence of ~1.1–1.3 kyr for the southern strand. Improved earthquake-timing data for the northern and southern strands help address questions regarding their simultaneous versus independent rupture. The strands have similar late earthquake histories and we explore several rupture scenarios that are allowed within the uncertainties of earthquake timing. Although complex rupture of the segment has likely occurred, our analysis indicates that for the majority of late Holocene earthquakes, the northern and southern strands have ruptured simultaneously. Our new paleoseismic data help refine the surface-faulting earthquake history of the Nephi segment, contribute to an improved understanding the complexities of surface rupture and moment release on the WFZ, and will contribute to more accurate probabilistic earthquake forecasts for the Wasatch Front region.

INTRODUCTION

Purpose and Scope

The five central segments of the Wasatch fault zone (WFZ) (figure 1) trend through the most densely populated part of Utah's Wasatch Front and have the potential to generate large-magnitude (M ~6.5–7.5) surface-faulting earthquakes. These segments have been the subject of numerous paleoseismic trench investigations, which have helped resolve their earthquake chronologies, recurrence intervals, and slip rates (Machette and others, 1992; Lund, 2005; DuRoss, 2008). However, at the time of this study, questions remained regarding the Nephi segment—the southernmost of the central segments, which bounds the southern Wasatch Front between Payson and Nephi. The Nephi segment had compelling evidence of late Holocene earthquakes, including the youngest surface-faulting earthquake and the shortest mean earthquake recurrence interval of the central segments, but the least well-constrained Holocene earthquake chronology. Principal, questions include: (1) conflicting paleoseismic data for the southern part of the segment, (2) limited paleoseismic data for the northern part of the segment, and (3) uncertainty in the rupture extent of Holocene earthquakes on the Nephi segment and the potential for coseismic rupture of the Nephi and Provo segments (DuRoss and others, 2008; Crone and others, in press). These questions are important for understanding the history and complexity of moment release on the WFZ and improving earthquake-probability forecasts and seismic-hazard assessments for the Wasatch Front region, and form the impetus for our paleoseismic study.

To refine and expand earthquake timing and displacement data for the entire Nephi segment, we excavated trenches at two sites—one on the northern part at the Spring Lake site and one on the southern part at the North Creek Site (figure 2). At each site, we 1) constructed detailed topographic and geologic maps of the trench site, 2) measured scarp profiles, 3) excavated a single trench and mapped the trench-wall exposures in detail, 4) sampled organic soil remains for radiocarbon (^{14}C) dating and fine-grained detrital sediment for luminescence dating, 5) developed probabilistic models of earthquake timing using OxCal software (Bronk Ramsey, 1995, 2001), and 6) estimated per-event vertical displacements. We used these paleoseismic data to calculate inter-event and mean earthquake recurrence intervals and vertical slip rates for the sites. Our results help refine the earthquake history of the Nephi segment, and when combined with paleoseismic data for the adjacent Provo segment, also allow us to discuss the segmentation of the southern WFZ.

This project was a collaborative effort between the Utah Geological Survey (UGS) and U.S. Geological Survey (USGS), involving substantial contributions on the part of numerous individuals. Michael Hylland, Adam Hiscock, and Greg McDonald (UGS), and Stephen Personius, Rich Briggs, Ryan Gold, Anthony Crone, Steve Angster, and Roselyn King (USGS) had a major role in the fieldwork at both trench sites. Gregg Beukelman and Ben Erickson (UGS) managed the trench photography, and with Adam Hiscock, constructed photomosaics for the trench walls. Adam McKean (UGS) helped describe sedimentary units at both sites. Shannon Mahan (USGS) provided equipment for luminescence sampling, preformed the luminescence dating, and provided helpful advice for interpreting the results.

Geologic Setting

The 350-km long WFZ is a complex normal fault that forms a prominent structural and topographic boundary between the actively extending Basin and Range Province to the west and the relatively more stable Middle Rocky Mountains and Colorado Plateau provinces to the east. The WFZ consists of three distinct subgroups defined using surface-faulting earthquake timing and slip rate: 1) the northern segments, composed of three segments that last ruptured prior to the highstand of Lake Bonneville (~18 ka; Oviatt and others, 1992; Oviatt, 1997) and have slow, less than ~0.1 mm/yr slip rates (Machette and others, 1992; Hylland, 2007a); 2) the central segments, comprising five segments that have evidence of recurrent Holocene surface-faulting earthquakes and ~1–2-mm/yr slip rates (Machette and others, 1992; Lund, 2005; DuRoss, 2008); and 3) the southern segments, which include two possibly Holocene-active segments that have slow, less than ~0.3 mm/yr slip rates (Machette and others, 1992; Hylland, 2007b). The central segments, which form the Wasatch Front between Brigham City and Nephi, include the Brigham City, Weber, Salt Lake City, Provo, and Nephi segments.

The Nephi segment has a complex, north-trending fault trace that bounds the west side of the Wasatch Range and, together with the southernmost Provo segment, forms a prominent west step in the trace of the WFZ (figure 1). The Nephi segment comprises two separate fault strands––the northern and southern strands (referred to as the eastern and western strands by Machette and others, 1992)—which have Holocene surface traces separated by a 4-km-wide right step in bedrock (figure 2). The southern terminus of the southern strand is 6 km north of surface faulting on the Levan segment to the south (Machette and others, 1992; Hylland and Machette, 2008), whereas the northern 12 km of the northern strand overlaps with the southern 13 km of the Provo segment to the east, forming a 5–9-km right step in the trace of the WFZ (Machette, 1992; Machette and others, 1992). From the northern terminus of the northern strand to the southern terminus of the southern strand, the Nephi segment is 43 km long (all length measurements in this section are linear, end-to-end).

The northern strand is 17 km long and bounds the west side of Dry Mountain (3006 m [9865 ft] elevation), which has about 1.2 km of vertical relief (figure 2). The 7-km-long, west-dipping Benjamin fault (Hintze, 1973; Machette, 1992; Solomon and others, 2007) makes up the northern part of the northern strand. Based on small, 1–2 m high scarps and the lack of uplifted bedrock along the Benjamin fault (Machette, 1992), it presumably has a slow slip rate. In addition, Machette (1992) and Solomon and others (2007) only mapped scarps along the northern 1.0–2.5 km and southern 1.0–1.5 km of the Benjamin fault; the 3–5-km-long center of the fault is concealed by Holocene stream and alluvial-fan sediments near Payson. South of the Benjamin fault, north- to northwest-oriented fault scarps, some of which form a complex zone of several overlapping and right-stepping scarps, follow a 2-km right step in the range front. The southern part of the northern strand bounds Dry Mountain and consists of large, continuous north-south oriented scarps along its length. The majority of fault scarps on the northern strand are below the Lake Bonneville highstand shoreline (~1550 m [5100 ft] elevation; Solomon and others, 2007) and near or above the Provo-phase shoreline (~1440–1450 m [4740–4760 ft] elevation; Solomon and others, 2007]; ~18–15 ka [Godsey and others, 2005, 2011); however, scarps on the southernmost part of the strand are above the highstand shoreline.

The southern strand extends for 25 km and bounds the west side of the Wasatch Range (figure 2), including Mount Nebo, which at 3635 m (11,928 ft) elevation (1.8 km of vertical relief) is the highest peak in the Wasatch Range. The southern strand has a mostly linear, north-south-oriented fault trace that is locally complex (including multiple parallel and anastomosing scarps) and extends along the base of the range front. Interestingly, the southern strand includes a 4-km long west-dipping fault (the Mendenhall fault of DuRoss, 2004) that branches to the northwest and continues to a distance of 2 km west of the range front. Similar to the Benjamin fault, the Mendenhall fault lacks uplifted bedrock along it and likely has a slow slip rate. At the southern end of the southern strand, short (< 1-km long) and disconnected scarps both north and southeast of Nephi mark the southern terminus of the Nephi segment. Scarps along the length of the southern strand are above the elevation of the Bonneville highstand shoreline.

Machette and others (1992) postulated that a northeast-trending and northwest-dipping normal fault in bedrock (Davis, 1983; Witkind and Weiss, 1985; Harty and others, 1997) provides a connection between the northern and southern strands. However, despite the connecting structure, DuRoss (2004) and DuRoss and Bruhn (2005) used scarp geomorphology, geometry, and relative timing to conclude that the step-over between the strands is a structural boundary that may have impeded some Holocene surface ruptures. More recently, DuRoss and others (2008) and Crone and others (in press) analyzed differences in paleoseismic earthquake chronologies for the northern and southern strands and raised important questions as to whether the fault strands rupture together or are separate sources of large earthquakes. An additional possibility is that the northern strand could rupture with the Provo segment. At the time of this study, existing paleoseismic data were insufficient to resolve the rupture extent of surface-faulting earthquakes on the Nephi segment.

Previous Paleoseismic Investigations

Previous paleoseismic data for the Nephi segment fall into three categories: (1) early trench investigations (North Creek and Red Canyon sites; table 1; figure 2) that revealed evidence of multiple surface-faulting earthquakes, but poorly constrained the timing of the events because of large dating uncertainties (e.g., bulk-soil ages and conflicting ^{14}C and luminescence ages); (2) more recent investigations that used modern dating methods (e.g., accelerator mass spectrometry [AMS] dating of charcoal) and OxCal modeling, but were only able to constrain the timing of earthquakes younger than about 2.5 ka (Willow Creek and Santaquin sites; table 1; figure 2), and 3) trenches excavated for educational purposes (geology field courses) (the Picayune Canyon site; table 1; figure 2) that have limited documentation. These previous data are summarized here; for additional discussions see DuRoss and others (2008) and Crone and others (in press). OxCal models of the North Creek, Red Canyon, Willow Creek, and Santaquin sites are included in Crone and others (in press) and DuRoss and others (in preparation).

Hanson and others (1981, 1982; included in Bowman and Lund, 2013) excavated trenches at the North Creek site on the southern strand (figure 2), but limited and conflicting numerical ages raise concerns regarding the Holocene earthquake chronology (Lund, 2005). Hanson and others (1981, 1982) found colluvial-wedge evidence of the youngest earthquake (NC1), but were only able to date organics from a soil within the faulted fan deposits (predating the colluvial wedge), thus loosely constraining the earthquake NC1 to <0.8–1.2 ka. An older earthquake (NC2) ruptured the site; however, seven ^{14}C ages for a soil A horizon developed on the event NC2 colluvial wedge yielded conflicting ages clustering at ~1.3–1.4 ka and ~3.7–4.1 ka. Hanson and others (1981, 1982) preferred the older age estimates for the timing of the earthquake; however, DuRoss and others (2008) and Crone and others (in press) note that a younger earthquake time (~1.4 ka) is also possible and more consistent with the ages for overlying alluvial-fan deposits. Hanson and others (1981, 1982) did not find stratigraphic evidence for an older earthquake (NC3) in their trenches, but used an inset terrace and a ^{14}C age for a charcoal sample from a natural exposure in the footwall of the fault (Bucknam, 1978; included in Bowman and Lund, 2013) to constrain the time of earthquake NC3 to less than ~5.3

ka. Using additional soil ages (~2.2 ka) from the hanging wall (Hanson and others, 1981, 1982), Crone and others (in press) report an earthquake NC3 time of ~1.9 ka.

Table 1. Summary of previous earthquake timing data for the Nephi segment.

Northern strand		**Southern strand**			**Segment-wide**
Picayune Canyon[1]	Santaquin[2]	North Creek[3]	Willow Creek[4]	Red Canyon[5]	Segment chronology[6]
~2.5 ka	0.5 ± 0.1 ka	0.4 ± 0.5 ka	0.2 ± 0.1 ka	0.5 ± 0.5 ka	0.2 ± 0.1 ka
~3.5 ka	*NE*	1.4 ± 0.3 ka	1.2 ± 0.1 ka	1.2 ± 0.3 ka	1.2 ± 0.1 ka
NE	-	1.9 ± 0.5 ka	1.9 ± 0.6 ka	*NE*	2.0 ± 0.4 ka
-	-	*NE*	4.7 ± 1.8 ka	4.7 ± 2.7 ka	4.7 ± 1.8 ka

[1] Based on preliminary data from Horns and others (2009); referred to as the Picayune Canyon site to avoid confusion with the Spring Lake site (this study). *NE* indicates that evidence of earthquake not exposed.
[2] Based on the OxCal model reported in DuRoss and others (2008). DuRoss and others (in preparation) include an alternative model with an earthquake time of 0.3 ± 0.2 ka.
[3] Based on the OxCal model reported in Crone and others (in press), using numerical data from Hanson and others (1981, 1982).
[4] Based on numerical data and the OxCal model of Crone and others (in press).
[5] Based on the OxCal model reported in Crone and others (in press) using numerical data from Jackson (1991).
[6] Segment-wide chronology developed for the Nephi segment (using southern-strand data) for the Working Group on Utah Earthquake Probabilities and reported in Crone and others (in press).

Near the southern terminus of the southern strand, Jackson (1991) excavated a trench at the Red Canyon site (figure 2). Jackson (1991) found evidence of three surface-faulting earthquakes; however, conflicting ^{14}C and thermoluminescence (TL) ages complicate the earthquake-timing interpretation. The youngest earthquake (RC1) occurred after 1.3–1.5 ka, but the event is not limited by a minimum constraint. Jackson (1991) reported conflicting ^{14}C and TL ages that constrain the second earthquake (RC2) to either ~1.1–1.7 ka or ~3.8 ka. Jackson (1991) considered the 1.1–1.7-ka ages too young and interpreted an earthquake RC2 time of ~3.0–3.5 ka; however, similar to North Creek, a younger event time is possible. Jackson (1991) found colluvial-wedge evidence for the oldest earthquake (RC3). A ^{14}C age on soil organics from the scarp colluvium provided a minimum time of ~3.6 ka; however, earthquake RC3 is not constrained by a maximum age. Considering the Bucknam (1978) charcoal sample from North Creek, Jackson (1991) reported an earthquake time of 4.0–4.5 ka for RC3.

A more recent trench investigation on the southern strand at Willow Creek (Machette and others, 2007; Crone and others, in press) (figure 2) improved the late-Holocene (younger than about 2.5 ka) earthquake chronology of the southern strand. Crone and others (in press) report three surface-faulting earthquakes constrained by OSL and ^{14}C ages: earthquake WC1 at ~0.3 ka, WC2 at ~1.2 ka, and WC3 at ~2.0 ka. These data yield a relatively short mean earthquake recurrence interval of ~0.9 kyr (WC3–WC1), which is considerably shorter than ~1.3–1.5-ky mean estimates for other WFZ segments (Lund, 2005, 2013). Crone and others (in press) also reported scarp-offset evidence of at least one older earthquake (WC4); however, stratigraphic (e.g., colluvial-wedge) evidence of the earthquake(s) was not exposed in the trenches. Using the earthquake WC3 time range and OSL ages for sediments exposed in the footwall of the fault, earthquake WC4 is broadly constrained to about 6.5–2.9 ka (Crone and others, in press).

DuRoss and others (2008) excavated trenches across a single-event scarp on the northern strand at the Santaquin site (figure 2). Although DuRoss and others (2008) were only able to constrain timing of the youngest event at the site, their investigation marks an important step in understanding the behavior of the northern strand. Earthquake SQ1 occurred at 0.5 ± 0.1 ka (DuRoss and others, 2008), or 0.3 ± 0.2 ka if a minimum limiting age (of 0.4 ka that is very close in age to the faulted soil) is excluded. Given the earthquake S1 uncertainty and broad time range of ~0.1–0.7 ka reported by DuRoss and others (in preparation), earthquake S1 could correlate with either the youngest earthquake on the southern strand (WC1 at ~0.3 ka) or the youngest earthquake on the Provo segment (~0.6 ka; Lund, 2005). DuRoss and others (2008) and DuRoss and others (in preparation) considered multiple correlation possibilities, but ultimately had insufficient data to draw conclusions regarding the behavior of the northern strand. DuRoss and others (2008) did not find geologic evidence for older events at their site, but ^{14}C ages suggest the next older event occurred before 1.5 ka (based on a soil-A-horizon age from within alluvial-fan sediments) and possibly prior to ~5–6 ka (using detrital-charcoal ages from alluvial-fan sediments).

About 3 km northeast of the Santaquin site, and 0.7 km south of the Spring Lake site (this study), Horns and others (2009) excavated a trench across a prominent scarp at the mouth of Picayune Canyon (figure 2) (Crone and others [in press] refer to this site as the Spring Lake site; however, to avoid confusion we herein refer to it as the Picayune Canyon site). Horns and others (2009) report earthquake times of ~2.5 ka (PC1) and ~3.5 ka (PC2) based on ^{14}C ages for soils faulted and buried by scarp-derived colluvium. Although the soil ages may reflect the approximate earthquake times, it is important to note that these earthquakes do not have minimum age constraints. Earthquake PC1 had about 3 m of vertical displacement; Horns and others (2009) did not report a displacement for earthquake PC2.

Immediately north of the alluvial fan at the Spring Lake site, Utah Valley University (UVU) faculty and students excavated trenches in hillslope colluvium in 2010, exposing evidence of at least two surface-faulting earthquakes (D. Horns, verbal communication, 2011). However, because of limited funding, the UVU trenches were only open for a few days, and only preliminary (unpublished) information on the trench and samples collected for radiocarbon dating were available at the time of this study. Because of the ongoing nature of the investigation, we do not consider these data in our analysis.

Why Trench the Nephi Segment?

The Nephi segment is one of the most active segments of the WFZ, having paleoseismic evidence for three surface-faulting earthquakes since about 2.5 ka. However, at the time of this study, important questions remained regarding the segment's Holocene earthquake history. For example, investigations of the southern strand identified earthquakes older than 2.5 ka, but geologic evidence in support of the earthquakes is weak and the events have large (~2–3-kyr) timing uncertainties. Furthermore, limited data for the northern strand only constrain 1–2 late Holocene earthquakes. A complete record of earthquakes on the Nephi segment since the mid

Holocene is important for (1) understanding the coseismic versus independent rupture behavior of the northern and southern strands, (2) calculating a more robust mean recurrence interval for the segment, (3) investigating the potential for interaction between the northern strand and the adjacent Provo segment, and (4) comparing Nephi segment paleoseismic data with those for other WFZ segments. These questions are important to estimating moment release on the WFZ, understanding the segmentation of the southern WFZ, and to forecasting the probability of a future large earthquake in the Wasatch Front region.

OVERVIEW AND METHODS

Trench Investigations

We identified trench sites on the Nephi segment using (1) fault-trace and surficial-geologic mapping by Machette (1992) and Harty and others (1997); (2) our interpretation of 1970s (low-sun-angle) aerial photographs (Cluff and others, 1973; included in Bowman and others, 2009) and 2006–2011 orthophotography from the National Agricultural Imagery Program (NAIP) (U.S. Department of Agriculture [USDA], 2013; Utah Automated Geographic Reference Center [AGRC], 2013); (3) 0.5-m-posting LiDAR data (and hillshade maps) for the Nephi segment (Open Topography, 2013); and (4) field reconnaissance. We also considered the discussions and analyses of Nephi segment paleoseismic data by the Utah Quaternary Fault Parameters Working Group (UQFPWG; e.g., Lund, 2005) and Working Group on Utah Earthquake Probabilities (e.g., Lund, 2010) prior to selecting preferred sites. Five sites appeared suitable for paleoseismic trenching: two on the northern strand and three on the southern strand. We selected two sites—the Spring Lake site on the northern strand and the North Creek site on the southern strand—because they had moderately large (~8-m high) scarps that were relatively unmodified by human activity and crossed approximately mid-Holocene or older alluvial-fan deposits.

Spring Lake Site

At the Spring Lake site, on the central part of the northern strand, a prominent, about 6–8-m high, west-facing scarp crosses a post-Bonneville alluvial-fan surface (Machette, 1992). The fan surface and fault scarp are set below the Bonneville highstand shoreline, but above the Provo shoreline. 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 disturbance based on the 1970s and 2006–2011 aerial photographs.

We excavated a 36-m long and less than 4-m deep trench at the Spring Lake site in May 2012. To map the exposures, we constructed a 1-m square grid using an electronic distance meter (Trimble TTS 500) (projecting points to an average, vertical plane parallel to the trench). We photographed the trench, and then color-balanced, cropped, and rectified the photos. To create photomosaics, we tiled the photos for both the northern and southern walls of the trench. Using the photomosaics, we mapped key stratigraphic contacts and faults observed in both trench walls at 1:20 scale on clear film (DuraLar). Plate 1 includes maps and photomosaics of the exposures with a single coordinate system referenced herein using horizontal (h-) and vertical (v-) meter marks. For example, the fault zone is exposed in the north wall at h-25 m, v-7 m (plate 1). Stratigraphic units are described in appendix A.

North Creek Site

The North Creek site is on the north-central part of the southern strand, where a prominent, about 9-m high, west-facing scarp crosses a Holocene alluvial-fan surface (Harty and others, 1997). The fault scarp and uplifted part of the fan surface are above the Bonneville highstand shoreline. 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 disturbance based on the 1970s and 2006–2011 aerial photographs. In addition, North Creek is the site of the original (1978) paleoseismic investigation by Hanson and others (1981, 1982), and thus, the site represented an opportunity to apply more modern trench-excavation and dating techniques and possibly resolve conflicting numerical ages for the earliest Nephi segment earthquakes.

We excavated a 40-m long and less than 4-m deep trench at the North Creek site in May 2012. We followed a similar process of photographing, creating photomosaics, and photo-mapping the North Creek trench exposures. However, because of difficulty accessing the upper part of the south wall, we limited our photomosaics and mapping to the entire north wall and lowermost part (from the fault zone to the west) of the south wall. Plate 2 includes maps and photomosaics of the exposures with a single coordinate system referenced herein using horizontal (h-) and vertical (v-) meter marks. For example, the fault zone exposed in the south wall is at h-21.5 m, v-2.0 m (plate 2). Stratigraphic units are described in appendix B.

Numerical Dating

Radiocarbon Dating

We sampled bulk soil A-horizon sediment (appendix C) and radiocarbon (^{14}C) dated discrete fragments of soil charcoal (appendices D and E) to estimate the ages of buried soil A horizons and limit the timing of paleoearthquakes. For discussions of common sources of uncertainty in radiocarbon 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-local (detrital) charcoal (e.g., conifer transported from higher elevations), PaleoResearch Institute (Golden, Colorado) separated and identified (if possible) charcoal fragments from the 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). For each sample, small, unidentified fragments were recombined into samples of at least ~0.5 mg, which then yielded composite charcoal ages.

We had partial success in identifying charcoal fragments (appendix C). At the Spring Lake site, only 2 of 23 individual charcoal samples could be identified, including *Artemisia* (flowering plants such as sagebrush) and *Asteraceae* (sunflower family) charcoal. At the North Creek site, 11 of 22 charcoal samples were identified, and included *Asteraceae*, *Quercus* (oak), *Juniperus*, and *Pseudotsuga menziesii* (Douglas fir) charcoal. We preferentially dated the

Asteraceae and *Quercus* charcoal samples over the longer-lived *Juniperus* and *Pseudotsuga menziesii* samples. The remaining Spring Lake and North Creek samples only produced collections of small, unidentified charcoal fragments.

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 ^{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 both sites (appendices F and G). 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 it may retain 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).

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 as the mean and one-sigma uncertainty rounded to the nearest decade (appendices F and G). However, where discussed in the text, the error is doubled (2σ rounded to the nearest century) for continuity with the calendar-calibrated radiocarbon 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 (2012) (ka) and do not account for the 62-year difference in the OSL sample date (2012) versus the reference standard for ^{14}C (1950). This difference is minor compared to the large OSL age uncertainties (between 0.3 and 1.9 kyr at 2σ), and is accounted for in later modeling of earthquake times in OxCal.

OxCal Modeling Methods

To quantitatively evaluate earthquake timing, we used OxCal radiocarbon calibration and analysis software (version 4.2; Bronk Ramsey, 1995, 2001; 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 OSL ages and historical constraints) included in a stratigraphic model (Bronk Ramsey, 2008, 2009). The program uses a Markov Chain Monte Carlo sampling method (Bronk Ramsey, 1995, 2001) to generate a probability density function (PDF) for each undated event in the model, or the likelihood that an earthquake occurred at a particular time, using the chronologic and stratigraphic constraints. For more detailed discussions of the application of OxCal modeling to paleoseismic data, see Lienkaemper and Bronk Ramsey (2009) and DuRoss and others (2011).

OxCal depositional models for the Spring Lake and North Creek sites (appendix H) use stratigraphic ordering information, radiocarbon and OSL ages, and a historical constraint that no large surface-faulting earthquakes (M ~6.5+) have occurred since about 1847 to define the time distributions of earthquakes identified at 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 agreement indices for the original (unmodeled) and modeled numerical ages and the OxCal model as a whole (Bronk Ramsey, 1995, 2008). We report earthquake times for each site as the mean and ~2σ uncertainty in thousands of calendar years B.P. (ka) rounded to the nearest century. For earthquakes having skewed (highly asymmetric) time distributions, we also report the mode (peak of the probability distribution) and 95% confidence interval. For skewed distributions, the mode better characterizes the earthquake time than the mean or median values, which are influenced by the tail of the time distribution.

SPRING LAKE TRENCH SITE

Surface Faulting and Geology

The Spring Lake site is on the north-central part of the northern strand, where a moderately large, north trending scarp offsets a small (~0.02 km^2) post-Bonneville alluvial-fan surface that is inset below Lake Bonneville transgressive and highstand sediments (Machette, 1992) (figures 3 and 4). The Spring Lake scarp, as well as discontinuous scarps immediately to the north and the Benjamin fault, make up the northern part of the northern strand that forms an en-echelon right step with the Provo segment (figure 2). The Spring Lake site is at ~1470–1510 m (~4800–5000 ft) elevation, below the elevation of the Bonneville highstand shoreline (~1500 m; ~5100 ft) and above the elevation of the Provo shoreline (~1440–1450 m; 4740–4760 ft) (based on mapping by Solomon and others, 2007).

Surficial geology near the Spring Lake site is dominated by Lake Bonneville lacustrine sediments and geomorphic features, and post-Bonneville alluvial-fan deposits. Deposits associated with the Lake Bonneville highstand include sand to coarse gravel that form wave-built terraces. The Provo-phase shoreline is less well expressed than the Bonneville shoreline, and below the elevation of the trench site. The post-Bonneville alluvial fan slopes gently west and is incised into the Lake Bonneville highstand sediments. The fan surface is underlain by stream and debris-flow sediments derived from a ~0.8 km^2 drainage basin cut in the Mississippian limestone bedrock of the Wasatch Range to the east (Solomon and others, 2007).

The Nephi segment is expressed at the Spring Lake site as a single, prominent, ~100-m long by 8-m high, west-facing scarp (figure 5). Locally, both the fault scarp and the uplifted fan surface have been incised by recent (late Holocene?) stream and debris flows as the locus of fan deposition has shifted west of the WFZ. We estimate 5.0-m of vertical surface offset across the scarp based on a 130-m long profile (figure 6); however, based on the trench stratigraphy (discussed below), it is unlikely that the fan surfaces above and below the scarp are contemporaneous.

Trench Stratigraphy and Structure

The Spring Lake trench exposed the northern strand of the Nephi segment as well as three distinct sedimentary packages: Lake Bonneville lacustrine sediments, post-Bonneville alluvial-fan deposits, and scarp-derived colluvium (colluvial wedges). In the footwall of the fault, Lake Bonneville transgressive and highstand lacustrine sediments are overlain by post-Bonneville stream and debris-flow deposits. In the hanging wall, presumably younger alluvial-fan sediments are interfingered with scarp-derived colluvial wedges deposited adjacent to the WFZ (figure 7; plate 1). Although we found similar stratigraphic units in both the north and south walls of the trench, we discuss sedimentary units (with the exception of colluvial wedges) as either those on the north wall (e.g., N1c), south wall (e.g., S1c), or for the trench as a whole (e.g., N1c/S1c). Colluvial wedges have a single unit designation for both walls (e.g., C1).

Lake Bonneville Sediments

The oldest units exposed at the Spring Lake site are in the footwall of the Nephi segment and consist of lacustrine sediments deposited during the transgression and highstand of Lake Bonneville. The lacustrine package comprises a distinct fining-upward sequence of interbedded gravel and sand (units N1a and S1a) overlain by thinly bedded medium to fine sand (units N1b1 and S1b1). The sand and gravel units are overlain by sand-rich units N1b2 and S1b2, which have remnants of preserved bedding, but are locally massive, and units N1c and S1c, which do not have preserved bedding. These units are overlain by a poorly sorted, boulder-rich deposit (units N1d and S1d). Although units N1b2/S1b2, N1c/S1c, and N1d/S1d were likely deposited in a subaerial environment, they occurred shortly after Lake Bonneville occupied the site, and thus we discuss them as part of the Lake Bonneville sedimentary package.

Units N1a/S1a and N1b1/S1b1 are likely sediments deposited during the transgression of Lake Bonneville across the site. The units slope gently west, are each about 2 m thick, and mostly consist of well-rounded gravel clasts and interbedded sand (units N1a/S1a) conformably overlain by continuous well-bedded sand (units N1b1/S1b1). These units are extensively faulted by west-dipping normal faults, which we could not trace into the overlying post-Bonneville sediments. Unit N1b1/S1b1 included a laterally continuous, 1–2-cm thick clay interbed that we used to measure fault displacement. In the north wall, an OSL sample for the well-bedded fine sand (unit N1b1; sample SL-L9) yielded an age of 17.3 ± 1.9 ka (2σ). This age corresponds well with the age of the latest highstand occupation (Bonneville flood) of 14,500 ^{14}C yr B.P. (Oviatt, 1997), which DuRoss and Hylland (in press) calendar calibrated to 17.6 ± 0.3 ka (2σ) using OxCal.

Units N1b1/S1b1 are overlain by well-sorted sand that locally has poorly preserved bedding (units N1b2/S1b2) but is mostly massive (units N1c/S1c). We interpret the mostly massive sand of units N1b2/S1b2 and N1c/S1c as Bonneville lacustrine sand (of an origin similar to S1b1/S1b1) that has been remobilized by eolian or slope-wash processes, or disturbed by bioturbation and weathering (e.g., soil creep and freeze-thaw processes). We do not consider remobilization by water (e.g., sheet flooding) likely on account of the limited stratification. An OSL age of 10.0 ± 1.2 ka (sample SL-L8) for unit N1c indicates deposition in a subaerial (post-Bonneville) environment. A wind-blown origin for units N1b2/S1b2 and N1c/S1c is most likely considering the well-sorted and unstratified character of the unit and the OSL age, which does not show evidence of sediment mixing (e.g., grains having inherited ages). Furthermore, the massive sand appears to have draped the local topography based on the slope-parallel nature of the unit N1b1–N1b2 and N1b2–N1c contacts, in contrast to the gentle, west-sloping, undisturbed Bonneville unit contacts. Units N1b2/S1b2 and N1c/S1c each have maximum thicknesses of about 1 m.

We exposed massive sand—units "N1c?" and "S1c?"—in the hanging wall of the Wasatch fault that possibly corresponds with footwall units N1c and S1c, respectively (plate 1). Units N1c?/S1c? consist of medium to coarse sand below colluvial-wedge unit C6 that is mostly massive, but locally has minor well-sorted sand lenses. Unit N1c? is possibly ~1.5 m thick, based on a discontinuous 1–2-cm-thick, sub-horizontal clay bed that we exposed at the base of a temporary exposure below the unit N1c?/S1c?–C6 contact (figure 8). However, because of the short (~1-hour) duration of the exposure (excavated prior to backfilling the trench), there is considerable uncertainty in the thickness and origin of N1c?/S1c?. OSL ages for the top of units N1c? and S1c? are 7.0 ± 0.7 ka (SL-L5) and 7.8 ± 1.0 ka (SL-L3), respectively, and indicate subaerial (post-Bonneville) deposition. On the basis of their thickness (>1 m), texture (massive well-sorted sand), and age (>7–8 ka), we tentatively correlate units N1c?/S1c? with footwall units N1c/S1c, which likely consist of Lake Bonneville sand reworked by eolian (and possibly slope-wash) processes. Although units N1c?/S1c? could have a colluvial origin—on the basis of scarp-parallel sand lenses thickening toward the Wasatch fault—we have low confidence in this interpretation because of the limited extent and duration of the exposure. Furthermore, the slope-parallel lenses could simply represent eolian deposition on a preexisting fault scarp near the fault zone, similar to that on well-bedded lacustrine sand (e.g., unit N1b) outside of the fault zone. About 5 m west of the Wasatch fault, units N1c?/S1c? are interfingered with and overlain by alluvial-fan units N3/S3 and soils S3aA/S3bA. The ~10-ka OSL age for unit N1c provides a possible maximum time of deposition of units N1c?/S1c?, whereas the ~7.0–7.8-ka OSL ages for N1c?/S1c? (samples SL-L3 and -L5) (which are similar to ~7.6–8.0-ka ages for soil S3bA; discussed below) indicate a possible younger depositional time.

Unit N1d/S1d is possibly a shoreline-related boulder deposit, or an early post-Bonneville debris flow sourced from near-shore (beach?) deposits above the site. Because units N1d/S1d clearly postdates the massive (disturbed?) sand of unit N1c in the north wall (h-19 m, v-11 m; plate 1), for which we have an OSL age of ~10 ka, we have greater confidence in the latter interpretation. Furthermore, the dramatic change in thickness from the south wall (~0.5-m; h-16-m, v-10.5 m, plate 1) to the north wall (~2.0 m; h-16 m, v-12 m, plate 1) supports a debris-flow origin. Thus, unit N1d/S1d postdates the Lake Bonneville transgressive sand (and period of bioturbation and erosion in the north wall possibly at about 10 ka) and predates the post-Bonneville alluvial fan sediments exposed in the footwall of the fault (units N2 and S2).

Post-Bonneville Alluvial-Fan Deposits

Alluvial-fan deposits exposed in the footwall and hanging wall of the Wasatch fault consist of laterally discontinuous stream and debris-flow deposits. Footwall units include N2 and S2 and subunits (e.g., N2a, S2a); hanging-wall units include units N3 and S3 and subunits (e.g., N3a, S3a, N3b1). Alluvial-fan units in the footwall likely predate those in the hanging wall based on the interbedded nature of the hanging-wall alluvial-fan units with the colluvial wedges, indicating that hanging-wall fan deposition occurred in between surface-faulting earthquakes.

Footwall alluvial-fan deposits: Footwall alluvial-fan units N2 and S3 include gently west-dipping coarse gravel interbeds (subunits N2a-c and S2a-c). The units reach a maximum thickness of about 3.2 m in the south wall and are laterally continuous for at least 5 m in the north wall and 15 m in the south wall, where they are fully exposed in the footwall of the fault. In the north wall, units N2a and N2b are locally incised into debris-flow unit N1d (h-14.7 m, v-12 m, plate 1). Individual subunits are about 0.4 to 1.5 m thick. Units N2 and S3 are faulted by the easternmost trace of the Wasatch fault (fault F1) in both walls, and in the south wall, extensively faulted along the main trace of the Wasatch fault zone (fault F1).

We mapped three soil A horizons within the footwall alluvial-fan units. Soil N2bA/S2bA is about 1 m below the ground surface and laterally discontinuous. Charcoal from soil S2bA (SL-R28) yielded an age of 13.7 ± 0.2 ka. However, charcoal from soil S2bA is older than the ~10-ka OSL age for unit N1c stratigraphically below it and may be detrital in origin. Soils S2cA1 and S2cA2 are formed on unit S2c about 0.5–1.0 m above soil N2bA. We differentiated these soils in the south wall, where soil S2cA1 has been faulted down along fault F1 and buried by scarp colluvium (unit CF3). Soil S2cA2 is formed on the scarp colluvium and merges with soil S2cA1 outside of the area of colluvial-wedge deposition (h-13 m, v-14 m, south wall, plate 1). A soil A horizon below unit CF3 was not present in the north wall. Charcoal from soil S2cA1 yielded an age of 6.1 ± 0.1 ka (SL-R24). Although we did not extract charcoal from soil S2cA2, the soil must be younger than 3.6 ± 0.1 ka based on the charcoal sample from scarp colluvium unit CF3 (SL-R25).

Hanging wall alluvial-fan deposits: The hanging-wall alluvial-fan units consist mostly of gently west-dipping coarse gravel interbeds and sub-horizontal channel cuts and fills (subunits N3a-g and S3a-j). The deposits reach a thickness of at least 4 m in the south wall, and individual subunits are <0.1 m to about 1.5 m thick. The deposits are mostly laterally discontinuous: although some subunits (e.g., S3h and N3d) can be traced horizontally for as much as about 18 m, most subunits (especially those lower in the fan sequence) are laterally continuous for only ~3–10 m. For this reason, there is significant uncertainty in the correlation of units along, and especially between, the north and south trench walls. Several of the hanging-wall fan units are faulted along fault F1, where they indicate fan deposition interspersed with surface-faulting earthquakes and colluvial-wedge deposition.

Soil horizons in units N3 and S3 include two buried soil A horizons and a modern soil A horizon. Soils N3aA and S3bA, which likely correlate, mark the oldest buried soil—an A horizon developed in the oldest alluvial-fan sediments exposed on the fault hanging wall (e.g., h-32 m, v-2.5 m, south wall, plate 1). These soils are laterally continuous for about 6–7 m, and extend to within about 6–7 m of fault F1, where they have been locally removed by cross-cutting alluvial-fan channels. Concordant OSL and ^{14}C ages indicate a soil burial time of about 7.6 ± 0.1 ka (SL-R2) to 8.0 ± 1.5 ka (SL-L2). About 2–3 m above S3bA, soil S3iA developed on unit S3i and overlain by units S3j and soil S3jA. In the north wall, a single soil N3A is developed on fan units N3g1, N3f, and N3g2, and likely correlates with both soils S3iA and S3jA in the south wall. Because the relation of soil S3iA to surface faulting is unclear, and because S3jA and N3A are modern soils, we did not sample these soils for ^{14}C dating.

Alluvial-fan units S3d, S3g, and S3h, all of which postdate soil S3bA, had detrital charcoal fragments dispersed throughout them. Charcoal samples SL-R1 and SL-R3 indicate ages of 7.2 ± 0.2 ka (SL-R3) and 7.5 ± 0.2 ka (SL-R1) for unit S3d. In contrast, an OSL sample (SL-L1) of unit S3d yielded an age of 5.2 ± 0.3 ka. We have low confidence in these detrital-charcoal ages as they conflict with several soil-charcoal and OSL ages from above and below unit S3d. Below unit S3d, ^{14}C and OSL ages for soil S3bA and units C6 and N1c?/S1c? are between ~6.1 ± 1.2 ka (SL-L4) and 8.0 ± 1.5 ka (SL-L2); above unit S3d, we have the most confidence in an OSL age of 5.7 ± 0.8 ka (SL-L6) for unit S3h. A charcoal fragment from unit S3h yielded an age of 7.1 ± 0.1 ka (SL-R11); however, we have low confidence in this age, as well as the 7.2–7.5-ka ages for unit S3d, because of the detrital nature of the charcoal dated (possibly having an inherited age component).

Scarp-Derived Colluvium

Scarp-derived colluvial wedges (units C1–C6 and CF1–3) at the Spring Lake site consist of lacustrine to alluvial-fan sediment eroded from scarps formed during individual surface-faulting earthquakes on the Nephi segment. The wedges have similar wedge-shaped geometries, horizontal extents (~2–5 m), and maximum thicknesses of about 0.3–0.7 m where unaffected by synthetic or antithetic faulting (table 2). Using units C1–C6, the mean of the maximum wedge thicknesses is 0.6 m. Although the youngest colluvial wedges (C1, CF1, and CF3) are not faulted, units C2–C6 and CF2 have been faulted down to the west along the Nephi segment. We group and discuss the colluvial wedges according to whether they 1) are interbedded with alluvial-fan deposits (units C6–C4), 2) post-date the majority of the alluvial-fan units (units C3–C1), or 3) formed as a result of rupture in the footwall of the fault (units CF1–3).

Units C4–C6 are the oldest colluvial wedges exposed at Spring Lake. These colluvial wedges are interbedded with alluvial-fan deposits, which indicate active fan deposition in between surface-faulting earthquakes. In addition, units C4–C6 mostly lack organic sediment (in contrast to abundant organic sediment in units C1–C3), likely reflecting active depositional processes (rather than soil development) during scarp formation and erosion. For the youngest colluvial wedges (C1–C3 and CF1-3), organic A-horizon soil matter is locally dispersed throughout the wedges, indicating cumulic A horizon development during wedge deposition.

Table 2. Colluvial-wedge thickness at the Spring Lake site.

Unit	North wall (m)	South wall (m)	Preferred (m)
C1	0.7	0.7	0.7
C2	0.5	0.5	0.5
C3	0.5	0.5	0.5
C4	0.3	~0.4†	0.4
C5	0.5	0.6	0.6
C6	0.7	>0.4†	0.7
CF1	0.6	*NE*	0.6
CF2	*NE*	0.6	0.6
CF3	0.3	0.3	0.3

† poor measurement because of bench (C4) or uncertainty in lower contact (C6).

NE – not exposed.

CF3 based on height of buried free face, rather than maximum wedge thickness.

Unit C6 is the oldest completely exposed colluvial wedge. The wedge consists mostly of sand that is massive to weakly bedded, and locally has slope-parallel fabric that unconformably overlies the sub-horizontal top of unit N1c? (h-28 m, v-3.2 m, north wall, plate 1) (figure 8). Unit C6 is a maximum of 0.7 m thick based on the north wall exposure and is overlain by several extensive alluvial-fan deposits (units S3c and N3d) that taper to the east, reflecting deposition on preexisting topography (the toe of the scarp). Unit C6 postdates the ages for unit N1c? (~7.0–7.8 ka) and soil S3bA (~7.6–8.0 ka). In the north wall, OSL and ^{14}C samples from the uppermost part of unit C6 provide minimum ages of 6.1 ± 1.2 ka (SL-L4) and 16.9 ± 0.3 ka (SL-R10). The anomalously old age for SL-R10 likely reflects detrital charcoal eroded from unit N1.

Scarp colluvium (unit C5), which overlies unit C6 and alluvial-fan units N3d and S3c, is likely evidence of a separate surface-faulting earthquake. Unit C5 is a maximum of about 0.5–0.6 m thick and has a limited horizontal extent of ~2.2–2.6 m. We were unable to sample unit C5 because of the lack of organic sediment for ^{14}C dating, or well-sorted sand for OSL dating. However, unit C5 must postdate the ~6.1-ka OSL age for C6, and may also postdate charcoal ages ~7.2–7.5 ka for unit S3d based on the correlation of alluvial-fan unit S3c across a prominent channel fill (unit S3g). However, it is possible that these detrital charcoal fragments sampled from unit S3d have an inherited age component as they are stratigraphically inverted with OSL ages L4 (~6.1 ka) and L5 (~7.0 ka). Unit C5 predates an OSL age of ~5.7 ka and a ^{14}C age on charcoal of 7.1 ka (SL-R11) for unit S3h1. Considering the similarity of the detrital-charcoal age for S3h1 (~7.1 ka) to those from unit S3d, we have low confidence in the 7.1-ka age.

Because unit C5 directly overlies part of unit C6 (north wall, h-27.5 m, v-4.2 m) and has a very limited area, C5 could be a younger pulse of unit C6 sedimentation. In this scenario, fan deposition (units S3c, S3e, and S3g) between units C6 and C5 would be contemporaneous with deposition of units C6 and C5. However, because the fan deposits between units C6 and C5 are extensive (laterally continuous for several meters and including several subunits), they likely indicate a period of scarp stabilization and fan deposition. In addition, OSL ages show that a significant amount of time (~1 kyr) elapsed between deposition of uppermost unit N1c? (~7 ka) and uppermost unit C6 (~6 ka). Considering this elapsed time, scarp erosion and colluvial-wedge (unit C6) deposition were likely complete by the time alluvial-fan units S3c and N3e were deposited, making unit C5 (similar in geometry to unit C6) a separate colluvial wedge related to a younger surface rupture. However, deposition of units C5 and C6 occurred in a relatively short time (~1.3 kyr between the 7.0-ka for uppermost unit N1c? and the 5.7-ka age for unit S3h1) and thus we cannot rule out the possibility that units C5 and C6 were deposited following a single earthquake.

Unit C4 postdates a period of alluvial-fan channel formation (erosion) and deposition (units S3g and N3e-f). Similar to C5, unit C4 has a limited lateral extent of ~2.5–4.3 m and a maximum thickness of ~0.3–0.4 m. In the south wall, unit C4 overlies alluvial-fan units S3g and S3h, as well as a weak carbonate soil horizon developed on these units (h-26 m, v-5.3 m, south wall, plate 1). OSL and ^{14}C ages for units S3g and S3h indicate that unit C4 deposition occurred after ~5.7 ka (OSL sample SL-L6), and possibly ~7.1 ka using the age for ^{14}C sample SL-R11. A ^{14}C sample of uppermost C4 colluvium yielded an age of 4.4 ± 0.1 ka (SL-R20). An additional sample of unit C4 colluvium consisted of sand likely eroded from the footwall (unit N1) and yielded an OSL age of 4.5 ± 0.5 ka (SL-L10). Unit C4 is overlain by a debris flow that is ~0.3 m thick in the south wall (S3h2) and ~0.2 m thick in the north wall (unit N3g1).

Considering the limited thickness and extent of unit C4 (particularly in the north wall), we cannot rule out the possibility that C4 is an earlier phase of the unit C3 colluvial wedge. However, the limited (~0.3-m) thickness for unit C4 in the north wall may be related to a limited exposure as the unit crosses a ~1.5-m-wide horizontal bench. In the south wall, C4 also has a limited thickness (again, possibly related to the limited exposure across a horizontal bench), but the unit has a geometry that is more consistent with younger colluvial wedges C1–C3. Alternatively, the limited thickness for C4 may stem from alluvial-fan deposition (unit S2h2) which occurred between C4 and C3, and may have taken up part of the accommodation space created by the C4 earthquake. Finally, ^{14}C ages for units C4 and C3 indicate that at least 1.1-kyr elapsed between deposition of these colluvial-wedge units. Thus, we consider it unlikely, that C3 and C4, which were deposited at least 1.1 kyr apart and are separated by a distinct alluvial-fan unit, formed in response to the same surface-faulting earthquake.

Scarp colluvium in unit C3 is the youngest wedge formed during the period of alternating alluvial-fan and colluvial-wedge deposition. Unit C3 has a horizontal extent of 2.6–4.5 m and a maximum thickness of ~0.5 m. Unit C3 is overlain by a debris flow (north wall unit N3g1); however, the likely corresponding debris flow in the south wall (unit S3i) is only exposed west of unit C3. Unit C3 postdates the 4.4–4.5-ka ages for unit C4, and predates an age of 3.5 ± 0.1 ka (SL-R19) for charcoal extracted from the upper part of the unit. Charcoal extracted from unit N3g1 (postdating unit C3) yielded an age of 5.7 ± 0.1 ka (SL-R27); however, this age is stratigraphically inverted with several ages (e.g., SL-L10 and SL-R20) and thus, we consider it a maximum age (likely for detrital charcoal) for unit N3g1. Unit C3 is extensively faulted by subsidiary fault traces.

Unit C2, which overlies unit C3 in the south wall and units C3 and N3g1 in the north wall, is the youngest faulted colluvial wedge along the main fault zone (fault F1). The colluvial wedge extends horizontally for 5.1–5.4 m and has a maximum thickness of ~0.5 m. Fault-related evidence for C2 includes subsidiary faults that displace the C3 wedge, but do not extend into unit

C2 (h-26 m, v-6.5 m, north wall, plate 1). Unit C2 post-dates the 3.5-ka age for unit C3 as well as the erroneously old 5.7-ka age for alluvial-fan unit N3g1 (SL-R27). Minimum ages for C3 deposition are derived from charcoal extracted from the uppermost part of the C2 colluvial wedge. In the south wall, two charcoal samples (SL-R17 and –R18) yielded ages of 2.3 ± 0.08 ka (SL-17) and 4.1 ± 0.1 ka (SL-R18). However, we dismiss the 4.1-ka age for SL-R18 as it is stratigraphically inverted with the 3.5-ka age (SL-R19) for the soil sediment (within unit C3) buried by unit C2. Sample SL-R18 likely contained charcoal eroded from the faulted soil sediment within unit C3. In the north wall, charcoal from unit C2 yields a minimum age of 1.1 ± 0.04 ka (SL-R22) for unit C2.

Unit C1 consists of unfaulted scarp colluvium that overlies unit C2 in the north and south walls. Unit C1 extends horizontally for about 4.7–5.6 m and has a maximum thickness of 0.7 m. Evidence for C1 includes silt, sand, and gravel that locally forms slope-parallel fabric and has buried a shear zone and eroded scarp free face. The timing of unit C1 deposition is complicated by poor agreement between the north- and south-wall ^{14}C ages. In the north wall, charcoal derived from C1 soil sediment provides a minimum age of 0.7 ± 0.04 ka (SL-R21); in the south wall, two charcoal samples from C1 yield minimum constraints of 0.7 ± 0.04 ka (SL-R15) and 2.4 ± 0.1 ka (SL-R16). However, we dismiss the 2.4-ka minimum age (SL-R17), which is for charcoal likely derived from ~2.3-ka soil sediment in the faulted C2 wedge (thus, predating unit C1 deposition). Maximum times of unit C1 deposition are 1.1 ± 0.1 ka based on north-wall sample SL-R22 and 2.3 ± 0.1 ka based on south-wall sample SL-R17. Based on these ages, unit C1 deposition likely occurred between ~0.7 and 1.1 ka.

Colluvial wedges CF1–CF3 were deposited following movement on faults F1 (CF1 and CF2) and F3 (CF3). Unit CF1 is only present in the north wall where it overlies sheared sediment near the top of the complex fault F1, and is east of the buried free face adjacent to colluvial wedge C1 (h-25 m, v-8m, plate 1). CF1 has a maximum thickness of 0.6 m; however, this is a poor estimate on account of its limited exposure (~0.6-m lateral extent). We also exposed a colluvial wedge, unit CF2, in the north wall and footwall of the faults within the F1 fault zone that underlie and are adjacent to colluvial wedges C1–C6. CF2 has a lateral extent of 3.0 m and a maximum thickness of 0.6 m. Unit CF3 is exposed on the down-thrown (west) side of fault F3 in both the north and south walls. The colluvial wedge has a lateral extent of ~2.6–3.3 m and a maximum thickness of ~0.3 m. Unit CF3 was deposited after a 6.1 ± 0.1-ka age (SL-R24) for soil S2cA1 (beneath unit CF3) and before a 3.6 ± 0.1-ka age (SL-R25) for the basal part of the unit. Units CF1 and CF2 do not have numerical ages constraining their deposition times.

Wasatch Fault Zone

The WFZ at the Spring Lake site is characterized by 1) a main and westernmost shear zone (F1), 2) a central zone of complex faulting primarily in Lake Bonneville lacustrine sediments (F2), and 3) an easternmost fault trace (F3) (plate 1).

Fault F1 comprises about 4–6 traces that juxtapose Lake Bonneville lacustrine and post-Bonneville alluvial-fan sediments in the footwall with alluvial-fan sediments and scarp-derived colluvium in the hanging wall (figure 7). These traces form a complex, upward-diverging fault zone about 0.3–1.2 m wide in the north wall and 0.4–2.1 m wide in the south wall. These fault zones consist of sheared silt, sand, and gravel containing clasts rotated parallel to one of several fault planes. In the south wall, the dip of the fault traces ranges from about 50° west to near vertical, and locally as much as about 20° overturned (east dipping); however, the main shear zone dips about 65° west. In the north wall, the fault-trace dip ranges from about 60° west to near vertical (locally 10° overturned), and the main shear zone dips about 70–80° west (h-25 m, v-5 m, south wall, plate 1).

Fault F2 consists of an about 6.5–8.0-m wide zone of complex and diffuse faulting primarily within Lake Bonneville lacustrine sediments (units S1 and N1). In both walls, the faults primarily dip 55–75° west; however, locally the faults have shallow (~35–50°) west or moderate (~60–75°) east dips. In the north wall, several minor-displacement faults in F2 terminate near the top of well-bedded unit N1b1 (e.g., h-18 m, v-10 m, north wall, plate 1). We did not observe faulting in overlying units N1b2, N1c, or N1d. Although the mostly massive character of these could have obscured evidence of faulting, we also observed faults that clearly displace unit N1b1, but are truncated by post-Bonneville alluvial-fan unit N2b (h-15 m, v-11.4 m, north wall, plate 1). In the south wall, several faults clearly displace well-bedded unit S1b1, but not the overlying units S1c and S1d. These fault terminations indicate at least one earthquake postdating the time of the Bonneville highstand, but predating the post-Bonneville alluvial fan (units N1d/S1d and N2/S2).

At the eastern end of the exposure, fault F3 consists of a single, west-dipping strand that displaces alluvial fan units N2 (h-11.2 m, v-14 m, north wall, plate 1) and S2 (h-11 m, v-14 m, south wall, plate 1). Fault F3 dips about 55–70° and vertically offsets S2 subunit contacts about 0.2 m and N2 subunit contacts about 0.2–0.4 m. Based on the minor displacement and single colluvial wedge exposed (unit CF3), we infer that movement of fault F3 has only occurred in a single earthquake.

We observed only minor rotation (flattening) of unit contacts in the hanging wall of fault F1. For example, in the north and south walls, the bases of lowermost colluvial wedges C5 and C6 are sub horizontal, whereas the base of the uppermost colluvial wedge C1 dips about 15–20° west. We did not observe significant fault rotation or drag (steepening on the hanging-wall contacts) along faults F2 or F3.

There is considerable uncertainty in the total vertical displacement at the Spring Lake site because of the deposition of alluvial-fan deposits on the hanging-wall following several surface-faulting earthquakes. As a result, footwall and hanging-wall alluvial fan sediments and soils are non-contemporaneous, which complicates both the measurement of total site displacement and the period of time over which that displacement occurred. One possibility is that the lowermost soil (S3sA/N3bA) exposed in the fault hanging wall, which has ages of ~7.6–8.0 ka (R2 and L2), is approximately contemporaneous with the soils (N2bA/S2bA or N2cA/S2cA) exposed near the surface of the fan exposed in the fault footwall. The footwall soils are broadly dated to ~6.1 ka (S2cA) to ~13.7 ka (S2bA). However, we have more confidence in the younger (~6.1 ka) soil age, which corresponds well with several mid-Holocene surface ruptures at the site and is stratigraphically consistent with the early Holocene (~10-ka) age for post-Bonneville unit N1c. Furthermore, the footwall (e.g., N2bA) and hanging-wall (e.g., N3bA) soils both postdate a period of alluvial erosion and deposition (units N2/S2 in the footwall and N3/S3 in the hanging wall) that occurred after deposition of massive (possibly eolian or slope-wash-derived) sand across the site (units N1c/S1c in the footwall and N1c?/S1c? in the hanging wall). If the footwall and hanging-wall soils are contemporaneous, then the total displacement at the site is 6.0–7.3 m, based on 6.0–7.1 m measured in the south wall and 7.0–7.3 m in the north wall. The range in these displacement values stems from the limited exposures of these soils and their projections into the main fault zone (F1).

We estimate the minimum site displacement by summing the individual colluvial wedge maximum thicknesses, which represent the minimum displacement in each earthquake (after DuRoss, 2008). The sum of the C6 to C1 colluvial wedges exposed along fault F1 is 3.4 m (using the preferred values in table 2); including the footwall colluvial wedges (CF1/CF2 and CF3), the minimum site displacement is 4.3 m. The total minimum displacement based on colluvial wedges C6–C1 (4.3 m) is several meters less than the stratigraphic offset of the soils (6.0–7.3 m). We have less confidence in the wedge-based value because of the alluvial-fan deposition on the hanging wall and adjacent to the fault zone that has occurred between several faulting events. Fan deposition along the fault occurred partly in response to surface faulting (the creation of accommodation space), which would have limited the amount of colluvial-wedge sedimentation.

Per-event vertical displacements for the Spring Lake site are based on the assumption that 1) each colluvial wedge along fault F1 represents a separate surface-faulting earthquake, 2) the maximum colluvial wedge height represents the minimum fault displacement, and 3) the maximum total displacement based on the stratigraphic offset of soils S3bA/N3bA represents a reasonable upper-bound displacement. To estimate the upper-bound displacement per event, we took the individual wedge thicknesses and increased them by 70%, so that their sum equaled the maximum stratigraphic offset at the site (7.3 m) (following DuRoss and others, in press). To account for the offset in footwall colluvial wedges CF1 (~0.6 m; north wall) and CF2 (~0.6 m; south wall), we allocated 0.6 m for these wedges (since they were exposed in opposite trench walls) equally to main-fault colluvial wedges C1–C6 prior to scaling. To account for colluvial wedge CF3, we added one-half of its 0.3-m height to colluvial wedges C4 and C3 (on the basis of their numerical constraints; discussed below) prior to the scaling. The revised heights for C1–C6 have a mean of 0.7 m, which we increased by 70%, yielding a scaled mean height of 1.2 m. Using the revised height as the lower bound and the scaled height as the upper bound, the midpoint and range displacements for C1–C6 have a mean of 1.0 ± 0.3 m and range from 0.8 ± 0.2 m (C2) to 1.1 ± 0.3 m (C1 and C6). These displacements are similar to a mean per-event vertical displacement of 1.0–1.2 m found by dividing the total site displacement (6.0–7.3 m) by six surface-faulting earthquakes (colluvial wedges C6–C1 that postdate soils S3bA and N3bA).

Because we did not expose lacustrine sediments on the hanging-wall of the fault, we were unable to constrain the total vertical displacement of the Lake Bonneville transgressive and highstand units.

Paleoseismology of the Spring Lake Site

Chronology of Surface-Faulting Earthquakes

OxCal models for the Spring Lake site constrain the timing of seven surface-faulting earthquakes that postdate the highstand of Lake Bonneville (~18 ka) (table 3). These earthquakes stem from the distinct colluvial-wedge units C1–C6 exposed along the main fault F1 (figure 9) and upward terminations of faults (F2) in the footwall of fault F1. We constructed several OxCal models for the Spring Lake site to account for 1) possibly erroneous ^{14}C and OSL ages (e.g., SL-L1 and SL-R11), 2) the possibility that the detrital-charcoal ages (for SL-R1, -R3, and -R11) do not reflect the time of fan deposition (are erroneously old), and 3) uncertainty in the context of samples SL-L3 and -L5. These models have agreement indices, or the overall agreement of the ages in the stratigraphic model, which varied from low (~30–40) to high (>100). We found the best agreement for models that excluded OSL sample SL-L1 and the detrital charcoal samples SL-R1, -R3, and -R11. Our preferred model (version 5; appendix H) excludes these ages, but includes the ages for SL-L3 and -L5, and has a model agreement of 107. Alternative models with high agreement exclude SL-L3 and (or) -L5, but we have less confidence in these results. After consideration of the SL-L3 and -L5 OSL-sample equivalent-dose populations as well as the context of the samples (using the photomosaics), we consider SL-L3 and -L5 to be good ages for units S1c? and C6, respectively.

Table 3. Earthquake timing and recurrence at the Spring Lake site.

	Earthquake timing		Earthquake recurrence	
Event[1]	**Mean ± 2σ**[2] (ka)	**Central 95%**[3] (ka)	**Inter-event** (kyr)	**Mean** (kyr)
SL7	13.1 ± 4.0	9.6–16.8	SL7–SL6: 6.5	SL7–SL1: 2.0
SL6	6.6 ± 0.7	5.9–7.3	SL6–SL5: 0.9	SL6–SL1: 1.2
SL5	5.7 ± 0.8	5.0–6.5	SL5–SL4: 1.0	SL5–SL1: 1.2
SL4	4.8 ± 0.8	4.3–5.6	SL4–SL3: 0.8	SL4–SL1: 1.3
SL3	4.0 ± 0.5	3.5–4.4	SL3–SL2: 1.0	SL3–SL1: 1.5
SL2	2.9 ± 0.7	2.3–3.5	SL2–SL1: 2.1	-
SL1	0.9 ± 0.2	0.7–1.1	-	-

[1] Spring Lake earthquakes; color shading indicates events that could possibly be grouped (e.g., SL6 and SL5 could be related to single earthquake); see text for discussion.

[2] Mean ± two sigma (2σ) based on OxCal model results (model v. 5; appendix H).

[3] Earthquake time range including 95.4% of the total area of the time distribution with the highest probability density (Bronk Ramsey, 2013).

SL7 is the oldest earthquake at the site, which occurred at 13.1 ± 4.0 ka based on our preferred OxCal model (appendix H). Several faults (F2) that complexly displace the Lake Bonneville highstand lacustrine sediments (unit N1b/S1b) but not overlying loess (unit N1c/S1c), debris-flow (N1d/S1d), or alluvial-fan sediments (N2/S2) provide evidence of earthquake SL7. Thus, earthquake SL7 has a maximum constraint of ~17.3 ka (OSL sample SL-L9 for unit N1b) and a minimum of ~10.0 ka (OSL sample SL-L8 for unit N1c). Earthquake SL7 also likely predates the ~7.0-ka OSL age for uppermost unit N1c? as well as the ^{14}C and OSL ages for soil S3bA that range from 7.0 to 8.0 ka (SL-L5, -L3, -L2, and -R2).

Earthquake SL6 occurred at 6.6 ± 0.7 ka. SL6 postdates the 7.0–8.0 ka ages for N1c? and S3bA (samples SL-L5, L3, L2, and R2) and predates an OSL age for C6 colluvium of 6.1 ± 1.2 ka (SL-L4). Because we consider the sample of uppermost unit N1c?, where buried by unit C6, to be a better approximation of the earthquake SL6 time than the minimum age of 6.1 ka from the uppermost part of unit C6, we used a Zero_Boundary grouping in OxCal to implement this interpretation (see DuRoss and others, 2011 for discussion). As discussed above, we excluded detrital charcoal ages (~7.2–7.5-ka for SL-R1 and -R3) for the overlying alluvial-fan unit S3d, which are stratigraphically inverted with samples L5 and L4 (~6.1–7.0 ka). If included, these ages result in an OxCal model with low agreement.

Earthquake SL5 occurred at 5.7 ± 0.8 ka. Although we did not sample sediment from the C5 colluvial wedge to date, earthquake SL5 is limited to a maximum by the 6.1-ka age (SL-L4) for uppermost unit C6, and to a minimum by an OSL age of ~5.7-ka (SL-L6) for alluvial-fan unit S3h, which clearly postdates unit C5. We excluded the detrital charcoal ages for units S3d (~7.2–7.5 ka) and S3h (7.1 ka). While there is stratigraphic consistency in these ^{14}C ages for the alluvial-fan sediment, the ages are stratigraphically inverted with the OSL ages and yield low OxCal-model agreement if included. Thus, we consider OSL ages for samples SL-L4 (~6.1 ka) and -L6 (~5.7 ka) to best constrain the time of earthquake SL5. As discussed previously, there is uncertainty in whether colluvial wedges C6 (SL6) and C5 (SL5) represent one or two earthquakes. Earthquakes SL6 and SL5 have mean times that are ~0.9-kyr apart and 95% ranges that have ~0.6-kyr of overlap (between 5.9 and 6.5 ka). Although we prefer a model of separate earthquakes for SL6 and SL5, considering the overlap in the earthquake times and the limited extent of the C5 colluvial wedge, we cannot rule out the possibility that these events represent separate pulses of colluvium deposited following the same earthquake.

Earthquake SL4 occurred at 4.8 ± 0.8 ka. The timing of earthquake SL4 is constrained to a maximum by the 5.7-ka OSL age for the alluvial fan unit S3h, and to a minimum of ~4.4–4.5 ka by a ^{14}C age (SL-R20) and OSL age (SL-L10) for uppermost C4 colluvium. Based on the maximum limiting ages, colluvium related to earthquake SL4 (C4) could also correspond with the footwall colluvial wedge CF3 along fault F3. However, CF3 is broadly constrained to ~3.6–6.1 ka based on maximum and minimum limiting ^{14}C ages (SL-R24 and -R25). Displacement along fault F3 in earthquake SL3 would help explain why the C4 colluvial wedge is poorly expressed along the main fault (F1). However, we have low confidence in this interpretation because the CF3 colluvial wedge is broadly constrained and could also correspond with earthquake SL3.

Earthquake SL3 occurred at 4.0 ± 0.5 ka using the 4.4–4.5-ka ages for C4 colluvium as a maximum constraint and a 3.5-ka ^{14}C age for C3 colluvium as a minimum. Using its minimum limiting age (3.5 ka), SL3 (and C3 colluvium) could correspond with footwall colluvial wedge CF3, which has an approximate age range of 3.6–6.1 ka. The 0.8-kyr time difference in the mean times for SL4 (~4.8 ka) and SL3 (~4.0 ka) and the minimal (~0.1-kyr) overlap in their 95% ranges supports our interpretation of two separate earthquakes. Although we prefer a model of separate earthquakes for SL4 and SL3, we cannot rule out a single-earthquake model.

Earthquake SL2 occurred at 2.9 ± 0.7 ka. The timing of earthquake SL2 is based on the 3.5-ka ^{14}C age for C3 colluvium (SL-R19) that provides a maximum constraint, and two ^{14}C ages of 1.1–2.3 ka for C2 colluvium (SL-R22 and -R17) that provided a minimum constraint. We excluded an additional age for the C2 colluvium of 4.1 ka (SL-R18) because it is stratigraphically inconsistent with SL-R17, -R22, and -R19. Sample SL-R18 likely included charcoal derived from the soil developed in unit C3.

Earthquake SL1 occurred at 0.9 ± 0.2 ka, postdating the 1.1–2.3-ka ^{14}C ages for C2 colluvium and predating two 0.7-ka ^{14}C ages for C1 colluvium. An additional sample of C1 colluvium yielded an age of 2.4 ka (SL-R16), which is significantly older than the 0.7-ka minimum ages and stratigraphically inverted with the 2.3-ka age for C2. We chose to exclude the 2.4-ka age for SL-R16 from the OxCal model as the charcoal dated is likely derived from the faulted soil in the C2 colluvial wedge.

Earthquake Recurrence and Fault Slip Rate

We calculated inter-event and mean recurrence intervals between individual Spring Lake earthquakes SL7 and SL1 using the mean earthquake times (table 3; appendix I). Inter-event recurrence is the elapsed time between two successive earthquakes (e.g., SL7–SL6); mean recurrence is the mean over several seismic cycles based on the elapsed time between the oldest and youngest earthquakes (e.g., SL7–SL1) divided by the number of closed inter-event intervals.

Inter-event recurrence intervals between earthquakes SL7 and SL1 have a broad range, varying from ~0.8 kyr for SL4–SL3 to ~6.5 kyr for SL7–SL6 (table 3). The relatively long interval between SL7 and SL6 is related to the poorly resolved time of earthquake SL7 (~4 kyr timing uncertainty at 2σ). In addition, we consider the SL7–SL6 interval a maximum value because of the limited (and short duration) exposure of units N1c?/S1c? in the fault zone, uncertainty in the correlation these unit with footwall units N1c/S1c, and the well sorted and unstratified texture of units N1c?/S1c? that could mask evidence of individual surface-faulting earthquakes. We also report a long, ~2.1-kyr elapsed time occurred between earthquakes SL2 and SL1. However, as opposed to the SL7–SL6 interval, we do not consider the SL2–SL1 interval poorly constrained on account of limited stratigraphy or limiting ages. Excluding the SL7–SL6 interval, the inter-event intervals are less than 2.1 kyr, and yield a coefficient of variation (COV) on recurrence—the standard deviation of the inter-event recurrence values divided by their mean—of 0.45 (0.52 kyr divided by 1.15 kyr).

To account for the long (~6.5 kyr) elapsed time between earthquakes SL7 and SL6 we considered the possibility that slope-parallel sand lenses in units N1c? and S1c? are related to at least one earthquake contemporaneous with deposition of these units over about 10–7 ka. The earthquake(s) would predate formation of hanging-wall soil N3aA/S3bA (~7.6–8.0 ka) and deposition of colluvial wedge unit C6 (~6.1 ka). Although earthquakes in this period would help explain the long gap in surface faulting between SL7 and SL6, we have low confidence in this interpretation because of the thick, massive character of units N1c/N1c? and S1c/S1c?. That is, without local changes in sedimentary texture or the presence of buried soils, colluvial wedges derived primarily from sandy unit N1c/S1c in the fault footwall would be difficult to discern from units N1c?/S1c? in the hanging wall. Reconstruction of the vertical displacement on fault F1 may help resolve the possibility for additional earthquakes between SL7 and SL6.

Mean recurrence intervals measured between earthquakes SL7 to SL3 and SL1 (e.g., SL7–SL1 or SL6–SL1) range from ~1.2 to ~2.0 kyr. Excluding the longest interval (~2.0 kyr for SL7–SL1), which is poorly constrained and possibly a maximum value, the mean intervals are between ~1.2 and 1.5 kyr, indicating a relatively constant rate of earthquakes when averaged over thousands of years. The best-constrained mean recurrence for the Spring Lake site is ~1.2 kyr for SL6–SL1, which excludes the SL7–SL6 interval, but includes five closed intervals between SL6 and SL1.

Table 4. Vertical slip rates at the Spring Lake site.

Event[1]	**Displacement**[2] (m)	**Total Displacement**[3] (m)	**Elapsed Time**[4] (kyr)	**Slip Rate**[5] (mm/yr)
SL7	unknown	-	-	-
SL6	1.1 (0.8–1.4)	5.9 (4.4–7.4) [SL6–SL1]	12.3 (8.7–15.9) [SL7–SL1]	0.5 (0.3–0.9)
SL5	1.0 (0.7–1.2)	4.8 (3.6–6.0) [SL5–SL1]	5.8 (5.0–6.5) [SL6–SL1]	0.8 (0.6–1.2)
SL4	0.9 (0.7–1.1)	3.8 (2.9–4.8) [SL4–SL1]	4.9 (4.1–5.6) [SL5–SL1]	0.8 (0.5–1.2)
SL3	1.0 (0.8–1.3)	2.9 (2.2–3.7) [SL3–SL1]	3.9 (3.3–4.7) [SL4–SL1]	0.7 (0.5–1.1)
SL2	0.8 (0.6–1.0)	1.9 (1.4–2.4) [SL2–SL1]	3.1 (2.6–3.6) [SL3–SL1]	0.6 (0.4–0.9)
SL1	1.1 (0.8–1.4)	1.1 (0.8–1.4) [SL1]	2.1 (1.4–2.7) [SL2–SL1]	0.5 (0.3–1.0)

[1] Earthquakes identified at the Spring Lake site and modeled in OxCal model v. 5 (appendix H).
[2] Vertical displacement per earthquake, reported as the midpoint and range (in parentheses); see table 2 and text for description.
[3] Total displacement is the sum of the per-event displacements (reported as the midpoint and range in parentheses) for earthquakes included in brackets.
[4] Mean elapsed time (with 95% ranges included in parentheses) between earthquakes included in brackets (e.g., 12.3 kyr between earthquakes SL7 and SL1).
[5] Vertical slip rate, based on total displacement divided by elapsed time. Ranges in parentheses approximate 95% uncertainty.

We calculated closed-seismic interval vertical slip rates for the Spring Lake site using the individual earthquake displacements and time ranges between events (table 4; appendix I). For example, ~4.8 m of displacement occurred in earthquakes SL5–SL1; using the total elapsed time of ~5.8 kyr between earthquakes SL6 and SL1 (excluding the elapsed time for SL7–SL6 and the time between SL1 and the present), the slip rate is ~0.8 mm/yr. Slip rates for the Spring Lake site vary from ~0.5 to 0.8 mm/yr. The lower-bound slip rates are ~0.5–0.6 mm/yr for the total displacement in earthquakes SL6–SL1 (which includes the poorly constrained total time interval for SL7–SL1) and SL2–SL1, and the individual displacement for earthquake SL1. The upper-bound slip rates are ~0.8 mm/yr using the total displacements in SL5–SL1, SL4–SL1, and SL3–SL1. We have the most confidence in the slip rate values between ~0.6 and 0.8 mm/yr, which account for several earthquake cycles and exclude the poorly constrained time interval for SL7–SL1.

NORTH CREEK TRENCH SITE

Surface Faulting and Geology

The North Creek site is on the north-central part of the southern strand, at the north end of a series of large, continuous scarps on late Pleistocene to Holocene alluvial-fan surfaces and bedrock that form the linear range front below Mount Nebo (Harty and others, 2007) (figure 10). To the north, less prominent (more degraded) and discontinuous scarps continue on trend with the southern strand (Machette and others, 1992), but also bifurcate to the northwest and northeast. About 1 km north of North Creek, discontinuous scarps associated with the Mendenhall fault branch to the northwest (DuRoss and Bruhn, 2005); about 2 km north of North Creek, large prominent scarps trend northeast into bedrock (Machette and others, 1992). The North Creek site is at ~1735 m (5690 ft) elevation, above the highstand shoreline of Lake Bonneville (Felger and others, 2004).

Surficial deposits at the North Creek site dominantly consist of stream and debris flow deposits sourced from a large (~3.7-km^2) drainage cut in the Cambrian to Pennsylvanian sedimentary bedrock (Witkind and Weiss, 1985; Felger and others, 2004) of the Wasatch Range to the east and a small (~0.3-km^2) drainage to the southeast ("South Creek" of Hanson and others, 1981) (figure 11). To the east, on the upthrown-side of the Wasatch fault, an ~0.01-km^2, mid-Holocene (Bucknam, 1978) alluvial-fan surface has been uplifted and incised. To the west, on the down-thrown side of the fault, alluvial-fan surfaces coalesce to form a broad west-sloping apron.

Holocene movement on the southern strand of the Nephi segment has created a single, prominent, ~150-m long by 9-m high, west facing fault scarp bounding the uplifted fan remnant (figure 12). Incision into the uplifted fan surface above the elevation of the fault scarp has shifted the locus of deposition west, to the hanging wall of the WFZ. We estimate 7.7-m of vertical offset across the scarp based on a 75-m long profile (figure 13); however, this offset represents a minimum mid-Holocene displacement because of younger alluvial-fan surfaces on the fault hanging wall (based on the trench stratigraphy discussed below).

Trench Stratigraphy and Structure

The North Creek trench exposed the southern strand of the Nephi segment as well as three distinct sedimentary packages: alluvial-fan deposits sourced from the North Creek drainage to the east, alluvial-fan deposits sourced from a drainage of more limited aerial extent to the south ("South Creek" of Hansen and others, 1981), and scarp-derived colluvium (colluvial wedges). Alluvial-fan sediments derived from the North Creek drainage are mostly exposed in the fault footwall, whereas fan deposits from the drainage to the south, which are interfingered with scarp-derived colluvial wedges deposited adjacent to the WFZ (figure 14; plate 2), are exposed in the fault hanging wall. We also describe an exposure of cultural (man-made) fill on the fault hanging wall related to the Hansen and others (1981) trench investigation at the site.

Footwall Alluvial-Fan Sediments

Alluvial-fan sediments exposed in the footwall of the fault consist of a 12-m thick package of vertically aggraded stream and debris flow deposits, which we subdivided into three units: 1a, 1b, and 1c. These units are sourced from the North Creek drainage based on the gentle west dip of the units and their setting east of the mouth of the drainage. East of the trench, the alluvial-fan surface (top of unit 1cA) continues east into the canyon. Units 1a–1c consist of coarse, poorly sorted gravel, and individually, are 2–6 m thick and can be traced laterally for a minimum of 1–12 m. Subunits within units 1b and 1c include individual deposits (stream and debris flows) that are a few centimeters (e.g., 1b-2) to a few meters (e.g., 1b-1) thick. Unit 1 is faulted by the main trace of the Wasatch fault (fault F1) in both walls.

A thin (~0.1–0.2-cm thick), but prominent soil A horizon (1bA), which contains abundant charcoal likely formed *in situ* (a "burn horizon"), is developed in the uppermost part of unit 1b and is buried by unit 1c (h-28 m, v-9 m, north wall, plate 2). Charcoal derived from soil 1bA yielded ages of 5.3 ± 0.1 ka (NC-R9) and 7.9 ± 0.1 ka (NC-R7). Because charcoal sampled from the youngest colluvial wedges, but likely sourced from soil 1bA, yielded ages of 5.4 ± 0.2 ka (NC-R13), 6.0 ± 0.1 ka (NC-R15), and 6.2 ± 0.1 ka (NC-R28), we prefer the 5.3-ka age to characterize the age of soil 1bA. Furthermore, this age is nearly identical to an age of 5.2 ± 0.6 ka (appendix E) for charcoal derived from the North Creek footwall (sampled and dated by Bucknam, 1978)

Hanging Wall Alluvial-Fan Sediments

Alluvial-fan sediments exposed in the fault hanging wall consist of sub-horizontal, well- to poorly sorted silt, sand, and gravel interbeds (units 2a–e and 3) that are locally interbedded with scarp-derived colluvial wedges (units C5 to C1) near fault F1. Units 2a–e and 3 are likely derived from South Creek based on the topography of the site, which shows a minor alluvial fan sourced from the drainage to the south that has partially buried North Creek fan sediments on the down-thrown side of the fault scarp (surface contours decrease in elevation and are convex to the north; figure 12). However, we cannot rule out North Creek (which is incised into the footwall fan units immediately north of the site) as an origin for these deposits. The hanging-wall fan sediments reach a thickness of at least 4 m in the south wall of the trench and include individual subunits that are <0.1 m (unit 2d2) to about 1.5 m thick (unit 2c). The fan units are laterally continuous for as much as 17 m. The majority of the hanging wall fan units are faulted by a series of antithetic and synthetic faults (F2–F7) in an about 13-m-wide graben (between faults F1 and F6).

Deposition of units 2a–e and 3 occurred after about 6 ka based on an OSL age of 6.0 ± 0.3 ka (NC-L1) for the oldest unit—a sub-horizontal silt bed (unit 2a) exposed in the footwall of graben-bounding fault F6 (h-8 m, v-1.7 m, south wall, plate 2). An OSL age for unit 2d—a <10-cm thick silt lens that overlies most of the hanging wall fan gravels—yielded an age of 1.5 ± 0.8 ka (NC-L2); however, this age is significantly older than an age of 0.2 ± 0.2 ka (NC-R22) for charcoal derived from the unit (nearly identical sample location within unit 2d) and stratigraphically inverted with several <1-ka radiocarbon ages for soils that are stratigraphically below unit 2d (e.g., soil 2cA). The youngest deposit (unit 3) is a coarse, poorly sorted historical debris flow containing fragments of metal (e.g., fencing materials).

Three distinct buried soils (h-6 m, v-2–4 m, south wall, plate 2) developed within the hanging-wall fan units also help constrain the ages of units 2a–e and 3. Soil 2bA is developed within the uppermost gravel of unit 2b and is laterally continuous for about 14–17 m. However, between faults F1 and F2, soil 2bA is overlain by soil 2b2A (h-15 m, v-1.5 m, south wall, plate 2), which may represent a younger part of soil 2bA formation west of fault F2. Sample NC-R19, which sampled charcoal from soil 2b2A, yielded an age of 4.1 ± 0.1 ka. Thus, soil 2bA (between faults F1 and F2) must be older than ~4.1 ka and may be approximately contemporaneous with deposition of the oldest colluvial wedge (unit C5), which predates a 4.0 ± 0.1-ka age (NC-R12) for charcoal derived from soil C5A. The similar stratigraphic positions (depth below younger soil 2cA) support this inference. Soil 2cA is formed in the uppermost gravel of unit 2c and is laterally continuous for about 17–19 m. Charcoal derived from soil 2cA yielded ages of 0.4 ± 0.1 ka (NC-R31) where buried by colluvial wedge Cg2 in the graben, to 1.2 ± 0.1 ka (NC-R16) where buried by colluvial wedge C2 adjacent to the main fault zone. The youngest buried soil in the graben fan sequence is soil 2cA/CgA, which is developed within colluvial wedges Cg1 and Cg2 in the graben (e.g., h-9 m, v-3.5 m, south wall, plate 2), but merges with soil 2cA beyond the extent of Cg1 and Cg2 (east of fault F3 and west of fault F6). Charcoal derived from soil 2cA/CgA, where developed within unit Cg1, yielded an age of 0.9 ± 0.1 ka (NC-R2).

Scarp-Derived Colluvium

Colluvial wedges (e.g., C1–C5) at the North Creek site consist of silt, sand, and gravel eroded from surface ruptures in the footwall and hanging-wall alluvial-fan sediments in separate surface-faulting earthquakes on the Nephi segment. These units range from about 0.8-m to 1.5-m thick (table 5) and extend horizontally for about 2–6 m. Units C1–C4 consist of probable colluvial wedges, which have similar wedge-shaped geometries, texture and sorting, and soil development. Unit C5 is a possible older colluvial wedge exposed below C4 near fault F1. We also describe colluvial wedges formed along synthetic and antithetic faults in the faulted graben between faults F1 and F6 (Cg1–3). Although the youngest colluvial wedges (e.g., C1 along fault F1) are not faulted, units C2–C5 have been faulted down to the west on the hanging wall of the Nephi segment.

Table 5. Colluvial-wedge thickness at the North Creek site.

Unit	North wall (m)	South wall (m)	Preferred (m)
C1	1.5	1.3	1.4
C2	1.2	0.9	1.1
C3	0.8†	1.0†	0.9
C4	1.3	1.4	1.4
C5	*NE*	*NE*	-
Cg1	0.2-0.3	0.3-0.4	0.2-0.4
Cg2	0.3-0.5	0.4-0.6	0.3-0.6
Cg3	0.3-0.5	*NE*	0.3-0.5

† poor measurement because unit crosses a horizontal bench and has been modified by fan unit 2c.
NE – not exposed.
For C5, the base of the colluvial wedge was not exposed.
Range in Cg1–3 measurements based on values including and excluding soil 2cA/CgA.

Unit C5 is possibly the oldest colluvial wedge at the site. However, the origin of this unit is questionable because of its very limited exposure at the bottom of the north and south walls in the hanging wall of fault F1 (h-20.5 m, v-1 m, south wall, plate 2). Evidence for a colluvial origin of unit C5 includes the texture of the unit and its stratigraphic position compared to hanging-wall fan units 2a and 2b, and soil 2bA, which is possibly contemporaneous with soil C5A. The most significant evidence for a C5 colluvial wedge is the interfingered gravel and soil of unit C5, which clearly predates colluvial wedge unit C4. Soil matter within unit C5 is 0.3-m below the top of soil C5A and thus, more similar to intra-wedge soil lenses in units C4 and C1 than to stream and debris-flow deposits in the footwall (units 1c-3 and 1c-4) or hanging wall (units 2b and 2c). Furthermore, an age for soil C5A of ~4 ka (NC-R12) indicates that soil development in unit C5 is considerably younger than that in the upper part of the footwall fan package (soil 1bA) at ~5–6 ka. Thus, unit C5 and soil C5A are more likely contemporaneous with hanging-wall gravel unit 2b and soil 2bA (~4 ka). Unit 2b is 1.4–1.5 m thick (where completely exposed west of fault F4), and based on the position of 2bA adjacent to C5A, likely interfingers with C5 colluvium (similar to the relation between C3 and unit 2c). Finally, if unit C5 has a similar thickness as that for colluvial wedges C1–C4 (~1–1.5 m), it likely postdates deposition of loess (unit 2a) on the hanging-wall. Based on the age of unit 2a (~6 ka; OSL sample NC-L1), the loess could be contemporaneous with the uppermost footwall fan units (deposited ~5–6 ka based on the ages for soil N1bA). Thus, C5 deposition occurred at ~6.0–4.0 ka, likely postdating footwall fan deposition, but contemporaneous with early alluvial-fan sedimentation on the hanging wall.

Unit C4 is the oldest colluvial wedge for which we had a complete exposure. The wedge extends horizontally about 3.2–5.0 m and has a maximum thickness of 1.3–1.4 m. Evidence for C4 includes a fault termination at the C5A–C4 contact (h-21 m, v-1.4 m, south wall, plate 2), slope parallel clast fabric, and an intra-wedge soil lens (soil C4A; h-20.7 m, v-1.6 m, south wall, plate 2). Unit C4 postdates formation of soil C5A, and likely soil 2bA, and predates formation of soil C4A. Unit C4 mostly predates, but is locally interfingered with soil 2b2A (h-19 m, v-1.5 m, south wall, plate 2), which is stratigraphically above soil 2bA. Differential displacement of soils 2bA (1.5–2.0 m) and 2cA (0.7–0.9 m) across graben faults F2–F6 provide additional evidence for an earthquake that postdates soil 2bA but predates unit C4 (discussed below in the Wasatch Fault Zone section).Charcoal from soil C5A (NC-R12) yields a maximum age of 4.0 ± 0.1 ka for C5. Charcoal (charred floral remains) from 2b2A yielded an age of 4.1 ± 0.1 ka (NC-R19). A charcoal sample of soil C4A (intra-wedge soil lens) yielded an age of 5.4 ± 0.2 ka (NC-R13); however, this sample likely contained charcoal fragments eroded from soil 1bA (~5 ka) exposed in the fault footwall.

Unit C3 consists of scarp colluvium interbedded with hanging-wall gravel unit 2c (h-18 m, v-2.2 m, south wall, plate 2). The colluvial wedge extends horizontally ~5.2–6.3 m and has a maximum thickness of ~0.8–1.0 m; however, there is considerable uncertainty in the thickness of C3 because it is locally interfingered with unit 2c. Although we consider unit C3 a probable colluvial wedge, evidence in support of this interpretation is weaker than for C1, C2, and C4. While C3 has a geometry that shows only minimal thickening toward fault F1, the colluvial wedge has been significantly modified by deposition of fan gravel in unit 2c, and the exposure of C3 adjacent to fault F1 was limited because of a short wall height and presence of sediment disturbed during the excavation (h-21.8 m, v-2.2 m, south wall, plate 2). Evidence for a colluvial origin for unit C3 includes sediment that unconformably overlies minor fault structures and fissures formed in unit C4 and soil C4A. In the south wall, unit C3 postdates the 4-ka age for 2b2A, but predates a 2.1-ka age (NC-R18) for charcoal extracted from the colluvium. Charcoal from soil 2cA, developed within the uppermost part of unit 2c, yielded an additional minimum age of 1.2 ± 0.1 ka (NC-R16). In the north wall, unit C3 is bracketed by ages of 0.2 ± 0.2 ka (NC-R29) and 0.6 ± 0.1 ka (NC-R23) for C4A and C3A, respectively; however, these anomalously younger ages are stratigraphically inverted with overlying units (e.g., C2A), and may be for burrowed sediment.

Scarp colluvium in unit C2 postdates units C3 and 2c, as well as soils C3A and 2cA, and is the youngest faulted colluvial wedge along fault F1. Evidence for C2 includes slope-parallel clast fabric and silt, sand, and gravel that have partially buried soil 2cA. Unit C2 has a maximum thickness of 0.9–1.2 m and a limited horizontal extent of about 1.9–2.8 m. Although we considered that unit C2 could possibly be the basal part of the youngest colluvial wedge (C1), the eastern part of unit C2 is unambiguously faulted by fault F1. Unit C2 is bracketed by soils 2cA (below) and C2A (above), which merge into a single soil (2cA) beyond the extent of C2. This relation is similar to that for colluvial wedge Cg1 in the graben (south wall; near fault F6), which is bracketed by soils 2cA (below) and 2cA/CgA (above). The maximum time of unit C2 deposition is 1.2 ± 0.1 ka based on charcoal derived from soil C2A (NC-R16). Charcoal from soil C2A yielded an age of 6.0 ± 0.1 ka (NC-R15); however, charcoal in this sample is likely derived from the unit 1bA burn horizon (~5 ka) in the footwall. An additional minimum age for C2 deposition is from the soil on unit Cg1 (2cA/CgA; 0.9 ± 0.1 ka for NC-R2). Considering the similar soil and stratigraphic relations for colluvial wedges C2 and Cg1 (both deposited on the unit 2c A horizon) and similar ages (~1.2-ka for soil 2cA and ~0.9 ka for soil CgA), we consider it likely that unit Cg1 was deposited contemporaneously with C2. Thus, unit C2 deposition occurred between about 0.9 and 1.2 ka.

Unit C1 is the youngest, unfaulted colluvial wedge adjacent to fault F1. The colluvium has a maximum thickness of 1.3–1.5 m and extends horizontally for 5.4–5.5 m. Evidence for C1 includes silt, sand, and gravel that form slope-parallel fabric and have buried a shear zone and 1.4–2.3-m high eroded scarp free face. Deposition of unit C1 occurred after the formation of soil C2A at about 0.3 ± 0.2 ka (NC-R21) in the north wall and likely after soil 2cA/CgA (~0.9 ka) in the south wall. Although the stratigraphic relation between units C1 and Cg2 are not clear, these main-fault and north-wall graben colluvial wedges may be contemporaneous. Unit Cg2 must be older than 0.4 ± 0.1 ka (NC-R31) based on charcoal sampled from soil 2cA (where buried by Cg2) and younger than 0.2 ± 0.2 (NC-R32) based on charcoal derived from unit Cg2. Deposition of unit C1 predates a charcoal age of 0.4 ± 0.1 for an intra-wedge soil lens (NC-R20). A second intra-wedge soil lens in unit C1 yielded an anomalously old age of 6.2 ± 0.1 ka, which likely is for charcoal derived from footwall soil 1bA. Two additional minimum ages for unit C1 are from unit 2d, which is a thin silt horizon locally below (but possibly interfingered with) unit C1. Charcoal from unit 2d yielded an age of 0.2 ± 0.2 ka (NC-R22c) and an OSL age for the silt is 1.5 ± 0.3 ka (NC-L2). We discount the OSL age considering the numerous young (<1 ka) ages for soil charcoal sampled from units stratigraphically below unit 2d. Considering these ages, unit C1 deposition occurred at about 0.2–0.4 ka.

Colluvial wedges formed by movement on graben faults F2–F7 include units Cg1–3. These colluvial wedges have limited (less than ~1.5-m wide) exposures and have maximum thicknesses of 0.2–0.6 m (table 5). Colluvium in unit Cg1 is adjacent to antithetic fault F6 and buries soil 2cA in both the north and south walls. Similarly, unit Cg2 is formed adjacent to synthetic fault F3 and buries soil 2cA in both walls. Unit Cg2 postdates faulting on antithetic fault F2; sediment in Cg2 overlies soil 2cA in the north wall. Although we did not map unit Cg2 in the south wall, we note that soil 2cA is over-thickened adjacent to fault F2, and thus, colluvium postdating soil 2cA is likely present.

Cultural Fill

We exposed cultural (man-made) fill (unit 4; plate 2) related to a fault-parallel trench excavated by Hansen and others (1981) in 1978. Unit 4 consists of a poorly sorted mixture of silt, sand, gravel, and organics, and near the base of the deposit, locally includes flagging, nails, and string line. Where best preserved in the south wall, unit 4 extends to a maximum depth of about 2.9 m below the surface and is about 1.3 m wide. Based on the position of unit 4 on the fault hanging wall, its north-south orientation, and decrease in depth to the north, we likely exposed the northernmost part of trench NC-1A of Hansen and others (1981).

Wasatch Fault Zone

The WFZ at the North Creek site consists of 1) a main, down-to-the-west shear zone (F1), and 2) an about 13-m wide graben between faults F1 and F6. The graben includes both synthetic (F3 and F5) and antithetic (F2, F4, and F6) faults.

Fault F1 consists of one to three fault traces (figure 14; plate 2) that juxtapose the footwall alluvial-fan gravel (units 1a and 1b) and hanging wall colluvial wedges (C2–C5). The relatively simple fault zone includes sheared silt, sand, and gravel containing clasts rotated parallel to one of several fault planes. In the north wall, fault F1 dips about 67º –80º west, and in the south wall, about 77º –85º west.

Faults F1 to F6 form an about 13-m wide graben in hanging wall alluvial fan units 2a–2c. The bulk of graben deformation is in the 5.3–6.1 m between faults F2 and F6, where both down-to-the-east and -west faults define narrow (<2-m wide) fault-bounded blocks. An additional antithetic fault (F7) is 2.6–3.1 m west of graben-bounding fault F6 (h-5.5 m, v-3 m, south wall, plate 2), but has only minor (~0.1–0.2-m) displacement. Faults F2–F6 displace soil 2cA, but not 2cA/CgA or overlying units 2d–e or 3. In the north wall, faults F2–F7 dip 80º–83º west and 74º–83º east, compared to 71º–84º west and 69º–87º east in the south wall.

The differential displacement of soils 2bA and 2cA across the graben provide evidence of two surface-faulting earthquakes. Soil 2bA is vertically displaced 1.5–2.0 m across faults F2–F6 (using horizontal projections of the soil). In contrast, soil 2cA is vertically displaced 0.7–0.9 m. This implies an initial event that displaced soil 2bA down to the east 0.7–1.1 m. Fault F2 provides good evidence of these two events, as soil 2bA is displaced 0.6–0.8 m, or ~0.3 m more than 2cA, which is displaced 0.3–0.5 m. We infer that the earlier graben earthquake predates soil 2b2A, which is restricted to the graben formed between faults F1 and F2. Soil 2b2A, which is likely contemporaneous with soil 2bA west of fault F2, has a vertical displacement of ~0.3–0.5 m, consistent with the displacement for soil 2cA rather than soil 2bA. Thus, the earlier graben faulting event likely predates both soil 2b2A and colluvial wedge C4. Extensive fan deposition in the graben (unit 2c) and subsequent soil development (soil 2cA) clearly postdates the earlier graben event. The second graben faulting event displaced soil 2cA a total of 0.7–0.9 m down to the east across faults F2–F6. Considering the continuity of soil 2cA beneath units C2, Cg1, and

Cg2, the younger graben event likely corresponds with the surface-faulting earthquake that occurred prior to C2 deposition.

The total displacement across the main fault (F1) is difficult to assess as we did not expose alluvial-fan deposits on the hanging wall that are correlative with those in the footwall (unit 1c). However, it is clear that hanging-wall alluvial-fan unit 2c postdates (or is contemporaneous with) deposition of colluvial wedges C4 to C1, which postdate the footwall stratigraphy. Using inferred thicknesses of units 2b and C5, it is likely that these units are contemporaneous with or postdate the footwall units as well. Thus, the minimum displacement of the footwall alluvial fan is equal to the vertical distance between its projection toward fault F1 and the base of the hanging wall trench exposure. However, using the ages of charcoal sampled from the upper part of the footwall fan (~5–6 ka for unit 1bA) and the basal hanging wall sequence (~6 ka for unit 2a), it is plausible that unit 2a, which likely predates unit C5 (using the thickness arguments) is roughly contemporaneous with the top of the footwall fan sequence. Using the north wall exposure, the vertical displacement of the footwall fan surface (top of unit 1c) and unit 2a between faults F6 and F7 (subtracting 0.1 m to account for fault F7) is 10.4 m.

We also estimate the total displacement post ~5–6 ka using the sum of the individual colluvial wedge maximum thicknesses. The sum for C1 to C4 is 4.8 m, or an average of 1.2 m. Assuming that the thickness of C5 is similar to the C1–C4 average, the total thickness is 6.0 m. However, we have lower confidence in the total wedge thickness because of the extensive graben faulting, which occurred in some, but not all earthquakes. The formation of a sediment trap through graben formation could result in an exaggerated colluvial-wedge thickness compared to events without graben faulting. Despite the uncertainty in the relation between colluvial-wedge thickness and displacement at North Creek, we still consider the values to be a good proxy for minimum fault displacement.

Estimating vertical displacement per event at the North Creek site is problematic because of considerable uncertainties in relating colluvial wedge thicknesses to displacement (mostly related to the extensive graben formation in some events). Thus, we do not scale the individual wedge thicknesses to reach the maximum displacement for the site as we did for the Spring Lake site. Although the wedge thicknesses may represent minimum per-event displacements ranging from 0.9–1.4 m (average of 1.2 m), we have low confidence in these values. Alternatively, the average per-event displacement at the site is 2.1 m, based on the total displacement at the site (10.4 m) divided by the number of events (5). However, the upper-bound displacements remain undefined. To estimate the upper-bound values, we added the difference between the mean displacement (2.1 m) and the mean colluvial-wedge thickness (1.2 m) to the mean displacement (2.1 m), resulting in an estimated maximum per-event displacement of 3.0 m. These displacement values require several assumptions regarding wedge formation and total displacement, and thus we consider per-event displacement at North Creek to be poorly constrained.

Paleoseismology of the North Creek Site

Chronology of Surface-Faulting Earthquakes

We used stratigraphic and numerical data from the North Creek site, including our observation of five separate colluvial wedges (C1 to C5), to construct several OxCal models for the North Creek site. These models constrain the timing of five surface faulting earthquakes in the mid to late Holocene (figure 15, table 6).

Table 6. Earthquake timing and recurrence at the North Creek site.

	Earthquake timing		Earthquake recurrence	
Event	**Mean ± 2σ**[1] *[mode]* (ka)	**Central 95%**[2] (ka)	**Inter-event** *[mode]* (kyr)	**Mean** *[mode]* (kyr)
NC5?	4.7 ± 0.7	4.1–5.3	NC5–NC4: 0.6	NC5–NC1: 1.1
NC4	4.0 ± 0.1	3.9–4.1	NC4–NC3: 1.4 *[1.8]*	NC4–NC1: 1.3
NC3	2.6 ± 0.9 *[2.2]*	2.0–2.5	NC3–NC2: 1.4 *[1.0]*	NC3–NC1: 1.2 *[1.0]*
NC2	1.2 ± 0.1	1.0–1.3	NC2–NC1: 0.9	-
NC1	0.2 ± 0.1	0.2–0.3	-	-

[1] Mean ± two sigma based on the OxCal model (model v3f) results.
[2] Earthquake time range including 95.4% of the total area of the time distribution with the highest probability density (Bronk Ramsey, 2013).

We constructed several OxCal models for the North Creek site, but ultimately preferred a model (v3d; appendix H) that (1) excluded near-modern ages likely derived from burrowed sediment, (2) excluded the ~5–6-ka ages for possibly recycled charcoal in the main-fault colluvial-wedges, and (3) included several ages from the 1978 Hanson and others (1981) investigation. We excluded several ages from the OxCal model that are clustered around 0.2–0.6 ka (NC-R29, -R23, and -R20). The anomalously young ages for these charcoal samples may reflect burrowing in the sampled sediment. Several charcoal ages are also clustered around 5.4–6.2 ka (NC-R13, -R15, and -R28). The anomalously old ages for these samples likely reflect charcoal derived from footwall soil (burn horizon) 1bA (~5 ka), which had abundant charcoal. Our North Creek investigation reoccupied the site of the original trench investigation by Hanson and others (1981). Because of similar stratigraphy exposed in these investigations, we chose to use several ^{14}C ages from Hanson and others (1981). We identified samples for which 1) there is minimal uncertainty in their stratigraphic context, especially when compared to our trench interpretation, and 2) the ages were deemed reliable and used in an OxCal model constructed for the original North Creek data by Crone and others (in press). The original North Creek ages include a 5.2-ka age for the footwall burn horizon (sampled and dated by Bucknam, 1978) and samples WC-12-80-6, -8, and -9 (~1.0–1.3 ka), which provide minimum constraints for the timing of earthquake NC2. These ages are in good agreement with ages from our investigation (at similar stratigraphic positions), and help constrain the North Creek earthquake times.

The oldest earthquake at the North Creek site, NC5, occurred about 4.7 ± 0.7 ka, based on our preferred OxCal model. This earthquake is based on the assumption that interbedded gravel and organic sediment below unit C4 are related to the oldest colluvial wedge at the site, which likely postdates the youngest footwall alluvial-fan units (e.g., burn horizon 1bA). However, because of the limited exposure of unit C5, we have less confidence in this event.

Earthquake NC5 postdates the 5.3–5.4-ka ages for the footwall burn horizon (unit 1bA) and predates ~2.0 ka (NC-R11) to ~4.0 ka (NC-R12) ages for charcoal derived from soil C5A. We disregard the ~2.0-ka age, which is anomalously young and stratigraphically inverted with ^{14}C ages for overlying units (e.g., NC-R19 for soil 2b2A).

Earthquake NC4 occurred at 4.0 ± 0.1 ka. The timing of this earthquake is well constrained as it postdates the 4.0-ka age (NC-R12) for soil C5A and predates the 4.1-ka age (NC-R19) for soil 2b2A, which likely formed contemporaneously with the deposition of unit C4. Although we considered the possibility that the 4.1-ka charcoal in soil 2b2A is derived from unit C5A, the charcoal consisted of floral remains, which were more likely burned in place than transported. Furthermore, the NC-12 and -19 mean ages are only 30 yr apart, which is less than their average 1-sigma uncertainty (~60 yr). We excluded likely burrowed charcoal from soil C4A, which yielded an age of ~0.2 ka (NC-R29), as well as the anomalously old age for an intra-wedge soil lens within unit C4 of ~5.4 ka (NC-R13), which likely is for charcoal derived from footwall soil 1bA.

Earthquake NC3 occurred at 2.6 ± 0.9 ka. Earthquake NC3 is poorly constrained to a maximum by the 4.1-ka age for soil 2b2A, which formed during, rather than following, colluvial-wedge unit C4 deposition. Charcoal derived from a soil developed within the uppermost part of unit C3 provides a minimum age of 2.1 ± 0.1 (NC-R18). An additional minimum age is 1.2 ± 0.1 ka (NC-R16) for soil 2cA, which postdates deposition of units C3 and 2c. Because we consider the ~2.1-ka minimum age to be a closer constraining age, we used a Zero_Boundary grouping in OxCal to implement this interpretation (see DuRoss and others [2011] for discussion). This results in an earthquake NC3 time distribution that has a mode of 2.2 ka, closer to the younger end of its 95% range (2.0–2.5 ka); we prefer the modal time (peak of the probability density function) because the Zero_Boundary command produces a highly skewed distribution. In constructing the OxCal model, we also evaluated ^{14}C ages for charcoal and bulk-soil samples that were part of the original North Creek trench investigation. Hanson and others (1981) reported a ~2.0-ka age (WC-12-80-3) for a soil sampled 2.0–2.5 m below the ground surface in their trench NC-1A, which we likely exposed (unit 4). Based on the depth of the sample location and its age, we suspect that Hanson and others (1981) sampled our soil 2bA, which is 1.8–2.4 m below the surface where we exposed Hanson and others (1981) trench. However, because of uncertainty in whether the soil sampled in WC-12-80-3 predates or postdates colluvial wedge C3, we excluded the age in our OxCal model.

Earthquake NC2 occurred at 1.2 ± 0.1 ka, following deposition of extensive alluvial-fan unit 2c. The ages for unit C3 and soil 2cA provide maximum constraints of 2.1 ka and 1.2 ka, respectively. An age of 0.9 ka (NC-R02) for soil 2cA/CgA, which postdates antithetic faulting along graben fault F6a, possibly provides a minimum constraint on the timing of earthquake NC2. This inference is based on the interpretation that between faults F1 and F2, soil 2cA splits to soil 2cA below unit C2 and soil C2A above it. This relation is similar to soils 2cA below colluvial wedges in the graben and 2cA/CgA above. Although we suspect soil 2cA in the graben continued forming after earthquake NC2 (as suggested by the <0.5-ka minimum and maximum limiting ages for colluvial wedge Cg2), the minimum age for colluvial wedge Cg1 suggests that it postdates earthquake NC2. To help limit the minimum time of earthquake NC2, we also included three ^{14}C ages from the original North Creek investigation. These ages are from trench

NC-3, which identified unambiguous evidence of two earthquakes. Hanson and others (1981) reported ages of ~1.0–1.3 ka (WC-12-80-6, -8, and -9) for soil sediment clearly postdating the penultimate colluvial wedge. Crone and others (in press) used these ages in their North Creek OxCal model, and thus we use them to limit the minimum time of earthquake NC2.

The youngest surface-faulting earthquake, NC1, occurred at 0.2 ± 0.1 ka. To limit the maximum time of earthquake NC1, we included a 0.3 ± 0.1 ka (NC-R21) age for soil C2A, and an age of 0.4 ± 0.1 ka (NC-R31) for soil 2cA, where buried by colluvial wedge Cg2. Charcoal samples of unit 2d (which postdates deposition of colluvial wedge C1) and colluvial wedge unit Cg2 provide minimum-constraining ages of 0.2 ± 0.2 ka (NC-R22c) and 0.4 ± 0.1 ka (NC-R31), respectively. A sample of the C1 colluvial wedge yielded a minimum age of 0.4 ± 0.1 ka (NC-R20); however, this age is stratigraphically inverted with the 0.2–0.3-ka ages for NC-R21 and NC-R31 (yields poor agreement in the OxCal model), and thus we excluded it.

Earthquake Recurrence and Fault Slip Rate

We calculated inter-event and mean recurrence intervals between individual North Creek earthquakes NC5 and NC1 using the mean earthquake times (table 6; appendix J).

Inter-event recurrence intervals between earthquakes NC5 and NC1 range from ~0.6 kyr for NC5–NC4 to ~1.4 kyr for NC4–NC3 and NC3–NC2 (table 6). However, using the modal time for earthquake NC3, yields inter-event recurrence times of 1.8 kyr for NC4–NC3 and 1.0 kyr for NC3–NC2. These mean inter-event recurrence times yield a coefficient of variation (COV) on recurrence of 0.35 (0.39 kyr standard deviation divided by 1.11 kyr mean recurrence). We also calculated a COV excluding the interval for NC5–NC4 on account of the uncertainty in the earthquake NC5 interpretation. The COV for NC4–NC1 is 0.22 (0.28 kyr divided by 1.27 kyr).

Mean recurrence intervals measured between earthquakes NC5 to NC3 and NC1 (e.g., NC5–NC1 or NC4–NC1) are consistently between 1.1 and 1.3 kyr (table 6). Using the modal time for earthquake NC3 results in a shorter mean recurrence for NC3–NC1 of 1.0 kyr. Similar to the Spring Lake site, the mean recurrence values indicate a more constant rate of earthquakes when averaged over thousands of years. We have the most confidence in the 1.3-kyr value, which includes three intervals between the four best-constrained earthquakes (NC4–NC1).

Because of uncertainty in the displacement per event at North Creek, we only calculate vertical slip rates using the sum of several surface faulting earthquakes (e.g., NC4–NC1) (table 7; appendix J). Based on our discussion of total displacement (Wasatch Fault section), the total displacement of possibly correlative units 2a and 1c is 10.4 m. This displacement postdates soil 1bA dated to about 5.3 ± 0.1 ka (NC-R9) or 5.2 ± 0.6 ka (sample USGSW-4057 of Bucknam, 1978). These ages yield a geologic (open-ended) slip rate of 2.0 mm/yr and an approximate 95% range of 1.1–2.9 mm/yr. We also calculated an interval slip rate by dividing the estimated displacement in earthquakes NC4–NC1 by the elapsed time between earthquakes NC5 and NC1. To estimate the NC4–NC1 displacement, we took the mean and lower- and upper-bound total displacement values (10.4 m, 6.0–14.8 m) and subtracted the mean per-event displacement of 2.1 m to account for the NC5 displacement. The resulting displacement for NC4–NC1 is 8.3 m (3.9–

12.7 m range). Using the ~4.4 kyr (3.8–5.1 kyr 95% range) closed seismic interval between NC5 and NC1, the slip rate is 1.9 mm/yr (0.8–3.3 mm/yr approximate 95% range).

Table 7. Vertical slip rates at the North Creek site.

Slip Rate Type[1]	Total Displacement[2] (m)	Elapsed Time[3] (kyr)	Slip Rate (mm/yr)
Geologic rate	10.4 (6.0–14.8) (units 1c/2a)	5.3 (5.0–5.4) (soil 1bA)	2.0 (1.1–2.9)
Interval rate	8.3 (3.9–12.7) (NC4–NC1)	4.4 (3.8–5.1) (NC5–NC1)	1.9 (0.8–3.3)

[1] Geologic rate – open-ended geologic slip rate (e.g., total displacement divided by unit or surface age). Interval rate – closed-interval slip rate (e.g., displacement in one or more earthquakes divided by their preceding time intervals).

[2] Total vertical displacement. For the geologic rate, the total displacement of units 1c and 2a is shown. For the interval rate, the total displacement is the displacement of units 1c and 2a minus 2.1 m to account for earthquake NC5 (see text for discussion).

[3] For the geologic rate, the elapsed time is the age of soil 1bA: the mean and lower-bound ages for soil 1bA are based on the 5.3-ka age for NC-R9; the upper-bound age is based on the 5.4-ka mean age of Bucknam (1978). For the interval rate, the elapsed time is the mean and central 95% time between earthquakes NC5 and NC1, modeled using OxCal (appendices H and J).

Comparison with Previous North Creek Data

We compare our North Creek earthquake chronology with the results of the original North Creek investigation, using the interpretation of Crone and others (in press). The Crone and others (in press) earthquake times are comparable to our results because they reflect similar assumptions regarding calendar calibration of ^{14}C ages (using Reimer and others, 2009) and stratigraphic model development and earthquake-time modeling in OxCal. Our North Creek investigation yielded four earthquakes at ~0.2 ka (NC1), ~1.2 ka (NC2), ~2.2–2.6 ka (NC3), and ~4.0 ka (NC4); a possible older earthquake occurred at ~4.7 ka (NC5). Based on the Hanson and others (1981) stratigraphic and numerical data, Crone and others (in press) report stratigraphic evidence for two earthquakes at ~0.4 ka and ~1.4 ka, and geomorphic evidence (a faulted terrace) for an additional event at ~1.9 ka (table 8).

Earthquakes NC1 (0.2 ± 0.1 ka) and NC2 (1.2 ± 0.1 ka) likely correspond with the most recent and penultimate earthquakes in the original investigation (table 8). The penultimate earthquake occurred at ~1.4 ± 0.3 ka, predating five charcoal and soil ages clustered between 1.0 and 1.5 ka (Crone and others, in press); the most recent earthquake occurred at 0.4 ± 0.5 ka, postdating these ages. The broad uncertainty for the most-recent earthquake time stems from the lack of a minimum limiting time constraint (Crone and others, in press). We note very similar colluvial packages for these earthquakes in both investigations. Units C2 (this study) and 5a (Hanson and others, 1981) are both somewhat limited colluvial wedges juxtaposed against sheared sediment. Hanson and others (1981) interpreted unit 5a as the basal part of the most-recent-earthquake colluvium at the site (unit 5b), showing the steep eastern boundary of unit 5a as a steeply dipping buried free face. In contrast, we break these units (units 5a and 5b of Hanson and others, 1981; units C2 and C1; this study) into separate colluvial wedges on the basis of unambiguous shearing (rotated clasts) in unit C2. Units C1 (this study) and 5b (Hanson and others, 1981) indicate the youngest, unfaulted colluvial wedges at both sites.

Table 8. Summary of earthquake timing data for the northern and southern strands of the Nephi segment.

Northern Strand[1]			Southern Strand[1]		
Spring Lake (ka)	Picayune Canyon (ka)	Santaquin (ka)	North Creek (ka)	Willow Creek (ka)	Red Canyon (ka)
13.1 ± 4.0 (SL7)	-	-	-	-	-
6.6 ± 0.7 (SL6)	-	-	-	-	-
5.7 ± 0.8 (SL5)	-	-	*not exposed*	*not exposed*	*not exposed*
4.8 ± 0.8 (SL4)	*not exposed*	-	4.7 ± 0.7 (NC5?)	4.7 ± 1.8 (WC4)	4.7 ± 2.7 (RC3)
4.0 ± 0.5 (SL3)	~3.5 (PC2)	*not exposed*	4.0 ± 0.1 (NC4)	*no evidence*	*no evidence*
2.9 ± 0.7 (SL2)	~2.5 (PC1)	*not exposed?*	2.2 (2.0–2.5) (NC3)	1.9 ± 0.6 (WC3)	*no evidence*
0.9 ± 0.2 (SL1)	*no evidence*	*no evidence*	1.2 ± 0.1 (NC2)	1.2 ± 0.1 (WC2)	1.2 ± 0.3 (RC2)
no evidence	*no evidence*	~0.3–0.5 (S1)	0.2 ± 0.1 (NC1)	0.2 ± 0.1 (WC1)	0.5 ± 0.5 (RC1)

[1] Color shading indicates earthquakes that likely correspond along the northern strand (lighter shading), along the southern strand (darker shading), and possibly along the entire Nephi segment (color shading). For earthquake NC3, the mode and 95% confidence range (in parentheses) are shown. For S1, the range reflects the mean values from the interpretations of DuRoss and others (2008) and DuRoss and others (in preparation).

Both North Creek investigations found stratigraphic evidence for an earthquake at about 2 ka (table 8). Earthquake NC3 occurred at 2.6 ± 0.9 ka; however, as discussed above the time distribution is asymmetrically skewed and yields a modal value of 2.2 ka. Comparably, the original North Creek data indicate an earthquake at 1.9 ± 0.5 ka (Crone and others, in press) based partly on a poorly understood soil sample (WC-12-80-3) from trench NC-1A (Hanson and others, 1981). Despite the uncertainty in this earthquake time, it does correspond well with the 2.2-ka modal time for earthquake NC3. In addition, the colluvial wedge for earthquake NC3 (unit C3) likely corresponds with unit 3 of the original investigation. Although Hanson and others (1981) interpreted unit 3 as a queried mudflow, we note that it has a wedge shape (very similar in shape and extent to their unit 5a) and buries a back-rotated soil (their soil 2s).

Our North Creek investigation includes two older earthquakes at 4.0 ± 0.1 ka (NC4) and 4.7 ± 0.7 ka (NC5), whereas Crone and others (in press) do not include earthquakes older than ~2 ka. Earthquake NC4 is based on a colluvial wedge (unit C4) that Hanson and others (1981) likely exposed, but did not date. Our colluvial wedge C4 likely corresponds with their unit 2a, described as scarp-derived colluvium or alluvium. Although Hanson and others (1981) did report an age for a soil developed on unit 2a (their soil 2s), the age is anomalously young at ~0.3 ka. Earthquake NC5 is likely the oldest earthquake that postdates the footwall fan gravel and soil. Colluvial wedge unit C5, which provides the basis for this earthquake, was likely not exposed in the Hanson and others (1981) trenches.

DISCUSSION

Paleoseismology of the Northern Strand

At least five to seven surface-faulting earthquakes have ruptured the Spring Lake site since ~13 ka (table 3). The five-event model assumes that colluvial wedges C3 and C4 were deposited following earthquake SL4, and C5 and C6 following earthquake SL6; the seven-event model accounts for separate earthquakes for each colluvial wedge exposed at the site. Although we cannot rule out the possibility of multiple distinct colluvial wedges (e.g., C6 and C5) deposited following a single surface-faulting earthquake, we consider the scenario of separate earthquakes for SL3, SL4, SL5, and SL6 to be most likely considering the stratigraphic information and numerical data. Although earthquake SL7 remains poorly constrained, we include this earthquake on account of the upward fault terminations exposed in the footwall of fault F1. These earthquakes show that the northern strand has been active over the Holocene, generating earthquakes about every 1.2 kyr (using earthquakes SL6 to SL1).

Our Spring Lake data compare well with previous data for the northern strand. The youngest earthquake, SL1 at ~0.9 ka, is likely a separate, older earthquake than earthquake S1 identified at the Santaquin site at ~0.3–0.5 ka (using the mean times from the interpretations of DuRoss and others [2008] and DuRoss and others [in preparation]). In either interpretation of S1, the upper bound of the 95% confidence range is ~0.5 ka, younger than the lower bound of 0.7 ka for earthquake SL1. In contrast, the two earthquakes identified at the Picayune Canyon site likely correspond with earthquakes interpreted at the Spring Lake site. Earthquakes PC1 and PC2 at Picayune Canyon occurred at ~2.5 ka and ~3.5 ka, respectively, based on maximum limiting soil-charcoal ages (Horns and others, 2009). These earthquake times are similar (but ~0.5-kyr younger) than earthquakes SL2 (~2.9 ka) and SL3 (~4.0 ka) at Spring Lake. The minor differences in these earthquake times may be related to the complexities of soil formation and sampling at the two sites. Importantly, correlating earthquakes SL3 and PC2 argues for two separate earthquakes for SL4 (unit C4) and SL3 (unit C3) since no older colluvial wedges predating earthquake PC2 (which could correspond with earthquake SL4) were present at the Picayune Canyon site.

These data suggest that at least seven (excluding Spring Lake earthquake SL5) to eight (including SL5) earthquakes have ruptured the northern strand since ~13 ka. Excluding poorly constrained earthquake SL7, both scenarios yield relatively short mean recurrence intervals for the northern strand. The mean recurrence is ~1.0 kyr using six intervals in the ~6.2 kyr elapsed time between earthquakes SL6 and S1, or ~1.2 kyr using five intervals in the same time period. Including only mid-Holocene or younger events (SL4–SL1 and S1), the mean recurrence is ~1.1 kyr (four intervals in the ~4.4-kyr elapsed time between SL4 and S1). These data correspond well with our Spring Lake mean recurrence estimate of 1.2 kyr (SL6–SL1) and the ~1-kyr elapsed time between PC2 and PC1, and indicate that the Santaquin site—which only identified a single late Holocene earthquake—is the exception rather than the rule.

Paleoseismology of the Southern Strand

At least four (NC1–NC4), and possibly five (including NC5) surface-faulting earthquakes have occurred on the southern strand since about 4.7 ka (table 6). Although earthquake NC5 remains questionable because of its very limited exposure, we include the earthquake considering the textural, stratigraphic, and timing data in support of it. These earthquakes show that the northern strand has been active since the mid-Holocene, generating large-displacement (~2-m) earthquakes about every 1.3 kyr (using earthquakes NC4 to NC1).

Our North Creek earthquake chronology compares remarkably well with the interpretation of southern strand data by Crone and others (in press) (table 8), which is largely based on the Willow Creek investigation. Crone and others (in press) included data from the original North Creek and Red Canyon investigations, but these data contribute little to the overall chronology because of their broadly defined earthquake times (table 1). In our discussion of these southern-strand earthquake data, we only include our results for the North Creek site; a discussion of how our results compare to those for the previous investigation (Hanson and others, 1981) is included above.

Four of five earthquakes identified in our North Creek investigation likely correspond with earthquakes previously identified on the southern strand (table 8). North Creek earthquake NC5 (~4.7 ka) likely corresponds with Willow Creek earthquake WC4 and (or) Red Canyon earthquake RC3, which both have mean times of 4.7 ka. However, uncertainty in this correlation stems from the broadly defined time distributions for WC4 and RC3 (1.8–2.7-kyr two-sigma uncertainties), and thus, WC4 and RC3 could possibly be earthquakes older than ~5 ka that predate the North Creek stratigraphic record. Earthquake NC4, which occurred at about ~4.0 ka, is the only earthquake that does not have corresponding evidence from the Willow Creek or Red Canyon sites. Earthquake NC3 occurred at about 2.6 ka, but the time distribution is asymmetrically skewed, and has a more meaningful modal time of 2.2 ka and 95% range of 2.0–2.5 ka. Thus, the time of earthquake NC3 is similar to the mean time of WC3 at ~1.9 ka. The Red Canyon site did not have evidence of an earthquake older than ~1.2 ka (and younger than ~4.7 ka). Finally, earthquakes NC2 (~1.2 ka) and NC1 (~0.2 ka) likely correspond with earthquakes at the Willow Creek and Red Canyon sites. Earthquakes NC2, WC2, and RC2 all have nearly identical mean times (~1.2 ka) and small (<0.3 kyr) two-sigma uncertainties. Earthquakes NC1, WC1, and RC1 also have similar mean times (~0.2–0.5 ka); however, the times for NC1 and WC1 are most similar, and are well constrained by maximum and minimum limiting ages. Earthquake RC1 is similar in time to NC1, but has a broad uncertainty (± 0.5 ka) that stems from the lack of a minimum time constraint.

These data suggest that at least five earthquakes have ruptured the southern strand since ~4.7 ka. This includes newly identified earthquake NC4, and the likely correlation of earthquakes NC5, WC4, and RC3. However, it is possible that WC4 and (or) RC3 could correspond with either NC4 or an older earthquake not identified at North Creek (prior to ~5–6 ka). These scenarios do not affect the mean recurrence for the southern strand, which is ~1.1 kyr using the four intervals between earthquakes NC5 (~4.7 ka) and NC1 (~0.2 ka), or ~1.3 kyr using three intervals between NC4 (~4.0 ka) and NC1 (~0.2 ka).

Paleoseismology of the Nephi Segment

Paleoseismic data for the North Creek and Spring Lake sites, as well as our analysis of how these data compare with previous data for the northern and southern strands, show that the Nephi segment has been very active during the Holocene. Since the mid-Holocene (~5 ka), where the earthquake record for the segment is best constrained, both strands have had at least five surface-faulting earthquakes (table 8). These earthquakes, as well as earthquakes at ~6 and 7 ka on the northern strand, yield similar mean recurrence intervals of ~1.0–1.2 kyr for the northern strand and ~1.1–1.3 kyr for the southern strand.

Rupture Behavior of the Northern and Southern Strands

One of the major goals of our study was to address the question of whether the northern and southern strands rupture together or independently. Although we cannot rule out separate surface-faulting earthquakes on the strands because of the moderate (~0.1–0.3-kyr) to large (>0.3-kyr) timing uncertainties, the strands have similar late Holocene earthquake histories. In particular, earthquakes at ~4.7–4.8 ka and ~4.0 ka ruptured both the northern and southern strands, based on our Spring Lake and North Creek data. The oldest earthquakes identified on the southern part of the southern strand (Willow Creek and Red Canyon sites) have similar mean times (~4.7-ka); however, these events have large (~2–3-kyr) timing uncertainties and could possibly be older earthquakes predating the North Creek stratigraphic record. An earthquake at ~3.5 ka at the Picayune Canyon site (between Spring Lake and North Creek) likely provides additional evidence of the ~4-ka event.

The strands both have evidence of three younger earthquakes; however, there is less overlap in their time ranges. The northern strand ruptured at about 2.3–3.5 ka (earthquakes SL2 and PC1) compared to an earthquake on the southern strand at ~2.0–2.5 ka (earthquakes NC3 and WC3). Earthquakes occurred at ~0.9 ka (SL1) and ~0.3–0.5 ka (S1) on the northern strand, whereas ruptures at ~1.2 ka and ~0.2 ka are well documented along the southern strand.

These data show that complex patterns of rupture have occurred on the Nephi segment during the late Holocene. Using possible correlations of individual earthquakes along the segment, we developed three rupture scenarios: (1) simultaneous rupture of both strands (the entire Nephi segment), (2) rupture of one strand plus partial rupture of the other strand, and (3) independent rupture of the strands.

Complete rupture of the Nephi segment is possible for earthquakes at ~4.7–4.8 ka and ~2.2–2.5 ka. The ~4.7–4.8-ka earthquake, which has been identified at Spring Lake and North Creek, likely predates the stratigraphic records at Picayune Canyon and Santaquin. The oldest ruptures at Willow Creek and Red Canyon may be evidence of the ~4.7–4.8-ka event; however, uncertainty remains on account of their large timing uncertainties. Earthquakes on the northern strand at ~2.2–3.5 ka and southern strand at ~1.3–2.5 ka may also be evidence of a full-segment rupture, but there is minimal overlap (at ~2.2–2.5 ka) in the time ranges for these events.

Two earthquakes on the Nephi segment may have ruptured one strand and only part of the other strand. The ~4-ka rupture, identified at Spring Lake, Picayune Canyon, and North Creek, is likely evidence of the full rupture of the northern strand and partial rupture of the southern strand. Evidence of the 4-ka earthquake was not identified south of North Creek, although the event likely predates the hanging-wall stratigraphic record exposed at Willow Creek. Full rupture of the southern strand and partial rupture of the northern strand may also have occurred at ~0.2–0.5 ka based on Santaquin earthquake S1 (~0.3–0.5 ka), which may be the northernmost extent of the southern strand most recent earthquake (MRE) at ~0.2 ka. DuRoss and others (2008) and Crone and others (in press) considered this possibility as well as a scenario where S1 is a separate rupture from the southern strand MRE and is possibly simultaneous with the ~0.6-ka MRE on the Provo segment. However, considering the similar earthquake times for

S1 and the southern strand MRE (NC1, WC1, and RC1), lack of evidence for an earthquake younger than 0.5-ka north of Santaquin (at the Spring Lake and Picayune sites), and the large (~3.0 m) displacement for S1 that suggests a rupture length in excess of the northern strand length (DuRoss and others, 2008), we have more confidence in correlating Santaquin earthquake S1 with the southern strand MRE identified in this study.

The penultimate earthquakes on the northern strand at ~0.9 ka and southern strand at ~1.2 ka can be interpreted as evidence of either independent or simultaneous rupture of the strands. Arguments for independent rupture include 1) the minimal overlap in the two-sigma time ranges (at ~1.1 ka), and 2) the absence of an earthquake in this time period (~0.9–1.2 ka) south of the Spring Lake site (at the Picayune and Santaquin sites). Furthermore, the SL1 time is very similar to an earthquake at ~0.9 ka interpreted from preliminary data derived from the Water Canyon trench site on the southernmost Provo segment (Ostenaa, 1990), raising the question of spill-over rupture from the southern Provo segment to the northern strand. However, we cannot rule out rupture of the northern and southern strands together at ~1.1 ka because of the overlapping earthquake time ranges.

Conclusions

Based on these data and interpretations, full segment rupture or rupture of one strand and partial rupture of the other strand appears to be the most common past rupture behavior of the Nephi segment. Independent rupture of the northern and southern strands or rupture of the Provo segment and northern strand together appear unlikely; however, these scenarios cannot be ruled out because of uncertainties in earthquake timing. Additional paleoseismic data for the Nephi segment and the analysis of per-event vertical displacements may help confirm and refine these rupture scenarios. In particular, data for the southernmost part of the southern strand are necessary to update legacy data (the Red Canyon site), and data for the southernmost part of the northern strand would serve to expand the paleoseismic record to the mid Holocene.

The similar northern and southern strand earthquake histories and our interpretation of the rupture extent of Nephi segment earthquakes suggests that the ~4-km step between the strands is not a significant barrier to rupture propagation. If the step over acted as a barrier, such as those between most WFZ segments (Machette and others, 1992), we would expect to see unique late Holocene surface-faulting chronologies on the fault strands (see for example, those for the Weber and Brigham City segments; DuRoss and others [2011], Personius and others [2012]). The similar earthquake histories for the strands, but somewhat variable rupture length may be related to the completeness of the paleoseismic records for the strands, or possibly to rupture nucleation and direction. For example, the scenario of full rupture of one strand and partial rupture of the other strand could be an indication of earthquake nucleation on one strand and the subsequent loss of rupture energy at the fault step over between the strands, resulting in the partial rupture of the other strand. In contrast, a bilateral rupture nucleating near the step over may have sufficient energy to rupture both strands in their entirety. Rupture of the northern and southern strands across the 4-km fault step is consistent with Wesnousky (2008), who concluded that most historical, laterally propagating surface ruptures (for multiple slip types) propagated across fault-trace discontinuities (e.g., gaps or step overs) of no more than about 3–4 km in dimension.

SUMMARY AND CONCLUSIONS

Paleoseismic investigations at Spring Lake and North Creek have helped refine the Holocene surface-faulting earthquake history of the Nephi segment. At least five to seven earthquakes ruptured the Spring Lake site at ~0.9 ka, ~2.9 ka, ~4.0 ka, ~4.8 ka, ~5.7 ka, ~6.6 ka, and ~13.1 ka, yielding mean recurrence intervals of ~1.2–1.5 kyr and vertical slip rates of ~0.5–0.8 mm/yr (excluding the poorly constrained ~13-ka earthquake). These data compare well with the results of previous investigations and show that the northern strand has been consistently active during the late Holocene and has a mean recurrence of ~1.0–1.2 kyr. At least five earthquakes ruptured the North Creek site at ~0.2 ka, ~1.2 ka, ~2.2–2.6 ka, ~4.0 ka, and ~4.7 ka, yielding mean recurrence intervals of 1.1–1.3 kyr and vertical slip rates of ~1.9–2.0 mm/yr. These data compare well with previous paleoseismic data and indicate a mean recurrence of ~1.1–1.3 kyr for the southern strand, which is very similar to that for the northern strand.

We compared late Holocene earthquake chronologies for the northern and southern strands to address the question of whether they rupture together or independently. Although uncertainty in the rupture behavior of the strands remains on account of their moderate to large individual earthquake timing uncertainties, the strands have similar late earthquake histories. These data provide evidence of complex rupture behavior, including rupture of both strands and the rupture of one strand and part of the other strand. We have less confidence in a model of independent strand rupture; however, this model, as well as the potential for simultaneous rupture of the northern strand and Provo segment, cannot be fully ruled out given the data. Our new paleoseismic data help refine the surface-faulting earthquake history of the Nephi segment and contribute to an improved understanding the complexities of surface rupture and moment release on the WFZ, such as the influence of structural and geometric barriers on rupture propagation. Ultimately, these data will contribute to more accurate probabilistic earthquake forecasts for the Wasatch Front region.

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Figure 1. Segments of the Wasatch fault zone (WFZ) in southern Idaho and northern Utah. The central WFZ, which has evidence of repeated Holocene surface-faulting earthquakes, is shown in red; less-active end segments of the WFZ are shown in black. Other Quaternary faults in northern Utah are shown in dark gray. Fault traces are from Black and others (2003); base map is true-color satellite image from the National Aeronautics & Space Administration (NASA, 2012; taken May 31, 2001).

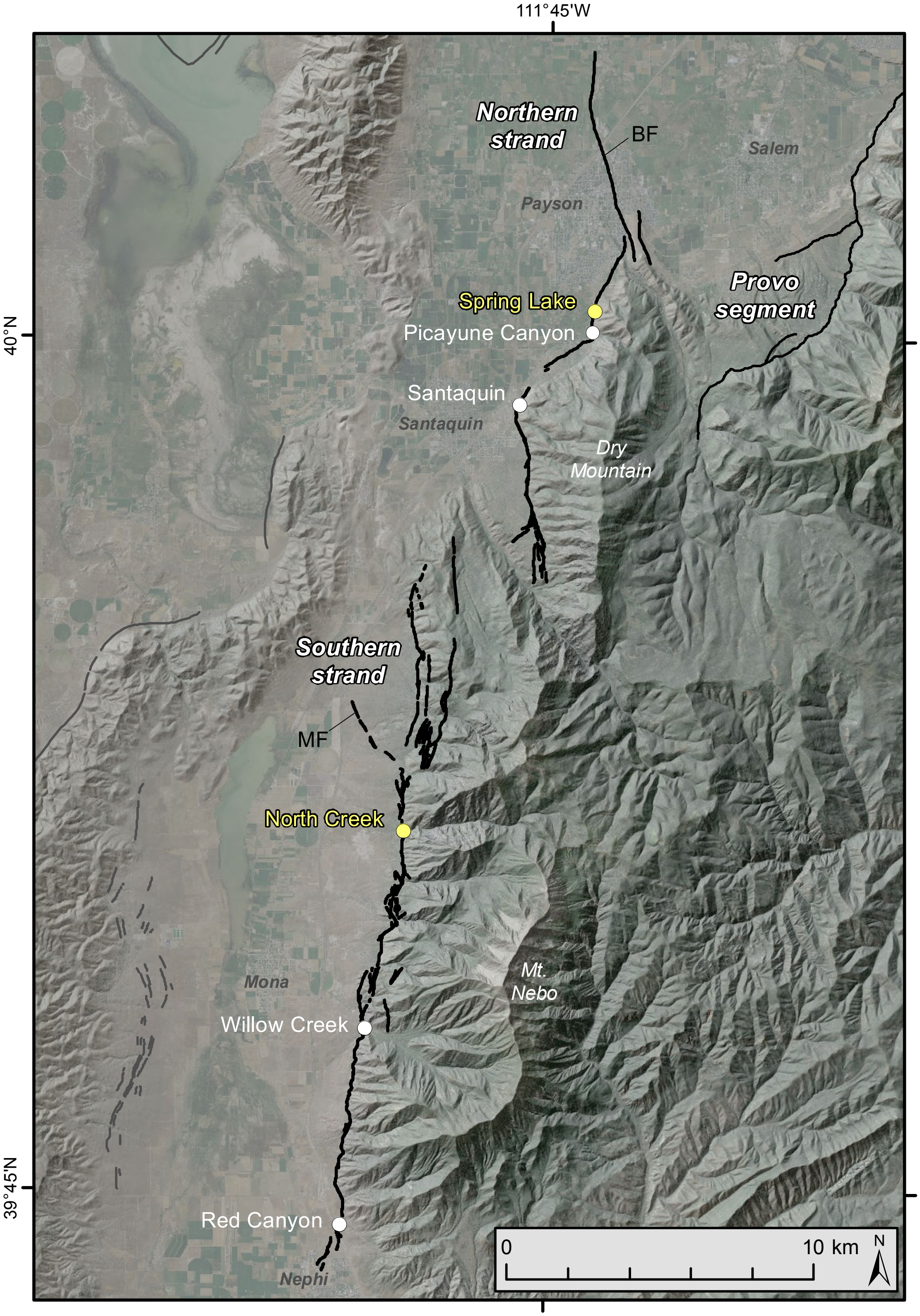

Figure 2. Nephi segment of the WFZ, showing the northern and southern fault strands and the southern extent of the Provo segment. Gray faults are other Quaternary faults in the area (all fault traces from Black and others, 2003). Circles indicate paleoseismic trench sites: white – previous investigations; yellow – this study. BF – Benjamin fault, MF – Mendenhall fault. Base maps are 2011 NAIP aerial photography (U.S. Department of Agriculture [USDA], 2013)

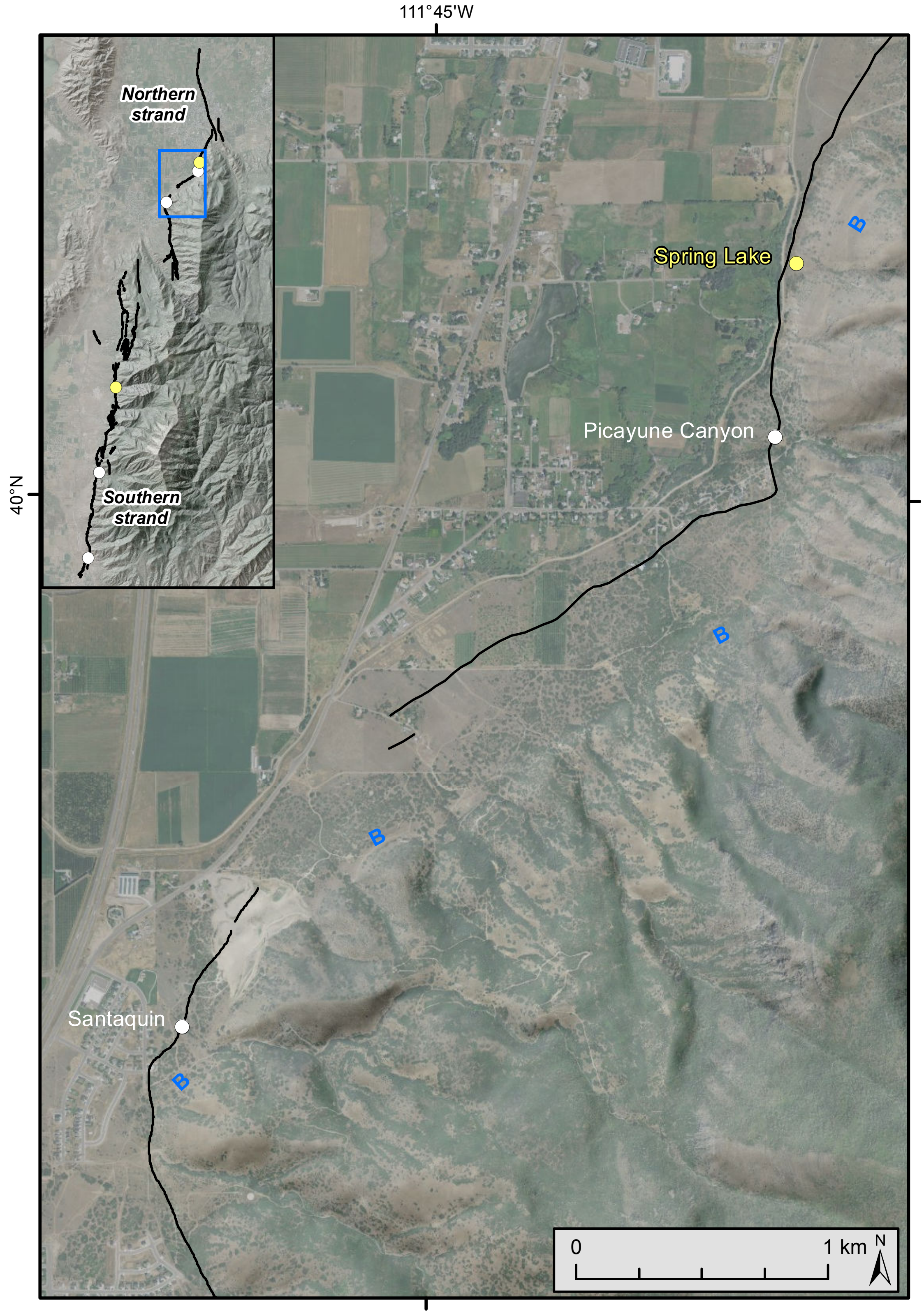

Figure 3. Northern strand of the Nephi segment showing the Spring Lake and adjacent trench sites. Fault traces from Black and others (2003) show the approximate location of the WFZ. B indicates highstand shoreline of Lake Bonneville. Base maps are 2011 NAIP aerial photography (USDA, 2013) overlain on a 10-m DEM with hillshade (AGRC, 2013).

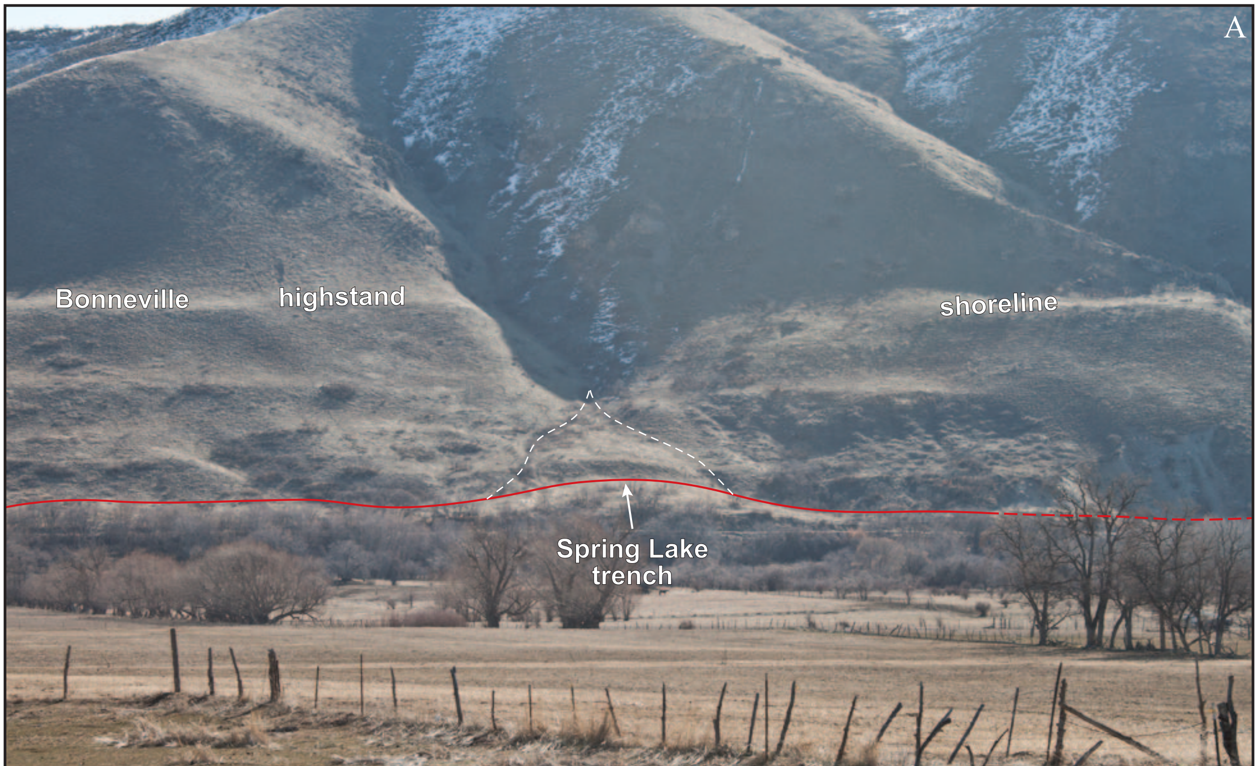

Figure 4. Spring Lake site on the northern strand. A) View to the east of the alluvial fan (white dashed lines) incised into Lake Bonneville highstand sediments on the footwall of the WFZ (red line). The Spring Lake site is below the Lake Bonneville highstand shoreline and above the elevation of the Provo shoreline (not shown). B) Excavation of the Spring Lake site. The scarp shown is approximately 8 m high. View to the southeast.

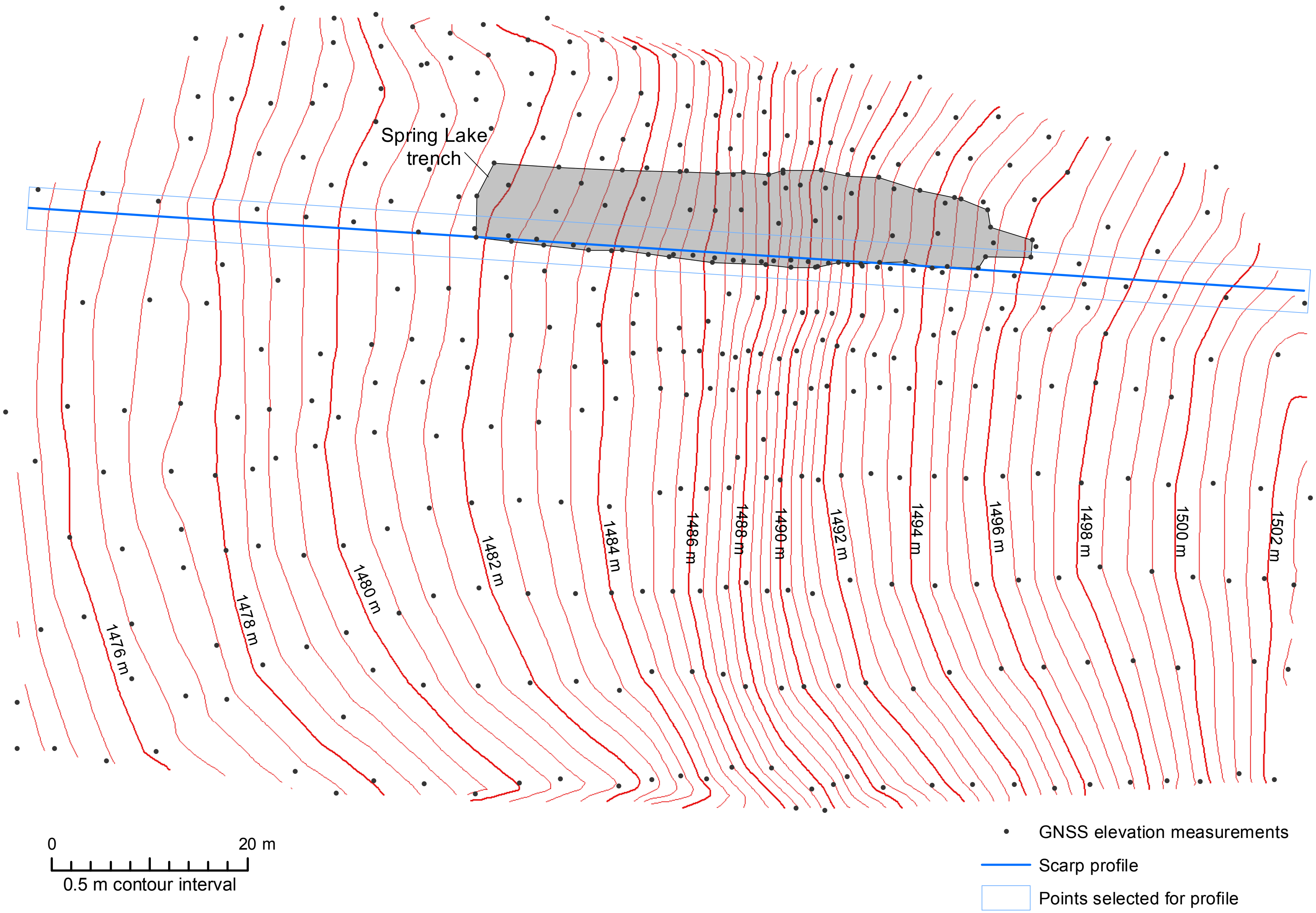

Figure 5. Topographic map of the Spring Lake site based on high-precision GNSS data measured prior to trench excavation. Gray-filled polygon indicates extent of the Spring Lake trench; blue line indicates scarp profile (figure 6). Contours interpolated from a triangulated irregular network (TIN) generated using the point elevation data.

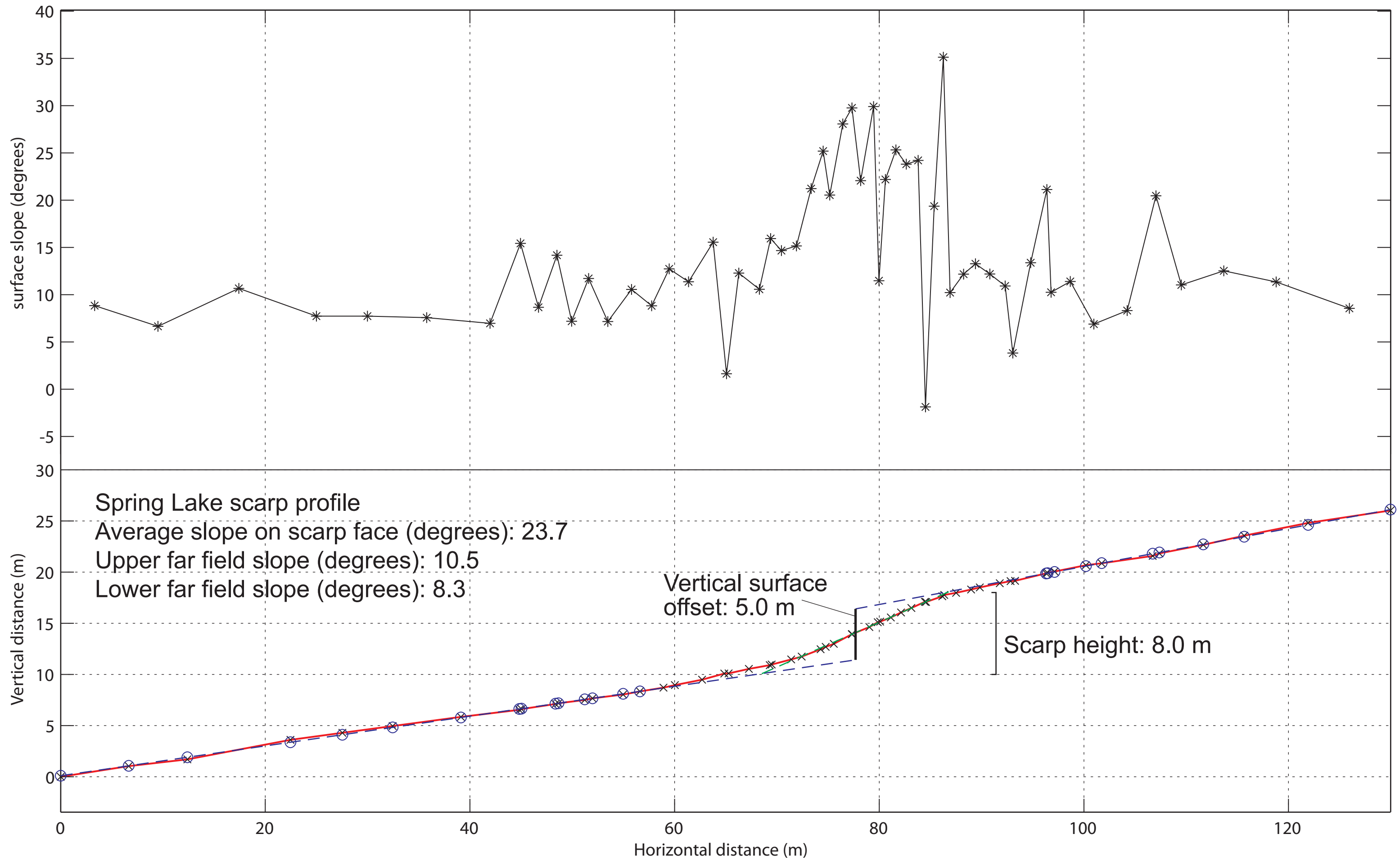

Figure 6. Scarp profile measured across the Spring Lake site. Profile points (X's) measured using high-precision GNSS; vertical distance is relative to the minimum surface elevation at the site (1475 m above mean sea level). Black asterisks show surface slope at midpoint distances between profile points. Blue circles indicate profile points selected for upper and lower surface-slope measurements. Vertical surface offset is the vertical separation of the projected upper and lower surface slopes measured at the horizontal midpoint of the maximum scarp slope (green dashed line). Scarp height is the vertical distance between the intersections of the maximum scarp slope with the upper and lower surface-slope projections.

Figure 7. North wall of the Spring Lake trench, showing the main traces of the Wasatch fault (fault F1) that juxtapose Lake Bonneville lacustrine sediments in the footwall with post-Bonneville alluvial-fan deposits in the hanging wall. Pink string lines show a 1-m square grid.

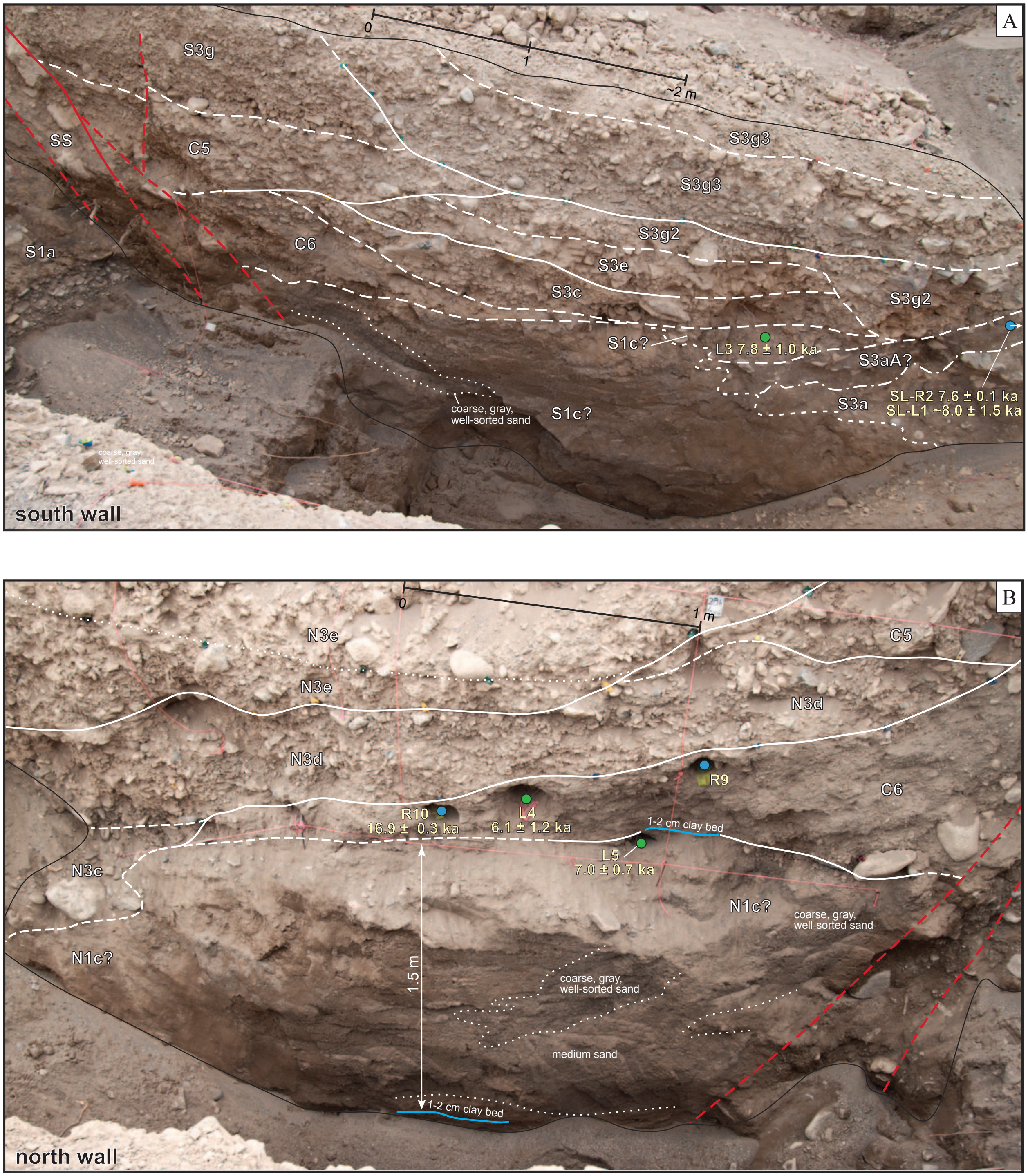

Figure 8. Colluvial-wedge unit C6 exposed adjacent to the Wasatch fault (red dashed lines). A) South-wall exposure, showing unit C6, which overlies massive sand in unit S1c?, and is overlain by several alluvial-fan deposits. Unit C6 likely postdates the ~7.8 ka OSL age for unit S1c? (sample SL-L3), which is interfingered with soils S3aA and S3bA (dated to ~7.6–8.0-ka based on OSL samples SL-L1 and -R2). B) North-wall exposure, showing unit C6 unconformably overlying the subhorizontal sand and fine silt and clay bed (upper blue line) in the uppermost part of unit N1c?. A lower clay bed in unit N1c? is the basis for a ~1.5-m minimum thickness of the unit. Unit C6 deposition predates the age for SL-L4 (~6.1 ka) and postdates the age for SL-L5 (~7.0 ka).

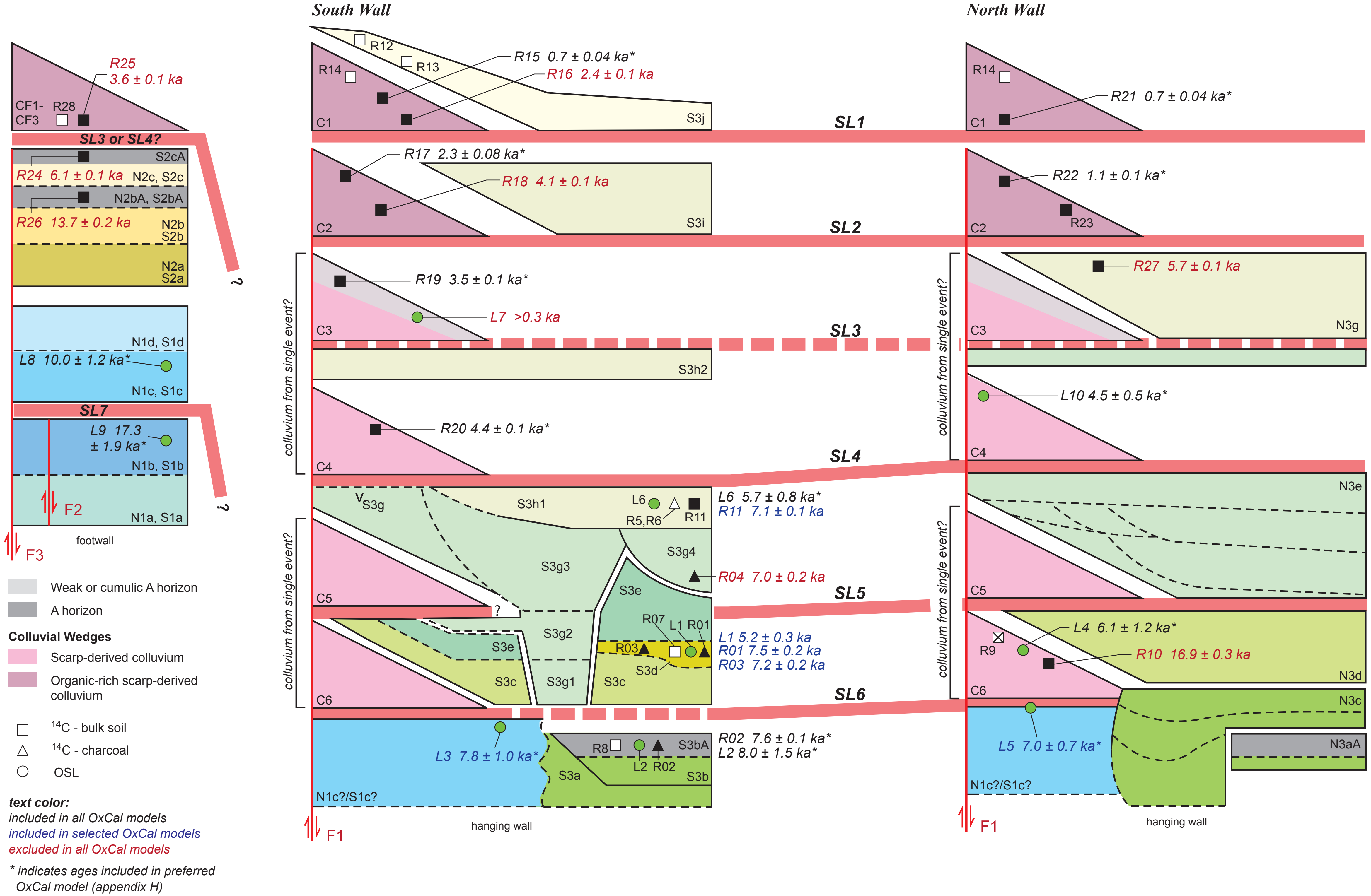

Figure 9. Summary of colluvial wedges exposed at the Spring Lake site and their relation to alluvial-fan and lacustrine sediments and 14C and OSL ages. Text color for numerical ages indicates placement in several OxCal models constructed for the site (appendix H). Horizontal red bars indicate surface-faulting earthquakes in the context of the sedimentary deposits and numerical ages.

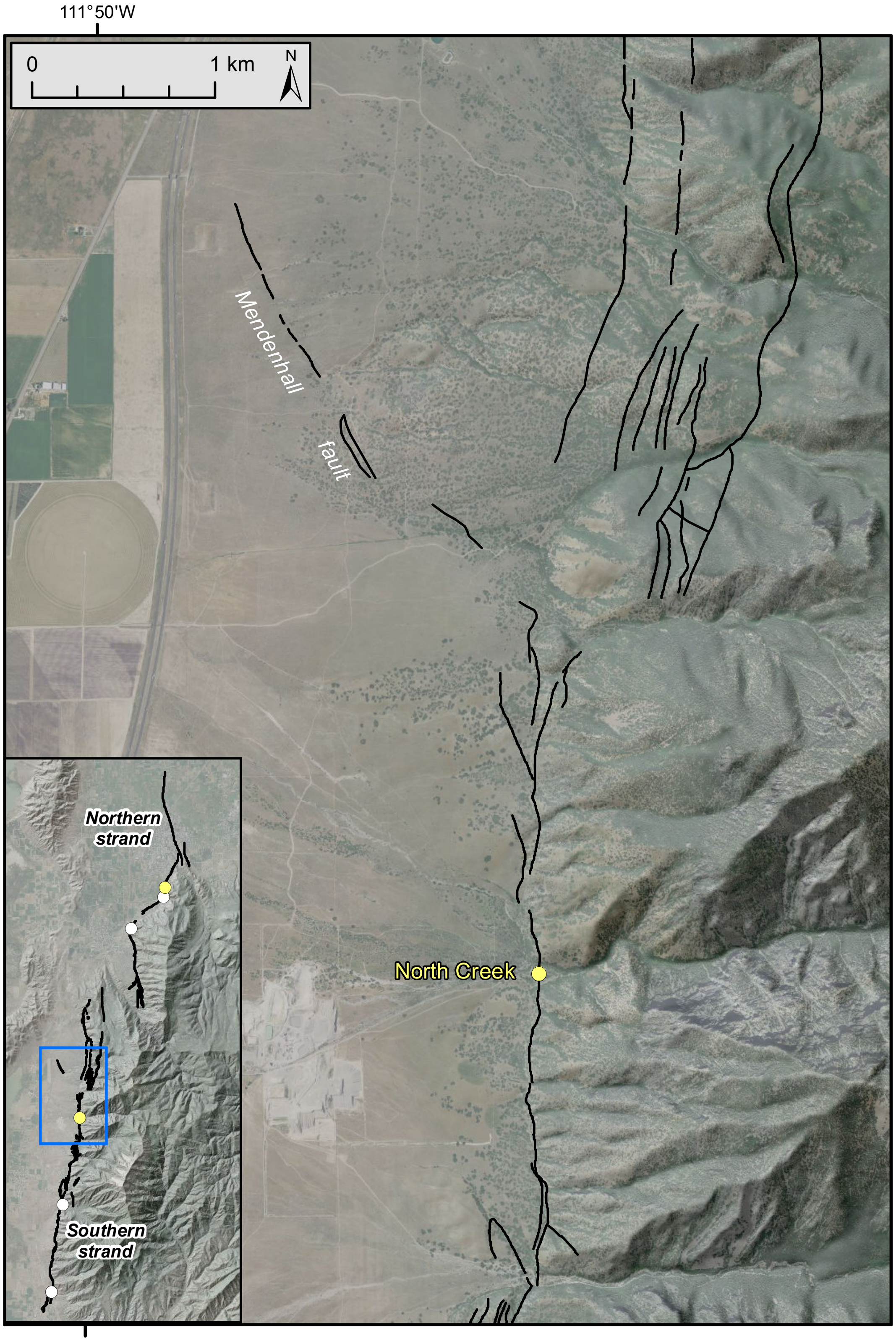

Figure 10. Southern strand of the Nephi segment showing the North Creek trench site. Fault traces from Black and others (2003) show the approximate location of the WFZ. Trace of the Mendenhall fault from Black and others (2003) and DuRoss (2004). Base maps are 2011 NAIP aerial photographs (USDA, 2013) overlain on a 10-m DEM with hillshade (AGRC, 2013).

Figure 11. North Creek site on the southern strand. A) View to the northeast of the North Creek drainage (photo taken on distal alluvial-fan sediments derived from North Creek). South Creek is a minor drainage to the south (after Hanson and others, 1981); alluvial-fan sediments from South Creek have partially buried North Creek alluvial-fan sediments on the hanging wall of the WFZ. B) Excavation of the North Creek site. The scarp shown is approximately 8 m high. View is to the southeast.

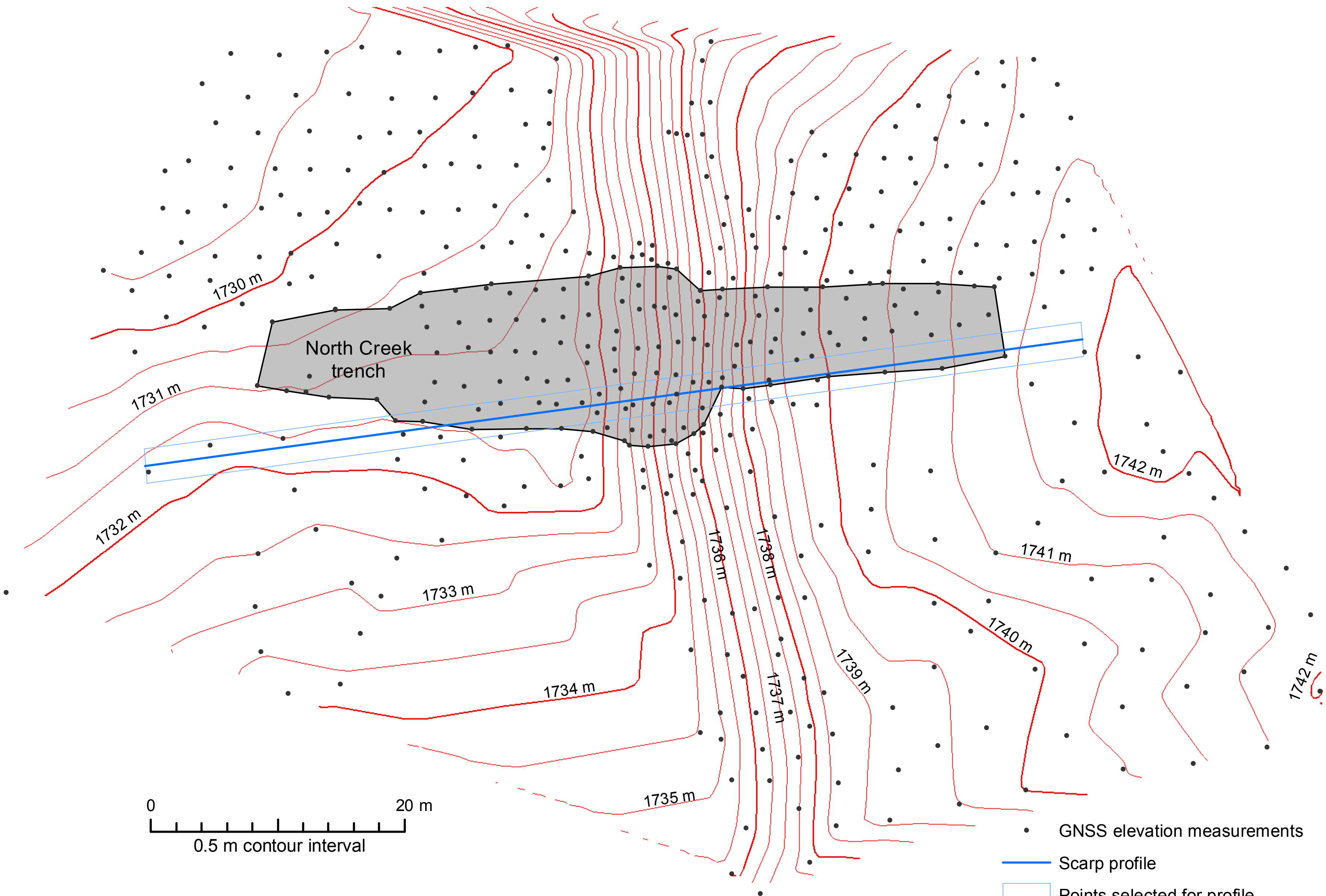

Figure 12. Topographic map of the North Creek site based on high-precision GNSS data measured prior to trench excavation. Gray-filled polygon indicates extent of the North Creek trench; blue line indicates scarp profile (figure 13). Contours interpolated from a triangulated irregular network (TIN) generated using the point elevation data.

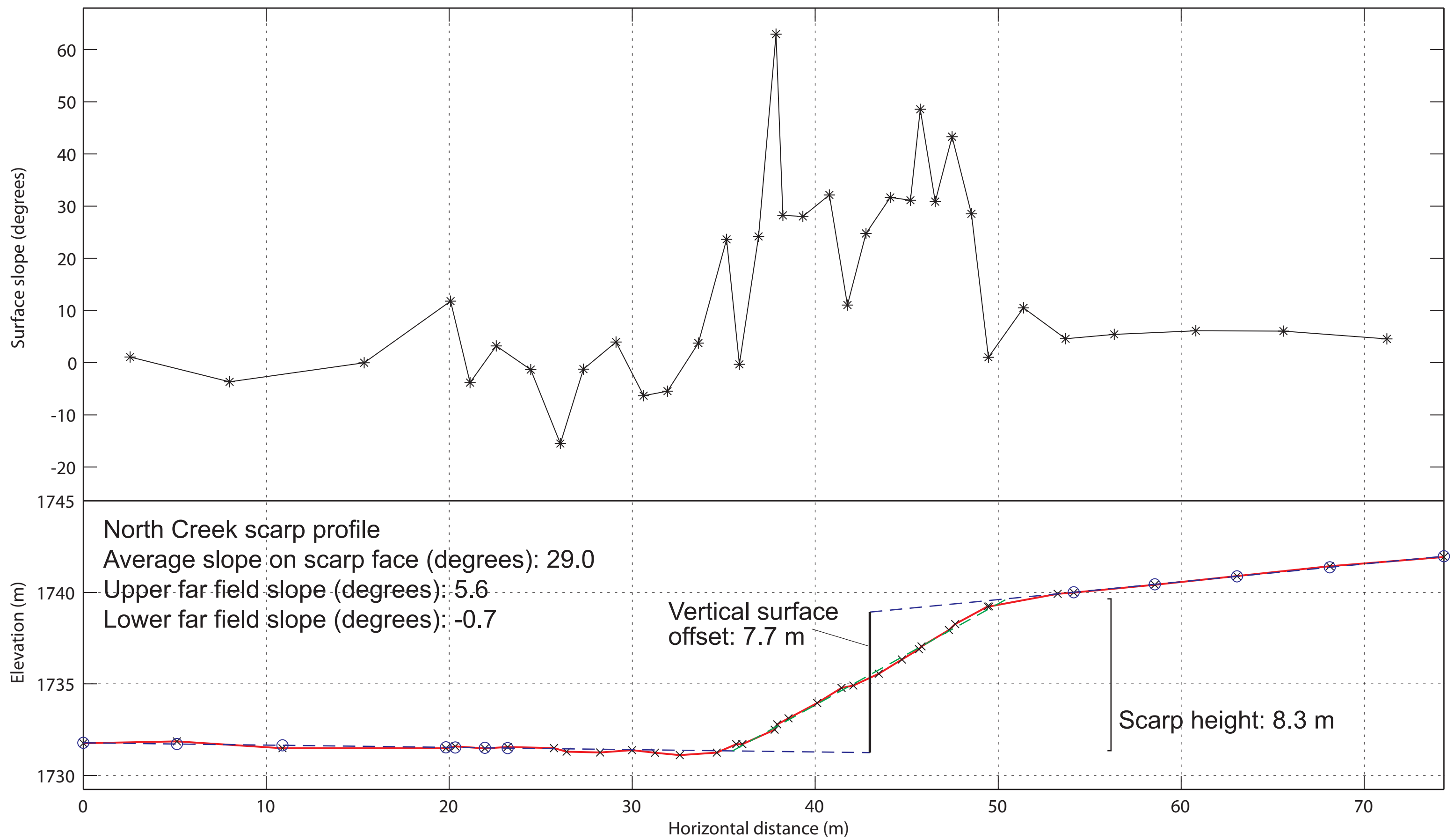

Figure 13. Scarp profile measured across the North Creek site. Profile points (X's) measured using high-precision GNSS; elevation is relative to mean sea level. Black asterisks show surface slope at midpoint distances between profile points. Blue circles indicate profile points selected for upper and lower surface-slope measurements. Vertical surface offset is the vertical separation of the projected upper and lower surface slopes measured at the horizontal midpoint of the maximum scarp slope (green dashed line). Scarp height is the vertical distance between the intersections of the maximum scarp slope with the upper and lower surface-slope projections.

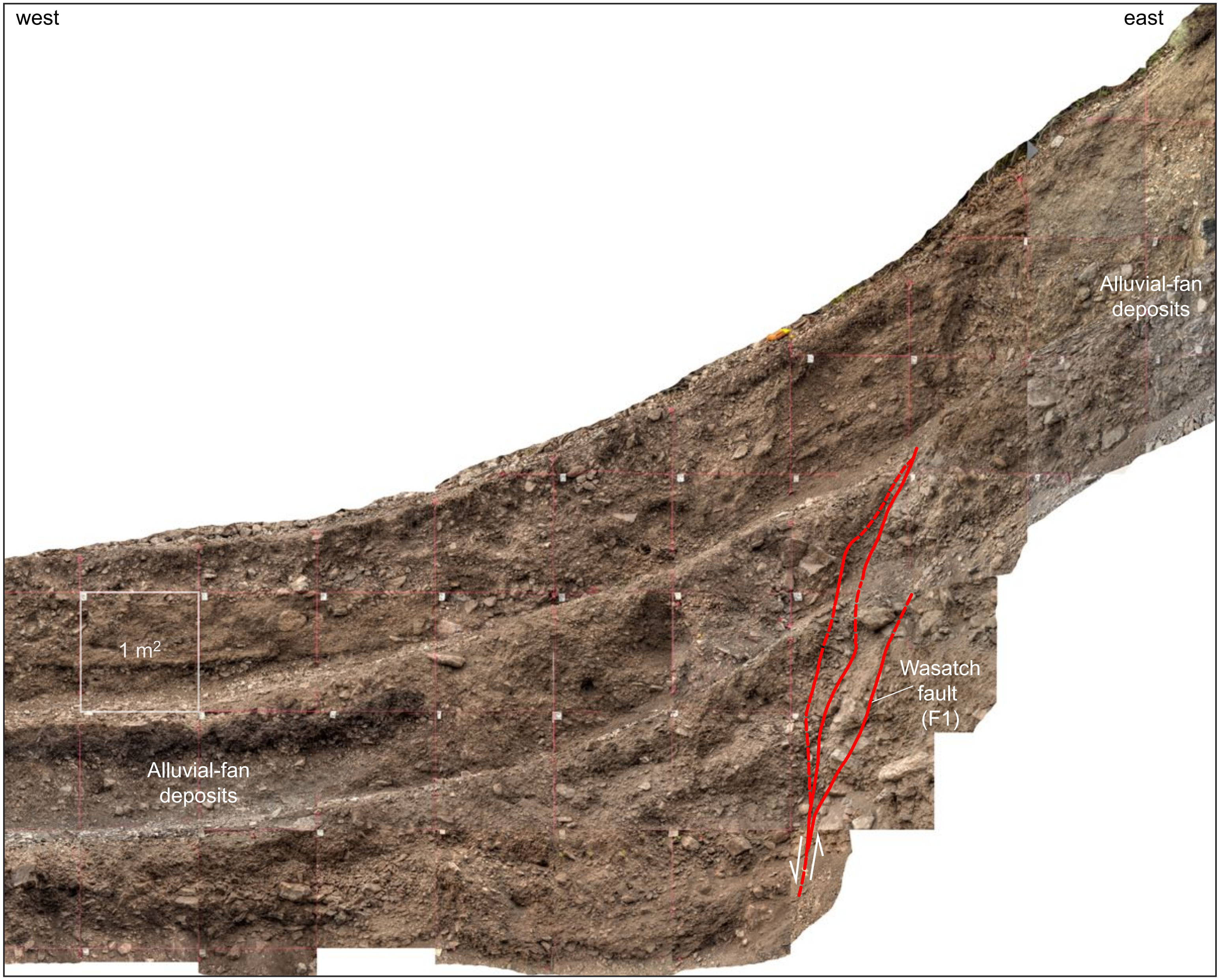

Figure 14. Subset of the photomosaic of the north wall of the North Creek trench, showing the main traces of the Wasatch fault (fault F1), which juxtapose alluvial-fan deposits sourced from the North Creek drainage in the footwall with younger alluvial-fan deposits likely sourced from a minor drainage to the south (South Creek) in the hanging wall. Pink string lines show a 1-m square grid.

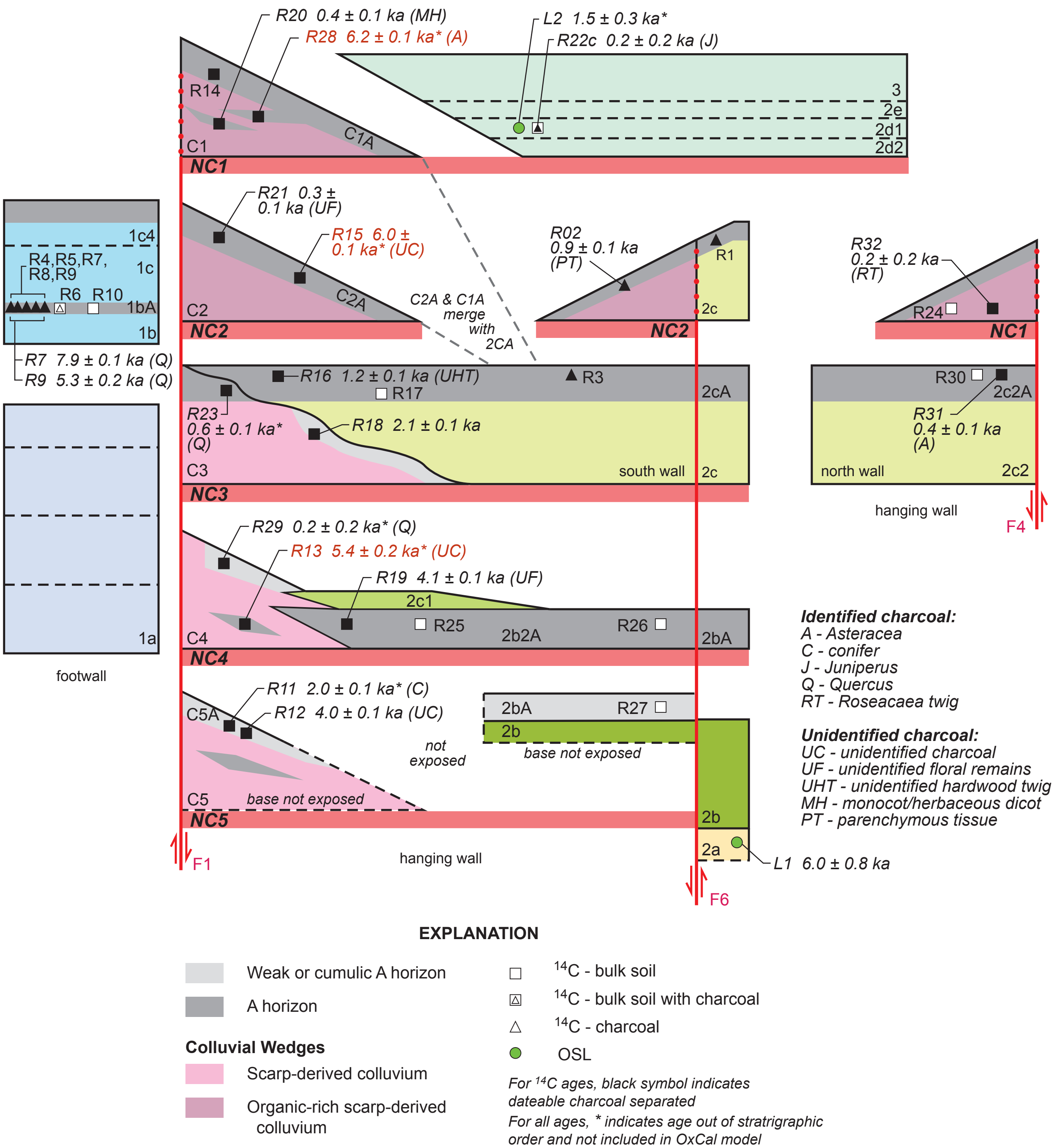

Figure 15. Summary of colluvial wedges exposed at the North Creek site and their relation to alluvial-fan sediments and 14C and OSL ages. Red text for numerical ages indicates 14C samples likely containing charcoal derived from soil 1bA in the footwall. Horizontal red bars indicate surface-faulting earthquakes in the context of the sedimentary deposits and numerical ages.

APPENDIX A. DESCRIPTION OF STRATIGRAPHIC UNITS IN TRENCHES AT THE SPRING LAKE TRENCH SITE

Unit, genesis[1]	Station no. (trench)[2]	Textural name[3]	Texture (%)[4]				Clasts		Plast-icity[3]	Density/ consistency[3]	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)											
N1a, L	24h, 6-7v	sandy gravel with cobles	5	40	45	10	21	2-6	none	very loose-loose	none-very weak	mod.-strong	round.-subround.	well bedded	some imbri-cation	mod. well	not exposed	*10YR 5/2 (10YR 3/3)*	Lacustrine (Bonneville transgressive) gravel with boulder lag at top; oldest unit exposed
N1b, L	19h, 9-10v	silty sand	19	80	1	-	2	0.01-0.03	non-plast.	loose	weak	strong	subang.	well bedded	low-angle trough cross bedding	well	clear	*10YR 6/3 (10YR 3/3)*	Lacustrine (Bonneville transgressive near-shore) sand, with cm-scale, alternating sand-clay/silt layers
N1c, L?	21h, 10-11v	massive silty sand with occasional gravel	10	85	5	-	9	3-4	non-plast.	loose	none-very weak	mod. strong	subround-subang.	no bedding; massive	none	poorly sorted	gradual	*10YR 6/2 (10YR 3/3)*	Possibly Bonneville sand reworked by eolian or slope-wash processes; massive
N1d, A?	16h, 12-13v	boulder/cobble flow with sandy matrix	10	40	10	40	80	20	non-plast.	med.-dense to loose	non-very weak	strong	subround.-subang.	no bedding	none	poorly sorted	clear	*10YR 6/3 (10YR 4/3)*	Likely post-Bonneville flood, sediment derived from Bonneville shoreline; unit includes subunits N1d1 and N1d2
N2, S-DF	15h, 11-13v	silty gravel with sand and cobbles	20	35	40	5	30	5-10	slight plast.	med.-dense to med. stiff	weak	strong	subround.-angular	weakly bedded	variable	variable	clear	*10YR 6/4 (10YR 5/4)*	Post Bonneville channel/debris flow deposits; mostly laterally discontinuous
N3aA, DF, A	33-39h, 1-2v	A horizon soil in silty sandy gravel with cobbles	10	30	50	10	15	0.5-3	low	med-high	weak	-	ang.-subang.	poor	none	poor	not exp.	-	Soil A horizon developed in debris flow; poor to no soil structure present
N3b, DF	36-42h, 0-1v	matrix supported gravel with cobbles	10	30	50	10	20	-	very low	med-high	weak-mod.	-	ang.-subang.	poor	none	poor-mod.	gradual to clear	-	Includes two matrix-rich debris flows
N3c, S-DF	31-43h, 1-5v	clast and matrix supported gravel with cobbles	5	25	50	20	40	-	low	mod-high	weak-mod.	-	ang.-subround.	poor-mod.	channel complex.	poor-mod.	clear to gradual	-	Includes series of channel complexes with clear cobble/gravel thalwegs
N3d, S-DF	31-37h, 2-3v	clast and matrix supported gravel with cobbles	10	30	50	10	22	-	low	low-high	weak-mod.	-	ang.-rounded	poor-mod.	channel complex.	poor-mod.	clear to gradual	-	Includes channel complexes with low angle margins
N3f, S-DF	31-44h, 1-6v	clast and matrix supported silty, sandy gravel	10	20	60	10	15	-	low	low-high	mod.		ang.-subround.	poor-mod.	none	mod.-well	gradual	-	Includes clast supported gravel with well sorted horizontal beds/lenses of open-work gravel; locally cemented
N3g, DF	31-44h, 1-6v	matrix supported sandy gravel with cobbles	10	20	35	35	40	-	low	med.-high	weak-mod.	-	ang.-subround.	poor	none	very poor	clear to gradual	-	Massive silt/sand supported gravel with cobbles
S3a-f, DF	31-41h, 0-3v	matrix (sand) supported gravel with cobbles	10	30	40	20	30	-	very low	med.-high	weak-mod.	-	ang.-subang.	poor	none	very poor	gradual to clear	-	Poorly sorted sand-supported gravel with cobbles; includes a poorly sorted pebble-rich debris flow
S3g, S-DF	31-42h, 3-4v	sand/pebble supported gravel with cobbles	5	25	50	20	45	-	low	low-high	mod.	-	subang.-rounded	poor-mod.	channel complex.	poor-mod.	clear to gradual	-	Series of stacked channels consisting of poor to well sorted pebble gravel
S3h, DF	31-45h, 3-5v	matrix supported gravel with cobbles	10	20	35	35	40	-	low	med.-high	weak	-	ang.-subround.	poor	none	poor	clear to gradual	-	Matrix supported massive gravel
S3i, DF	31-45h, 3-6v	matrix supported gravel with cobbles	15	15	50	20	20	-	low	med.-high	weak	-	subang.-subround.	poor	none	mod.-poor	clear to gradual	-	Matrix supported massive gravel
S3j, DF	31-43h, 4-6v	matrix supported gravel with some cobbles	20	10	60	10	15	-	low	med.-high	weak	-	subang.-subround.	poor	none	mod.	clear to gradual	-	Matrix supported massive gravel
C1, C	26-27h, 7v	gravely silt with some fine sand and cobbles	50	15	30	5	10	2-5	mod.	medium stiff	weak	strong	angular to subang.	weak slope fabric	slope fabric	poorly sorted	gradual	*10YR 6/2 (10YR 3/2)*	Colluvial wedge C1

C2, C	27h, 6v	gravelly sandy silt with cobbles	40	20	25	15	25	5-10	slight	medium stiff	weak	strong	angular to subang.	slope fabric	slope fabric	poorly sorted	gradual	*10YR 5/2 (10YR 3/3)*	Colluvial wedge C2
C3, C	27h, 6v	gravelly sandy silt with cobbles	35	25	25	15	30	5-10	slight	stiff to loose	weak	very strong	angular to subang.	weak slope fabric	slope fabric	poorly sorted	gradual	*10YR 7/3 (10YR 5/4)*	Colluvial wedge C3
C4, C	27h, 5v	sandy gravel with silt and small cobbles	30	35	30	5	15	2-5	none to slight	loose to med. dense	weak	very strong	angular to subang.	very weak slope fabric	slope fabric	mod. sorted	gradual	*10YR 7/3 (10YR 5/3)*	Colluvial wedge C4
C5, C	27h, 4v	sandy gravel with cobbles	15	40	30	15	40	5-10	non-plast.	loose	weak to none	strong	angular to subround.	weak slope fabric	slope fabric	poorly sorted	gradual	*10YR 6/3 (10YR 4/4)*	Colluvial wedge C5
C6, C	28h, 3v	sand (massive)	10	84	5	1	10	0-5	non-plast.	loose to med. dense	none	strong	subang. to subround.	massive to weak slope fabric	none	mod. to well sorted	gradual	*10YR 6/2 (10YR 4/2)*	Colluvial wedge C6
CF3	11.4h, 14.2v	cobble gravel with clayey sand	5	25	40	30	25	3-8	high	med.	none	mod. strong	subround. to ang.	none	none	poorly sorted	clear	*10YR 4/2 (10YR 3/2)*	Footwall colluvial wedge; moderately organic rich; stage 1 carbonate development
CF1	21.3h, 10.2v	gravel with sand	30	25	40	5	15	3-9	low	loose	none	strong	subang. to ang.	none	none	poorly sorted	clear	*10YR 6/2 (10YR 5/3)*	Footwall colluvial wedge; moderately organic rich; stage 1 carbonate development

[1] Units correspond with plate 1. Genesis: S - stream, DF - debris flow, L - lacustrine, C - colluvium, F - fill. A indicates A horizon soil.

[2] Horizontal and vertical meters correspond to the north wall (plate 1).

[3] Texture name approximated using 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. F – fines (silt and clay), S – sand, G – gravel, C/B – cobbles and boulders. We used a U.S. Standard #10 (2 mm) sieve to separate matrix (clay, silt, and sand) 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. DESCRIPTION OF STRATIGRAPHIC UNITS IN TRENCHES AT THE NORTH CREEK TRENCH SITE

Unit, genesis[1]	Station no. (trench)[2]	Textural name[3]	Texture (%)[4]				Clasts		Plast-icity[3]	Density/ consistency[3]	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)											
1a, S-DF	23h, 3v	gravely sand with some large boulders	10	25	50	15	50	25	non-plast.	nonsticky	weak	strong	subround.	well bedded	none	poorly sorted	clear	*10YR 7/3 (10YR 6/3)*	Interbedded stream and debris flow deposits in fault footwall
1b, S	31h, 10v	silty gravel with some cobbles	25	10	40	25	40	10	slight. plast.	sticky	mod.	strong	subang.	well bedded	none	mod. sorted	diffuse	*10YR 6/3 (10YR 5/3)*	Interbedded stream deposits; locally contains open-work gravel
1c, S-DF	37h, 12-13v	silty sand with some cobbles	35	30	25	10	20	5-10	slight. plast.	sticky	strong	very strong	subang.	poor	none	poorly sorted	clear	*10YR 6/3 (10YR 4/2)*	Alluvial-fan deposits; locally contains channels
2a, S	8h, 1v	silt with occasional cobbles	79	10	1	10	30	<1	plast	very sticky	strong	strong	angular	none	none	poorly sorted	not exp.	*10YR 6/3 (10YR 4/2)*	Silt horizon at base of hanging wall exposure
2b, S	8h, 2v	sandy gravel with occasional cobbles	10	20	50	20	20	5	non-plast.	nonsticky	weak	mod. strong	subround.	mod. bedded	none	mod. sorted	clear	*10YR 6/3 (10YR 5/3)*	Fluvial gravel package
2c, S	7h, 3v	sandy gravel with occasional cobbles	5	20	55	20	10	5	non-plast.	nonsticky	weak	mod. strong	subround	mod. bedded	none	mod. sorted	clear	*10YR 6/2 (10YR 5/3)*	Fluvial gravel package
2d1, S	17h, 3v	silt	88	5	5	2	5	<2	very plast.	very stick	strong	very strong	subang.	none	none	well sorted	clear	*10YR 4/3 (10YR 3/3)*	Thin silt bed
2d2, S	17h, 3v	silty sand with gravel	30	40	25	5	30	5	slight. plast.	slightly sticky	mod.	strong	subang. to ang.	poor	none	poorly sorted	abrupt	*10YR 4/4 (10YR 3/3)*	Fluvial sand
3, DF	15h, 3v	silty gravel	25	15	30	30	25	10	slight. plast	slightly sticky	mod.	strong	subang. to ang.	none	none	poorly sorted	clear	*10YR 5/2 (10YR 4/2)*	Debris flow
Cg2, C	12h, 2v	silty gravel	25	15	40	20	6	2-5	plast.	sticky	mod.	strong	subround.	some slope fabric	none	poorly sorted	clear	*10YR 4/3 (10YR 3/2)*	Colluvial wedge in the hanging wall graben
C1, C	22h, 5v	sandy gravel with cobbles	5	20	55	20	20	10	non-plast.	nonsticky	mod.	strong	subround. to subang.	well-defined slope fabric	slope fabric	mod. sorted	gradual	*10YR 5/4 (10YR 4/3)*	Youngest colluvial wedge (C1)
C2, C	21h, 4v	sandy gravel with cobbles	15	30	35	20	15	5	slight. plast.	slightly sticky	weak	strong	subround.	weak slope fabric	slope fabric	poorly sort.	clear	*10YR 6/3 (10YR 5/2)*	Colluvial wedge C2
C3, C	20h, 3v	silty gravel with cobbles	35	15	30	20	14	5	plast.	sticky	mod.	strong	subround. to subang.	none	none	poorly sorted	gradual	*10YR5/2 (10YR 3/3)*	Colluvial wedge C3
C4, C	21h, 1v	silty gravel with cobbles	25	15	35	25	14	10	plast.	sticky	strong	strong	subround. to subang.	weak-mod. slope fabric	slope fabric	poorly sorted	gradual	*10YR 5/4 (10YR 4/3)*	Colluvial wedge C4
C5?, C	21h, 1v	silty gravel	30	20	35	15	17	2-4	slight. plast.	slightly sticky	weak-mod.	-	subang.	none	none	poorly sorted	not exp.	*10YR 6/4 (10YR 4/4)*	Basal colluvial wedge exposed along main fault (F1)

[1] Units correspond with plate 2. Genesis: S - stream, DF - debris flow, L - lacustrine, C - colluvium, F - fill. A indicates A horizon soil.

[2] Horizontal and vertical meters correspond to the north wall (plate 2).

[3] Texture name approximated using 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. F – fines (silt and clay), S – sand, G – gravel, C/B – cobbles and boulders. We used a U.S. Standard #10 (2 mm) sieve to separate matrix (clay, silt, and sand) 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.

EXAMINATION OF CHARCOAL AND BULK SOIL SAMPLES FOR RADIOCARBON DATABLE MATERIAL FROM THE SPRING LAKE NORTH AND NORTH CREEK TRENCH SITES ON THE NEPHI SEGMENT OF THE WASATCH FAULT ZONE, UTAH

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INTRODUCTION

Bulk soil samples and detrital charcoal samples from trenches at the Spring Lake North (SPL) site and the North Creek (NC) site were examined to recover organic fragments suitable for radiocarbon analysis. Trenches were excavated to investigate the timing of Holocene surface-faulting earthquakes on the northern and southern parts of the Nephi segment of the Wasatch Fault, central Utah. Samples were recovered from scarp-derived colluvium and alluvial fan sediments. Botanic components and detrital charcoal were identified, and potentially radiocarbon datable material was separated. Charred material will be submitted to Woods Hole Oceanographic Institution for dating.

METHODS

Flotation and Identification

The bulk samples were floated using a modification of the procedures outlined by Matthews (1979). Each sample was added to approximately 3 gallons of water. The sample was stirred until a strong vortex formed, which was allowed to slow before pouring the light fraction through a 150-micron-mesh sieve. All material that passed through the screen was retained for possible microcharcoal or particulate soil organics extraction. Additional water was added and the process repeated until all visible macrofloral material was removed from the sample (a minimum of five times). The material that remained in the bottom (the 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 4-mm, 2-mm, 1-mm, 0.5-mm, and 0.25-mm openings) to separate the charcoal debris and to initially sort the remains. The contents of each screen then were examined. Charcoal fragments 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 remaining light fraction in the 4-mm, 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 coarse or heavy fractions also were screened and examined for the presence of botanic remains. Remains from both 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.

Detrital charcoal samples were water-screened through a 250-micron mesh and allowed to dry. Samples initially were examined under a binocular microscope at a magnification of 10x. Charcoal fragments were separated from the water-screened sample matrix and 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.

Macrofloral remains, including charcoal, were identified using manuals (Carlquist 2001; Core et al. 1976; Hoadley 1990; Martin and Barkley 1961; Panshin and de Zeeuw 1980;

Petrides and Petrides 1992) 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

It is now possible to recover microscopic charcoal and particulate soil organics from sediments for the purpose of obtaining an AMS radiocarbon age. A chemical extraction technique based on that used for pollen, and relying upon heavy liquid extraction, has been modified to recover microscopic charcoal and particulate soil organics for the purpose of obtaining an AMS radiocarbon age. Hydrochloric (HCl) acid (10%) was added to the material retained from flotation that had passed through the 250 micron mesh sieve to remove calcium carbonates. The sample then was rinsed until neutral, and a small quantity of sodium hexametaphosphate was added to begin clay removal. Sample beakers 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 to remove more clays.

Once the clays had been removed, the samples were freeze-dried. Sodium polytungstate (SPT) with a density of 1.8 was used for the flotation process. The dry 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 microscopic charcoal was decanted. Sodium polytungstate again was added to the inorganic fraction to repeat the separation process until the organic material had been recovered (usually three repetitions). The microscopic charcoal fragments were recovered from the SPT by diluting this mixture with RODI and centrifuging, after which they were rinsed thoroughly with RODI water.

This resulting mixture of charcoal and particulate soil organics was then subjected to the standard acid-base-acid chemical pre-treatment required prior to radiocarbon dating. Following completion of this, the sample was subjected to a nitric acid treatment in which a small quantity of concentrated hot nitric acid was added to each sample tube, which was then allowed to sit for approximately 15 minutes. Following this treatment the sample was rinsed copiously with RODI water, vacuum dried, then examined again using a binocular microscope at a magnification of up to 30x to check for the presence of charcoal and particulate organics. If uncharred particulate organics remain and the quantity of the sample is large enough the nitric acid treatment was repeated. The freeze-dried microscopic charcoal fragments were then weighed and placed in a glass tube for shipment.

DISCUSSION

The Spring Lake North and North Creek sites are located on west-facing alluvial-fan surfaces along the western base of the Wasatch Range in central Utah. The alluvial-fan surfaces are noted to be approximately middle to early Holocene in age and have been vertically offset by the Wasatch fault. Local vegetation in these areas consists primarily of grasses and mountain brush, mostly oak (*Quercus*).

Spring Lake North Site

The Spring Lake North site is situated south of Payson, Utah, at an elevation of 1480–1490 meters. This elevation is below the highest shoreline of Lake Bonneville. The trench exposed Lake Bonneville lacustrine sediments, stream and debris flow (alluvial-fan) deposits, and fault scarp-derived colluvium. The drainage basin that is the source of the alluvial fan deposits ranges in elevation from 1510–1780 meters. A wildfire in 2001 burned both the trench site and the drainage basin. A total of 8 detrital charcoal samples and 15 bulk soil samples were examined from this site.

Unit C1A

Bulk samples SLN-R15 and SLN-R16 were recovered from an A horizon developed on or within (organic stringer) scarp colluvium in Unit C1A (Table 1). Sample SLN-R15 contained several fragments of charcoal too small for identification that weighed a total of 0.0011 g (Tables 2 and 3). Since the minimum weight of charred material needed for dating reported by Woods Hole Oceanographic Institution is 0.5 mg (0.0005 g), the 0.0011 g of charcoal recovered in sample SLN-R15 should be sufficient for AMS radiocarbon dating. The sample also contained an uncharred *Lactuca* seed, an uncharred Poaceae A floret, a few root fragments, and numerous rootlets from modern plants in the area. A few insect chitin fragments, two insect puparia, and several snail shells also were noted.

Several fragments of charcoal too small for identification and weighing 0.0019 g were present in sample SLN-R16, which should be a sufficient weight for dating. Two uncharred Poaceae stem fragments note modern grasses. In addition, the sample yielded a few root fragments, numerous rootlets, numerous snails with a depressed shape, and a few snails with an oblong shape.

Unit C1

Samples SLN-R13 and SLN-R21 were collected from scarp colluvium in Unit C1. Sample SLN-R13 yielded two fragments of Asteraceae charcoal weighing 0.0016 g, reflecting a woody member of the sunflower family that burned. Several fragments of charred monocot/herbaceous dicot stem fragments weighing 0.0026 g might reflect local grasses and other herbaceous plants that burned. A single insect puparium, a moderate amount of snail shells with a depressed shape, and seven snails with an oblong shape also were noted.

Detrital charcoal sample SLN-R21 was examined first. This sample consisted of several pieces of unidentified hardwood charcoal weighing 0.0006 g. A few rootlets and sclerotia were present. Because this charcoal is close to the minimum weight of 0.0005 g for dating, bulk sample SLN-R21 was floated to recover additional material. An additional 0.0003 g of unidentifiable charcoal fragments were recovered from the bulk sample, for a total charcoal weight of 0.0009 g. The sample also yielded root and rootlet fragments, a few insect chitin fragments, and a few depressed snail shells.

Unit C2

Bulk samples SLN-R23, SLN-R17, and SLN-R18 were taken from an A horizon developed on or within scarp colluvium in Unit C2A. The 15 fragments of charcoal in sample SLN-R23 were too small for identification and weighed only 0.0005 g. Extraction of microcharcoal is likely to result in additional charred material to supplement the charcoal for radiocarbon dating.

Several fragments of *Artemisia* charcoal in sample SLN-R17 yielded a total weight of 0.0074 g, which is sufficient for dating. Numerous snails with a depressed shape were noted in this sample, as well as fewer snails with an oblong shape. A few insect chitin fragments note insect activity in the area, while root fragments and rootlets represent modern plants.

Sample SLN-R18 yielded several pieces of charcoal too small for identification, although the total weight of 0.0014 g should be adequate for radiocarbon dating. Sub-surface disturbance indicators include a few insect chitin fragments, an insect puparium, a few depressed snails, several oblong snails, and a moderate amount of worm castings. The sample also yielded a few sclerotia. Sclerotia are commonly called "carbon balls." They are small, black, solid or hollow spheres that can be smooth or lightly sculpted. These forms range from 0.5 to 4 mm in size. Sclerotia are the resting structures of mycorrhizae fungi, such as *Cenococcum graniforme*, that have a mutualistic relationship with tree roots. Many trees are noted to depend heavily on mycorrhizae and might not be successful without them. "The mycelial strands of these fungi grow into the roots and take some of the sugary compounds produced by the tree during photosynthesis. However, mycorrhizal fungi benefit the tree because they take in minerals from the soil, which are then used by the tree" (Kricher and Morrison 1988:285). Sclerotia appear to be ubiquitous and are found with coniferous and deciduous trees including *Abies* (fir), *Juniperus communis* (common juniper), *Larix* (larch), *Picea* (spruce), *Pinus* (pine), *Pseudotsuga* (Douglas fir), *Alnus* (alder), *Betula* (birch), *Populus* (poplar, cottonwood, aspen), *Quercus* (oak), and *Salix* (willow). These forms originally were identified by Dr. Kristiina Vogt, Professor of Ecology in the School of Forestry and Environmental Studies at Yale University (McWeeney 1989:229-230; Trappe 1962).

Sample SLN-R22 was recovered in the north wall of Unit C2 from scarp-derived colluvial wedge. Charcoal in this sample includes a single vitrified piece of twig charcoal weighing 0.0008 g and several fragments of charcoal too small and vitrified for identification weighing 0.0002 g. The single piece of vitrified twig charcoal, either alone or combined with the unidentified charcoal fragments, can be submitted for radiocarbon dating. In addition, the sample contained a few uncharred rootlet fragments and numerous uncharred root fragments from modern plants, as well as a few depressed snail shells and a single oblong-shaped snail shell.

Unit C3A

Bulk sample SLN-R19 reflects an A horizon developed on or within scarp colluvium in Unit C3A. The sample contained four fragments of charred parenchymous tissue weighing 0.0008 g that can be submitted for dating, although it is possible that these fragments represent roots. Parenchyma is the botanical term for relatively undifferentiated tissue composed of many similar cells with thin primary walls. Parenchyma occurs in many different plant tissues in varying amounts, especially large fleshy organs such as roots and stems, but also in fruits, seeds, cones, periderm (bark), leaves, needles, etc. (Hather 2000:1; Mauseth 1988). A sufficient amount (0.0010 g) of very small, unidentifiable charcoal fragments also were present. We recommend keeping these charcoal fragments separate from the charred parenchyma fragments, since the latter might represent roots. Non-floral remains include a few uncharred bone fragments and a moderate amount of snail shells.

Unit N3g

Bulk sample SLN-R27 represents alluvial fan sediments in Unit N3g. This sample yielded several fragments of charcoal too small for identification and weighing a total of 0.0010 g, which should be sufficient for radiocarbon dating. Numerous uncharred rootlets from modern plants and a few snail shells were the only other remains to be recovered.

Unit C4

Bulk sample SLN-R20 was recovered from scarp colluvium in Unit C4. This sample also contained several fragments of charcoal too small for identification that weighed 0.0008 g. This weight should be adequate for radiocarbon dating. Root and rootlet fragments, a moderate amount of depressed snail shells, and a few oblong snail shells also were noted.

Units S3g/h/N3e

Detrital charcoal samples SLN-R05 and SLN-R06 were taken from alluvial-fan sediments in Unit S3g/h/N3e. Two tiny pieces of unidentifiable charred tissue weighing less than 0.0001 g were noted in sample SLN-R06, while the six fragments of charcoal in sample SLN-R05 also were too small for identification and too small for dating, weighing less than 0.0001 g. An additional bulk sample SLN-R11 from Unit S3h1 was recovered adjacent to samples SLN-R05 and SLN-R06. This sample also yielded several fragments of charcoal too small for identification; however, a total weight of 0.0022 g for these charcoal fragments should be adequate for radiocarbon dating. A few uncharred roots and rootlets from modern plants also were present.

Unit S3bA

Sample SLN-R02 consists of charcoal from the A horizon developed on or within alluvial-fan sediments in Unit S3bA. The several fragments of charcoal present in this sample were too small and vitrified for identification; however, the fragments weighed a total of 0.0012 g, which should be sufficient for radiocarbon dating. Vitrified charcoal has a shiny, glassy appearance that can range from still recognizable in structure “to a dense mass, completely ‘molten’ and non-determinable” (Marguerie and Hunot 2007; McParland et al. 2010). Although vitrification of charcoal has been attributed to burning at high temperature and/or burning green wood, it currently is not clear what conditions produce vitrified charcoal. It likely is a combination of factors (McParland, et al. 2010). We have noted that vitrified charcoal often loses more mass during chemical pre-treatment than charcoal that is not vitrified.

Unit S3d

Detrital charcoal samples SLN-R01, SLN-R03, and SLN-R04 were collected from alluvial-fan sediments in Unit S3d. Sample SLN-R01 yielded a single piece of charred parenchymous tissue weighing 0.0018 g that can be submitted for radiocarbon dating. A single piece of unidentified hardwood twig charcoal in sample SLN-R03 weighs 0.0012 g and also can be submitted for dating. The small pieces of unidentified hardwood charcoal in sample SLN-R04 yielded a weight of 0.0009 g. Single pieces of charcoal, when compared to multiple pieces with the same weight, usually loose less mass during chemical pre-treatment.

Unit C6

Samples SLN-R09 and SLN-R10 were recovered from scarp colluvium in Unit C6. Detrital charcoal sample SLN-R09 contained only a few small rocks; therefore, bulk sample SLN-R09 was processed. The bulk sample yielded five fragments of charcoal too small for identification and weighing less than 0.0001 g. The probability of obtaining sufficient microscopic charcoal from this bulk sample is small because the visible charcoal recovered from this bulk sample weighed so little.

Bulk sample SLN-R10 yielded five fragments of charred parenchymous tissue weighing less than 0.0001 g and five pieces of charred, vitrified tissue weighing 0.0007 g. This amount of charred material should be sufficient for radiocarbon dating.

Unit CF3

Bulk sample SLN-R25, collected from scarp colluvium in Unit CF3, yielded only three pieces of charcoal too small for identification and weighing less than 0.0001 g. Numerous uncharred rootlets and a few rocks were the only other remains to be recovered. A very minute quantity of visible charcoal was noted in this sample; however, it was selected for microcharcoal extraction. This sample yielded 0.0345 g of microscopic charcoal that can be submitted for dating.

Unit S2bA

Bulk sample SLN-R26 was taken from an A horizon developed on or within alluvial-fan sediments in Unit S2bA. Five fragments of charred, vitrified tissue were noted in this sample, weighing total of 0.0005 g. No other charred remains were recovered. The sample did contain root fragments and rootlets from modern plants, as well as a few oblong snail shells. It is likely that microscopic charcoal can be extracted from this bulk sample to boost the weight for dating.

Unit S2cA

The nine pieces of charcoal in sample SLN-R24, collected from an A horizon developed on or within alluvial-fan sediments in Unit S2cA, were too small and vitrified for identification. These charcoal fragments yielded a total weight of 0.0012 g, which should be sufficient for AMS radiocarbon dating. Numerous uncharred rootlets, an insect puparium fragment, and a few depressed and oblong snail shells also were noted.

North Creek Trench Site

The North Creek Trench site is located northeast of Mona, Utah, at an elevation of 1730–1740 meters. This elevation is above the highest shoreline of Lake Bonneville. Stream and debris flow (alluvial-fan) deposits and fault scarp-derived colluvium were exposed in the trench. The drainage basin that is the source of the alluvial fan deposits ranges in elevation from 1170–3300 meters. In addition to mountain brush, conifers are noted in the drainage basin. A total of 11 detrital charcoal samples and 13 bulk soil samples were examined from this site.

Unit C1A

Charcoal and bulk sample NC-R14 was taken from an A horizon developed on or within (organic stringer) scarp colluvium in Unit C1A (Table 4). The charcoal sample contained nine fragments of charcoal too small for identification and weighing 0.0006 g (Tables 5 and 3). Because this weight is so close to the minimum weight of 0.0005 g needed for radiocarbon dating, bulk sample NC-R14 was floated. An additional 0.0020 g of unidentifiable charcoal fragments were recovered, for a total charcoal weight of 0.0026 g. This amount should be sufficient for dating. The sample also yielded a moderate amount of root fragments and rootlets, a few sclerotia, a moderate amount of insect puparia, and two snail shell fragments with a depressed shape.

Unit C1

Charcoal sample NC-R28 and bulk sample NC-R20 were recovered from an A horizon developed on or within scarp colluvium in Unit C1. Charcoal sample NC-R28 contained a piece of Asteraceae charcoal weighing 0.0007 g, a piece of *Juniperus* charcoal weighing 0.0024 g, a *Pseudotsuga menziesii* charcoal fragment weighing 0.0016 g, and three pieces of unidentified hardwood charcoal too small for identification and weighing 0.0004 g. Because western juniper and Douglas-fir can be relatively long-lived trees, the Asteraceae charcoal should be combined with the unidentified hardwood charcoal to obtain a total weight of 0.0011 g and submitted for dating.

Bulk sample NC-R20 contained a single charred monocot/herbaceous dicot stem fragment weighing 0.0010 g that can be submitted for dating. Twelve fragments of conifer charcoal weighing 0.0009 g and thirteen pieces of charcoal too small for identification and weighing 0.0005 g also were noted. The single charred stem fragment would be preferential for dating, although the unidentified charcoal can be combined with it for a total weight of 0.0014 g and also sent for dating. The sample yielded a moderate amount of root fragments, numerous rootlets, a moderate amount of insect eggs and insect puparia, a few depressed snail shells, and a single oblong snail shell.

Unit 2d1

Sample NC-R22c consists of detrital charcoal from alluvial fan sediments in Unit 2d1. This sample contained seven pieces of *Juniperus* charcoal, reflecting juniper that burned. These charcoal fragments yielded a total weight of 0.0046 g, which is sufficient for radiocarbon dating.

Unit C2A

Bulk samples NC-R21 and NC-R15 were recovered from an A horizon developed on or within scarp colluvium in Unit C2A. Pieces of *Juniperus* charcoal weighing 0.0069 g also were present in sample NC-R21 that can be submitted for radiocarbon dating. A single piece of *Quercus - Leucobalanus* group charcoal weighing 0.0007 g and three charred dry fruit fragments weighing 0.0008 g also were noted. Because of the potential for long-lived junipers, the *Quercus* charcoal and/or charred unidentified fruit fragments would be the preferred material for dating. Modern plants at the site are reflected by an uncharred Poaceae A floret, an uncharred unidentified dry fruit fragment, numerous root fragments, a few rootlets, and a moderate amount of sclerotia.

The charcoal fragments in sample NC-R15 were too small for identification; however, these charcoal fragments yielded a total weight of 0.0020 g that should be sufficient for radiocarbon dating. The sample also contained a moderate amount of root fragments and rootlets, a few sclerotia, and a few depressed and oblong snail shells.

Unit 2c2A

Bulk sample NC-R16 was taken from an A horizon developed on or within alluvial-fan sediments in Unit 2c2A. Several types of charcoal were noted in this sample, including eight pieces of conifer weighing 0.0027 g, six fragments of *Pseudotsuga menziesii* weighing 0.0016 g, seven fragments of *Quercus* weighing 0.0010 g, two pieces of unidentified hardwood twig charcoal weighing 0.0033 g, fragments of unidentified hardwood charcoal too small for identification weighing 0.0013 g, one piece of vitrified hardwood charcoal weighing 0.0027 g, and two pieces of charcoal too small for identification weighing 0.0008 g. Many of these charcoal types are of a sufficient weight for radiocarbon dating, although the unidentified hardwood twig charcoal is the preferred material for dating. This sample also presents the option of dating some of the charcoal representing longer-lived trees, budget permitting. The advantage in doing this is to have some comparison between dates on the presumably shorter-lived woody plants represented by the unidentified hardwood twig charcoal and the longer-lived *Pseudotsuga* and *Quercus* charcoal fragments to better understand the age offsets that might be typical at this location and represented in other samples.

Charcoal sample NC-R01, charcoal sample NC-R03, and bulk sample NC-R31 were taken from an A horizon developed on or within alluvial-fan sediments in Unit 2c2A. Charcoal sample NC-R01 contained four fragments of unidentified hardwood charcoal weighing 0.0032 g that can be submitted for dating. The three pieces of charred parenchymous tissue in sample NC-R03 weighed a total of 0.0009 g, which should be sufficient for dating.

Several types of charcoal were present in bulk sample NC-R31, including two pieces of Asteraceae weighing 0.0008 g, a single fragment of conifer charcoal weighing less than 0.0001 g, a piece of *Juniperus* charcoal weighing 0.0037 g, two fragments of *Quercus - Leucobalanus* group charcoal weighing 0.0028 g, a small piece of *Quercus* charcoal weighing 0.0001 g, and two pieces of Salicaceae charcoal with a diffuse porous distribution of vessels that weighed 0.0017 g. The Salicaceae charcoal is the preferred material for dating. The Asteraceae charcoal could be combined with the Salicaceae charcoal to provide additional material. In addition, the sample contained a moderate amount of root fragments and rootlets, a moderate amount of sclerotia, a few uncharred bone fragments, numerous insect eggs, a few depressed snail shells, and a moderate amount of worm castings.

Unit CHA

Charcoal sample NC-R02 and bulk sample NC-R32 were collected from an A horizon developed on or within scarp colluvium in Unit CHA. Charcoal in sample NC-R02 consists of three pieces of conifer weighing 0.0005 g, two fragments of *Pseudotsuga menziesii* weighing 0.0002 g, a piece of unidentified hardwood charcoal weighing 0.0006 g, and three fragments of charcoal too small for identification weighing 0.0002 g. These charcoal types can be combined to produce a total weight of 0.0015 g that can be sent for radiocarbon dating.

Charred remains noted in bulk sample NC-R32 include three pieces of parenchymous tissue weighing 0.0029 g, six fragments of conifer charcoal weighing 0.0066 g, a piece of *Juniperus* charcoal weighing 0.0020 g, four pieces of *Pseudotsuga menziesii* charcoal weighing 0.0057 g, ten fragments of *Quercus* charcoal weighing 0.0083 g, a single Rosaceae twig charcoal fragment weighing 0.0016 g, and four fragments of unidentified hardwood charcoal weighing 0.0038 g. Although all of these charcoal types are present in sufficient quantities for dating, the single piece of Rosaceae twig charcoal is the preferred charcoal type for dating. Most woody members of the rose family have short to moderate lifespans and single pieces of charcoal are preferable for dating, when they exist. The sample also contained a moderate amount of root fragments and rootlets, a few sclerotia, three snail shells with a depressed shape, and a moderate amount of worm castings.

Unit C3A

Bulk samples NC-R23 and NC-R18 were taken from an A horizon developed on or within scarp colluvium in Unit C3A. Sample NC-R23 yielded several types of charcoal, including ten fragments of conifer weighing 0.0017 g, four fragments of *Juniperus* weighing 0.0035 g, four pieces of *Pseudotsuga menziesii* weighing 0.0010 g, eight fragments of *Quercus* weighing 0.0016 g, a piece of *Quercus* - *Leucobalanus* group charcoal weighing less than 0.0001 g, a piece of Salicaceae weighing 0.0001 g, several fragments of unidentified hardwood charcoal weighing 0.0026 g, and eight pieces of charcoal too small for identification weighing 0.0011 g. Recovery of five uncharred *Artemisia* wood fragments notes modern sagebrush in the area, while several uncharred fragments of conifer wood reflect modern conifers. To be consistent with recommendations for other samples, the unidentified hardwood charcoal is the preferred charcoal type for AMS radiocarbon dating. If desired, the small quantities of *Quercus* and Salicaceae charcoal may be added to this charcoal to increase the sample weight. A single charred Poaceae B caryopsis fragment weighing 0.0001 g reflects grasses that burned. The sample also yielded a moderate amount of uncharred root fragments, a few rootlets, a moderate amount of sclerotia, a few insect chitin fragments, and a few depressed-shaped snail shells.

The four pieces of conifer charcoal weighing 0.0008 g, the two fragments of unidentified hardwood charcoal weighing 0.0004 g, and the two fragments of charcoal too small for identification weighing 0.0003 g in sample NC-R18 could be added together to obtain 0.0015 g of charcoal for radiocarbon dating. Other items noted in this sample include a moderate amount of root fragments and rootlets, numerous sclerotia, a few depressed snail shells, and several oblong snail shells.

Unit C4A

Bulk sample NC-R29 was recovered from an A horizon developed on or within scarp colluvium in Unit C4A. Small fragments of conifer charcoal weighing 0.0013 g, two pieces of *Juniperus* charcoal weighing 0.0101 g, a fragment of *Pseudotsuga menziesii* charcoal weighing 0.0001 g, nine *Quercus* charcoal fragments weighing 0.0012 g, and two pieces of hardwood charcoal too small for further identification weighing 0.0007 g were noted in this sample and reflect juniper, Douglas-fir, possibly another type of conifer, oak, and possibly another type of hardwood that burned. The *Quercus* charcoal is the preferred charcoal for dating. The unidentified hardwood charcoal could be added to the *Quercus* charcoal to provide additional material for dating. Uncharred conifer wood fragments again note modern conifers. In addition, the sample contained root fragments, rootlets, sclerotia, a few insect chitin fragments, and a single oblong-shaped snail shell.

Unit C4

Sample NC-R13 consists of charcoal from an A horizon developed on or within scarp colluvium in Unit C4. Nine fragments of vitrified unidentified hardwood charcoal weighing 0.0021 g can be submitted for radiocarbon dating. A few uncharred periderm fragments and two sclerotia also were noted.

Unit 2bA

Bulk sample NC-R19 was collected from an A horizon developed on or within alluvial-fan sediments in Unit 2bA. Several charred fragments of a dry fruit (0.0090 g) and 14 pieces of unidentified hardwood charcoal (0.0057 g) are present in sufficient quantities for radiocarbon dating. The charred dry fruit fragments represent an annual that can be dated, while dating the unidentified hardwood charcoal would be more consistent with wood charcoal selected for dating from other samples. In addition, the sample contained two pieces of conifer charcoal weighing 0.0009 g, three fragments of charcoal too small for identification weighing 0.0006 g, a moderate amount of root fragments and rootlets, numerous sclerotia, a moderate amount of snail shells with a depressed shape, and several snail shells with an oblong shape.

Unit 1bA

Charcoal samples NC-R05, NC-R07, and NC-R09 were taken from an A horizon developed on or within alluvial-fan sediments in Unit 1bA. All three samples yielded sufficient charcoal for AMS radiocarbon dating. Sample NC-R05 contained 20 pieces of unidentified hardwood charcoal weighing 0.0093 g. The nine fragments of *Quercus* charcoal in sample NC-R07 yielded a total weight of 0.0035 g, while the 10 pieces of *Quercus* charcoal in sample NC-R09 weighed a total of 0.0042 g.

Unit 1c4A

Samples NC-R12 and NC-R11 also were collected from an A horizon developed on or within alluvial-fan sediments. Bulk sample NC-R12 contained several fragments of charcoal too small for identification that weighed a total of 0.0008 g. This weight may be sufficient for AMS radiocarbon dating. The sample also yielded root fragments, rootlets, sclerotia, and an oblong snail shell and snail shell fragment.

Charcoal sample NC-R11 contained only a few pieces of uncharred periderm and three sclerotia. As a result, bulk sample NC-R11 was floated. The bulk sample contained six pieces of conifer charcoal weighing 0.0021 g, as well as seven fragments of charcoal too small for identification weighing 0.0004 g. The conifer charcoal is present in sufficient quantity for radiocarbon dating. Other remains noted in the sample include root fragments, rootlets, numerous sclerotia, a few insect chitin fragments, and a few depressed and oblong snail shells.

SUMMARY AND CONCLUSIONS

Examination of detrital charcoal samples and flotation of bulk samples from trenches at the Spring Lake North (SPL) site and the North Creek (NC) site on the northern and southern parts of the Nephi segment of the Wasatch Fault, Utah, resulted in recovery of charcoal and other charred botanic remains that can be sent for radiocarbon dating to investigate the timing of Holocene surface-faulting earthquakes in the area. A total of 17 samples yielded macroscopic charcoal in sufficient quantities for AMS radiocarbon dating. The charcoal types represent woody vegetation found in either the trench sites or the drainage basins identified as the sources of the alluvial-fan deposits. Fewer fragments of charcoal and fewer charcoal types were noted in the Spring Lake North samples. The majority of the charcoal fragments in the SLN samples were too small for identification. Identifiable pieces of *Artemisia* and Asteraceae charcoal reflect sagebrush and another woody member of the sunflower family. A few fragments of charcoal could at least be identified as a type of hardwood. In order to obtain sufficient charred material for radiocarbon dating, sample SLN-R25 was processed to extract microscopic charcoal. A total of 0.0345 g of microcharcoal was recovered, which can be submitted for dating.

By comparison, samples from the North Creek site yielded a variety of charcoal, including conifers from the drainage basin. Ten of the NC samples contained charcoal identified only as conifer, while identifiable juniper charcoal was present in 7 samples and identifiable Douglas-fir charcoal was noted in six samples. Oak charcoal was found in seven of the NC samples, and three samples yielded oak charcoal identifiable as part of the white oak group. Charcoal from a woody member of the sunflower family and charcoal from a woody member of the willow family were noted in two samples each. A single sample contained a twig fragment from a woody member of the rose family. Twelve samples contained pieces of hardwood charcoal, while charcoal in eleven of the samples was too small for identification. All of the samples from the North Creek site contained charcoal or other charred botanic material in sufficient quantities for dating.

TABLE 1
PROVENIENCE DATA FOR SAMPLES FROM THE SPRING LAKE NORTH TRENCH SITE
ON THE NEPHI SEGMENT OF THE WASATCH FAULT ZONE, UTAH

Sample No.	Wall	Unit	Relation to Earthquake	Description/ Provenience	Analysis
SLN-R15	South	C1A	Min P1	A horizon developed on or within (organic stringer) scarp colluvium	Float
SLN-R16				A horizon developed on or within (organic stringer) scarp colluvium	Float
SLN-R13		C1		Scarp colluvium	Float
SLN-R21	North			Charcoal and scarp colluvium	Charcoal ID/Float
SLN-R23		C2A	Min P2, Max P1	A horizon developed on or within scarp colluvium	Float
SLN-R17	South			A horizon developed on or within scarp colluvium	Float
SLN-R18				A horizon developed on or within scarp colluvium	Float
SLN-R22	North	C2		Scarp-derived colluvial wedge	Float
SLN-R19	South	C3A	Min P3, Max P2	A horizon developed on or within scarp colluvium	Float
SLN-R27	North	N3g		Alluvial fan sediments	Float
SLN-R20	South	C4	Min P4, Max P3	Scarp colluvium	Float
SLN-R05		S3g/h / N3e	Min P5, Max P4	Detrital charcoal from alluvial-fan sediments	Charcoal ID
SLN-R06				Detrital charcoal from alluvial-fan sediments	Charcoal ID
SLN-R11		S3h1		Detrital charcoal from alluvial-fan sediments	Float
SLN-R02		S3bA	Min P6, Max P5	Detrital charcoal from A horizon developed on or within alluvial-fan sediments	Charcoal ID
SLN-R01		S3d		Detrital charcoal from alluvial-fan sediments	Charcoal ID
SLN-R03				Detrital charcoal from alluvial-fan sediments	Charcoal ID

TABLE 1 (Continued)

Sample No.	Wall	Unit	Relation to Earthquake	Description/ Provenience	Analysis
SLN-R04	South	S3d	Min P6, Max P5	Detrital charcoal from alluvial-fan sediments	Charcoal ID
SLN-R09	North	C6	Min P6, Max P5	Charcoal and scarp colluvium	Charcoal ID/Float
SLN-R10				Scarp colluvium	Float
SLN-R25	South		Min CF3	Scarp colluvium	Float Microcharcoal
SLN-R26		S2bA	Max CF3	A horizon developed on or within alluvial-fan sediments	Float
SLN-R24		S2cA		A horizon developed on or within alluvial-fan sediments	Float

CF = Earthquake related to footwall colluvial wedge deposits (correlation to P1-P6 not known)

TABLE 2
MACROFLORAL REMAINS FROM THE SPRING LAKE NORTH TRENCH SITE
ON THE NEPHI SEGMENT OF THE WASATCH FAULT ZONE, UTAH

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
SLN-R15	Liters Floated						1.50 L
Unit C1A	Light Fraction Weight						0.934 g
Min P1	FLORAL REMAINS:						
	Lactuca	Seed			1		
	Poaceae A	Floret			1		
	Roots					X	Few
	Rootlets					X	Numerous
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.25 mm						0.0011 g
	Unidentifiable -small	Charcoal		X			0.0011 g
	NON-FLORAL REMAINS:						
	Insect	Chitin				X	Few
	Insect	Puparia			2		
	Rock					X	Moderate
	Snail shell - depressed ≥ 1 mm				32	9	
	Snail shell - depressed < 1 mm				X	X	Few
	Snail shell - oblong ≥ 0.5 mm				5	2	
SLN-R16	Liters Floated						1.30 L
Unit C1A	Light Fraction Weight						0.452 g
Min P1	FLORAL REMAINS:						
	Poaceae	Stem				2	0.0051 g
	Roots					X	Few
	Rootlets					X	Numerous
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.25 mm						0.0019 g
	Unidentifiable - small	Charcoal		X			0.0019 g
	NON-FLORAL REMAINS:						
	Rock					X	Numerous
	Snail shell - depressed ≥ 1 mm				26	11	
	Snail shell - depressed < 1 mm				X	X	Numerous
	Snail shell - oblong ≥ 0.5 mm				4		
	Snail shell - oblong < 0.5 mm					X	Few

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
SLN-R13	Liters Floated						1.90 L
Unit C1	Light Fraction Weight						1.587 g
Min P1	FLORAL REMAINS:						
	Monocot/Herbaceous dicot	Stem		23			0.0026 g
	Unidentified	Seed		1			< 0.0001 g
	Roots					X	Moderate
	Rootlets					X	Numerous
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.5 mm						0.0016 g
	Asteraceae	Charcoal		2			0.0016 g
	NON-FLORAL REMAINS:						
	Insect	Puparia			1		
	Rock					X	Moderate
	Snail shell - depressed ≥ 1 mm				36	28	
	Snail shell - depressed < 1 mm				X	X	Moderate
	Snail shell - oblong ≥ 0.5 mm				7		
SLN-R21	Bulk Sample Liters Floated						1.10 L
Unit C1	Bulk Sample Light Fraction Weight						0.775 g
Min P1	Charcoal Sample Weight						0.002 g
	FLORAL REMAINS:						
	Roots					X	Moderate
	Rootlets					X	Numerous
	Sclerotia				X	X	Few
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.25 mm						0.0009 g
	Unidentified hardwood twig	Charcoal		X			0.0009 g
	NON-FLORAL REMAINS:						
	Rock					X	Few
SLN-R23	Liters Floated						1.00 L
Unit C2A	Light Fraction Weight						0.869 g
Min P2,	FLORAL REMAINS:						
Max P1	Roots					X	Few
	Rootlets					X	Moderate

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
SLN-R23	CHARCOAL/WOOD:						
Unit C2A	Total charcoal ≥ 0.25 mm						0.0005 g
Min P2,	Unidentifiable - small	Charcoal		15			0.0005 g
Max P1	NON-FLORAL REMAINS:						
	Insect	Chitin				X	Few
	Insect	Puparia			2		
	Rock					X	Moderate
	Snail shell - depressed ≥ 0.5 mm					2	
	Snail shell - depressed < 0.5 mm					X	Few
SLN-R17	Liters Floated						1.80 L
Unit C2A	Light Fraction Weight						0.769 g
Min P2,	FLORAL REMAINS:						
Max P1	Roots					X	Few
	Rootlets					X	Numerous
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.5 mm						0.0074 g
	Artemisia	Charcoal		36			0.0074 g
	NON-FLORAL REMAINS:						
	Insect	Chitin				X	Few
	Rock					X	Numerous
	Snail shell - depressed ≥ 1 mm				23		
	Snail shell - depressed < 1 mm				X	X	Numerous
	Snail shell - oblong ≥ 0.5 mm				13	15	
	Snail shell - oblong < 0.5 mm					X	Few
SLN-R18	Liters Floated						1.40 L
Unit C2A	Light Fraction Weight						1.828 g
Min P2,	FLORAL REMAINS:						
Max P1	Roots					X	Few
	Rootlets					X	Numerous
	Sclerotia				X	X	Few
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.25 mm						0.0014 g
	Unidentifiable - small	Charcoal		X			0.0014 g

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
SLN-R18	NON-FLORAL REMAINS:						
Unit C2A	Insect	Chitin				X	Few
Min P2,	Insect	Puparia			1		
Max P1	Rock					X	Moderate
	Snail shell - depressed ≥ 1 mm				2		
	Snail shell - depressed < 1 mm				2	X	Few
	Snail shell - oblong ≥ 0.5 mm				27	26	
	Worm castings				X	X	Moderate
SLN-R22	Liters Floated						0.80 L
Unit C2	Light Fraction Weight						0.950 g
Min P2,	FLORAL REMAINS:						
Max P1	Roots					X	Few
	Rootlets					X	Numerous
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.25 mm						0.0010 g
	Unidentifiable - small, vitrified	Charcoal		10			0.0002 g
	Unidentifiable twig - vitrified	Charcoal		1			0.0008 g
	NON-FLORAL REMAINS:						
	Rock/Gravel					X	Moderate
	Snail shell - depressed				X	X	Few
	Snail shell - oblong				1		
SLN-R19	Liters Floated						1.50 L
Unit C3A	Light Fraction Weight						0.950 g
Min P3,	FLORAL REMAINS:						
Max P2	Parenchymous tissue ≥ 0.25 mm			4			0.0008 g
	Roots					X	Few
	Rootlets					X	Numerous
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.25 mm						0.0010 g
	Unidentifiable - small	Charcoal		X			0.0010 g

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
SLN-R19	NON-FLORAL REMAINS:						
Unit C3A	Bone ≥ 1 mm					1	0.0003 g
Min P3,	Bone < 1 mm					2	
Max P2	Rock					X	Moderate
	Snail shell - depressed ≥ 1 mm				15	3	
	Snail shell - depressed < 1 mm				X	X	Moderate
	Snail shell - oblong ≥ 0.5 mm				3	2	
SLN-R27	Liters Floated						1.10 L
Unit N3g	Light Fraction Weight						0.707 g
Min P3,	FLORAL REMAINS:						
Max P2	Rootlets					X	Numerous
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.25 mm						0.0010 g
	Unidentifiable - small	Charcoal		X			0.0010 g
	NON-FLORAL REMAINS:						
	Rock					X	Moderate
	Snail shell - depressed ≥ 0.25 mm				1		
	Snail shell - oblong ≥ 0.5 mm				6	1	
SLN-R20	Liters Floated						1.30 L
Unit C4	Light Fraction Weight						0.869 g
Min P4,	FLORAL REMAINS:						
Max P3	Roots					X	Moderate
	Rootlets					X	Numerous
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.25 mm						0.0008 g
	Unidentifiable - small	Charcoal		X			0.0008 g
	NON-FLORAL REMAINS:						
	Rock					X	Moderate
	Snail shell - depressed ≥ 1 mm				1		
	Snail shell - depressed < 1 mm					X	Few
	Snail shell - oblong ≥ 0.5 mm				1		

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
SLN-R05	Sample Weight						0.019 g
Unit S3g/h / N3e	CHARCOAL/WOOD:						
	Unidentifiable - small	Charcoal		6			< 0.0001 g
	NON-FLORAL REMAINS:						
	Sediment					X	Few
SLN-R06	Sample Weight						0.035 g
Unit S3g/h / N3e	FLORAL REMAINS:						
	Unidentifiable - small	Tissue		2			< 0.0001 g
	NON-FLORAL REMAINS:						
	Sediment					X	Few
SLN-R11	Liters Floated						1.20 L
Unit S3h1 Min P5 Max P4	Light Fraction Weight						0.187 g
	FLORAL REMAINS:						
	Roots					X	Few
	Rootlets					X	Moderate
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.25 mm						0.0022 g
	Unidentifiable - small, vitrified	Charcoal		X			0.0022 g
	NON-FLORAL REMAINS:						
	Rock					X	Moderate
SLN-R02	Sample Weight						0.991 g
Unit S3bA Min P6, Max P5	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.25 mm						0.0012 g
	Unidentifiable - vitrified	Charcoal		31			0.0012 g
	NON-FLORAL REMAINS:						
	Rock/Sand					X	Few
SLN-R01	Sample Weight						0.176 g
Unit S3d Min P6, Max P5	FLORAL REMAINS:						
	Parenchymous tissue			1			0.0018 g
	NON-FLORAL REMAINS:						
	Sand					X	Few
SLN-R03	Sample Weight						0.001 g
Unit S3d	CHARCOAL/WOOD:						
	Unidentified hardwood twig	Charcoal		1			0.0012 g

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
SLN-R04	Sample Weight						0.026 g
Unit S3d	CHARCOAL/WOOD:						
Min P6,	Total charcoal ≥ 0.25 mm						0.0009 g
Max P5	Unidentified hardwood - small	Charcoal		X			0.0009 g
SLN-R09	Bulk Sample Liters Floated						1.50 L
Unit C6	Bulk Sample Light Fraction Weight						2.575 g
Min P6,	Charcoal Sample Weight						0.007 g
Max P5	FLORAL REMAINS:						
	Roots					X	Few
	Rootlets					X	Moderate
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.25 mm						< 0.0001 g
	Unidentifiable - small	Charcoal		5			< 0.0001 g
	NON-FLORAL REMAINS:						
	Rock/Sand					X	Moderate
SLN-R10	Liters Floated						1.50 L
Unit C6	Light Fraction Weight						1.681 g
Min P6,	FLORAL REMAINS:						
Max P5	Parenchymous tissue ≥ 0.5 mm			5			< 0.0001 g
	Vitrified tissue ≥ 0.5 mm			5			0.0007 g
	Roots					X	Moderate
	Rootlets					X	Numerous
	NON-FLORAL REMAINS:						
	Gravel/Sand					X	Moderate
	Snail shell - depressed ≥ 1 mm				1		
SLN-R25	Liters Floated						0.90 L
Min CF3	Light Fraction Weight						0.533 g
	FLORAL REMAINS:						
	Rootlets					X	Numerous
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.25 mm						< 0.0001 g
	Unidentifiable - small	Charcoal		3			< 0.0001 g
SLN-R25	NON-FLORAL REMAINS:						
	Rock					X	Moderate

TABLE 2 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
SLN-R26	Liters Floated						0.70 L
Unit S2bA Min CF3	Light Fraction Weight						0.173 g
	FLORAL REMAINS:						
	Vitrified tissue ≥ 0.25 mm			5			0.0005 g
	Roots					X	Few
	Rootlets					X	Moderate
	NON-FLORAL REMAINS:						
	Rock/Gravel					X	Moderate
	Snail shell - oblong ≥ 0.5 mm				2	3	
SLN-R24	Liters Floated						1.00 L
Unit S2cA Min CF3	Light Fraction Weight						0.485 g
	FLORAL REMAINS:						
	Rootlets					X	Numerous
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.25 mm						0.0012 g
	Unidentifiable - small, vitrified	Charcoal		9			0.0012 g
	NON-FLORAL REMAINS:						
	Insect	Puparia				1	
	Rock					X	Moderate
	Snail shell - depressed ≥ 1 mm				3		
	Snail shell - depressed < 1 mm					X	Few
	Snail shell - oblong ≥ 0.5 mm				2	3	

W = Whole
F = Fragment
g = grams
L = liters
mm = millimeters
X = Presence noted in sample

TABLE 3
INDEX OF MACROFLORAL REMAINS RECOVERED FROM
THE SPRING LAKE NORTH TRENCH SITE AND THE NORTH CREEK TRENCH SITE
ON THE NEPHI SEGMENT OF THE WASATCH FAULT ZONE, UTAH

Scientific Name	Common Name
FLORAL REMAINS:	
Lactuca	Lettuce
Monocot/Herbaceous dicot	A member of the Monocotyledonae class of Angiosperms, which include grasses, sedges, members of the agave family, lilies, and palms/ A non-woody member of the Dicotyledonae class of Angiosperms
Periderm	Technical term for bark; Consists of the cork (phellum) which is produced by the cork cambium, as well as any epidermis, cortex, and primary or secondary phloem exterior to the cork cambium
Poaceae	Grass family
Poaceae A	Members of the grass family with larger-sized caryopses, such as *Agropyron* (wheatgrass), *Elymus* (ryegrass), *Bromus* (brome grass), etc.
Poaceae B	Members of the grass family with medium-sized caryopses, such as *Festuca* (fescue), *Hordeum* (wild barley), *Stipa* (needlegrass), etc.
Parenchymous tissue	Relatively undifferentiated tissue composed of many similar cells with thin primary walls–occurs in different plant organs in varying amounts, especially large fleshy organs such as roots and stems, but also fruits, seeds, cones, periderm (bark), leaves, needles, etc.
Vitrified tissue	Charred material with a shiny, glassy appearance due to fusion by heat
Sclerotia	Resting structures of mycorrhizae fungi
CHARCOAL/WOOD:	
Asteraceae	Sunflower family
Artemisia	Sagebrush
Conifer	Cone-bearing, gymnospermous trees and shrubs, mostly evergreens, including the pine, spruce, fir, juniper, cedar, yew, hemlock, redwood, and cypress
Juniperus	Juniper
Pseudotsuga menziesii	Douglas-fir

TABLE 3 (Continued)

Scientific Name	Common Name
Quercus	Oak
Quercus - *Leucobalanus* group	White oak group - Species in the white oak group exhibit earlywood vessels occluded with tyloses, thin-walled and angular latewood vessels, and longer rays than species in the red oak group
Salicaceae	Willow 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 - small	Charcoal fragments too small for further identification
Unidentifiable - vitrified	Charcoal exhibiting a shiny, glassy appearance due to fusion by heat
NON-FLORAL REMAINS:	
Chitin	A natural polymer found in insect and crustacean exoskeleton
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
Snail shell - depressed	Snail shell with a depressed (flat) shape where the width is much bigger than the height
Snail shell - oblong	Snail shell with an oblong shape where the height is much bigger than the width

TABLE 4
PROVENIENCE DATA FOR SAMPLES FROM THE NORTH CREEK TRENCH SITE
ON THE NEPHI SEGMENT OF THE WASATCH FAULT ZONE, UTAH

Sample No.	Wall	Unit	Relation to Earthquake	Description/ Provenience	Analysis
NC-R14	South	C1A	Min P1	Charcoal and A horizon developed on or within (organic stringer) scarp colluvium	Charcoal ID/Float
NC-R28		C1		Charcoal and A horizon developed on or within scarp colluvium	Charcoal ID
NC-R20	North			A horizon developed on or within scarp colluvium	Float
NC-R22c		2d1		Detrital charcoal from alluvial fan sediments	Charcoal ID
NC-R21		C2A	Min P2, Max P1	A horizon developed on or within scarp colluvium	Float
NC-R15	South			A horizon developed on or within scarp colluvium	Float
NC-R16		2c2A	Max P2	A horizon developed on or within alluvial-fan sediments	Float
NC-R03			Max CH	Detrital charcoal from A horizon developed on or within alluvial-fan sediments	Charcoal ID
NC-R31	North			A horizon developed on or within alluvial-fan sediments	Float
NC-R01	South	CHA	Min CH	Detrital charcoal from A horizon developed on or within alluvial-fan sediments	Charcoal ID
NC-R02			Min CH	Detrital charcoal from A horizon developed on or within scarp colluvium	Charcoal ID
NC-R32	North			A horizon developed on or within scarp colluvium	Float
NC-R23		C3A	Min P3, Max P2	A horizon developed on or within scarp colluvium	Float
NC-R18	South		Min P3	A horizon developed on or within scarp colluvium	Float

TABLE 4 (Continued)

Sample No.	Wall	Unit	Relation to Earthquake	Description/ Provenience	Analysis
NC-R29	North	C4A	Min P4, Max P3	A horizon developed on or within scarp colluvium	Float
NC-R13	South	C4	Min P4	Charcoal and A horizon developed on or within scarp colluvium	Charcoal ID
NC-R19		2bA		A horizon developed on or within alluvial-fan sediments	Float
NC-R05		1bA	Max P4	Detrital charcoal from A horizon developed on or within alluvial-fan sediments	Charcoal ID
NC-R07				Detrital charcoal from A horizon developed on or within alluvial-fan sediments	Charcoal ID
NC-R09				Detrital charcoal from A horizon developed on or within alluvial-fan sediments	Charcoal ID
NC-R12		1c4A?		A horizon developed on or within alluvial-fan sediments	Float
NC-R11	North			Charcoal and A horizon developed on or within alluvial-fan sediments	Charcoal ID/Float

CH = Earthquake related to hanging-wall colluvial wedge deposits (likely corresponds to P1 or P2)

TABLE 5
MACROFLORAL REMAINS FROM THE NORTH CREEK TRENCH SITE
ON THE NEPHI SEGMENT OF THE WASATCH FAULT ZONE, UTAH

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
NC-R14	Bulk Sample Liters Floated						2.60 L
Unit C1A	Bulk Sample Light Fraction Weight						1.037 g
Min P1	Charcoal Sample Weight						0.010 g
	FLORAL REMAINS:						
	Roots					X	Moderate
	Rootlets					X	Moderate
	Sclerotia				X	X	Few
	CHARCOAL/WOOD:						
	Total charcoal ≥ 2 mm						0.0026 g
	Unidentifiable - small	Charcoal		X			0.0026 g
	NON-FLORAL REMAINS:						
	Insect						
	Rock/Gravel						
	Snail shell - depressed ≥ 0.5 mm					2	
NC-R28	Sample Weight						0.005 g
Unit C1	CHARCOAL/WOOD:						
Min P1	Total charcoal ≥ 0.25 mm						0.0051 g
	Asteraceae	Charcoal		1			0.0007 g
	Juniperus	Charcoal		1			0.0024 g
	Pseudotsuga menziesii	Charcoal		1			0.0016 g
	Unidentified hardwood - small	Charcoal		3			0.0004 g
NC-R20	Liters Floated						1.80 L
Unit C1	Light Fraction Weight						1.513 g
Min P1	FLORAL REMAINS:						
	Monocot/Herbaceous dicot	Stem		1			0.0010 g
	Roots					X	Moderate
	Rootlets					X	Numerous
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.25 mm						0.0014 g
	Conifer	Charcoal		12			0.0009 g
	Unidentifiable - small	Charcoal		13			0.0005 g

TABLE 5 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
NC-R20	NON-FLORAL REMAINS:						
Unit C1A	Insect	Egg			X		Moderate
Min P1	Insect	Puparia			X	X	Moderate
	Rock					X	Numerous
	Snail shell - depressed ≥ 1 mm				3		
	Snail shell - depressed < 1 mm					X	Few
	Snail shell - oblong ≥ 0.5 mm				1		
NC-R22-c	Sample Weight						0.962 g
Unit 2d1	CHARCOAL/WOOD:						
Min P1	Total charcoal ≥ 1 mm						0.0046 g
	Juniperus	Charcoal		7			0.0046 g
	NON-FLORAL REMAINS:						
	Rock/Sand					X	Few
NC-R21	Liters Floated						2.30 L
Unit C2a	Light Fraction Weight						2.251 g
Min P2,	FLORAL REMAINS:						
Max P1	Unidentified B	Fruit		3			0.0008 g
	Poaceae A	Floret			1		0.0021 g
	Unidentified	Fruit			1		0.0012 g
	Roots					X	Numerous
	Rootlets					X	Few
	Sclerotia				X	X	Moderate
	CHARCOAL/WOOD:						
	Total charcoal ≥ 1 mm						0.0076 g
	Juniperus	Charcoal		13			0.0069 g
	Quercus - Leucobalanus group	Charcoal		1			0.0007 g
	NON-FLORAL REMAINS:						
	Rock					X	Numerous
NC-R15	Liters Floated						2.20 L
Unit C2a	Light Fraction Weight						1.515 g
Min P2,	FLORAL REMAINS:						
Max P1	Roots					X	Moderate
	Rootlets					X	Moderate
	Sclerotia				X	X	Few

TABLE 5 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
NC-R15	CHARCOAL/WOOD:						
Unit C2a	Total charcoal ≥ 0.25 mm						0.0020 g
Min P2,	Unidentifiable - small	Charcoal		X			0.0020 g
Max P1	NON-FLORAL REMAINS:						
	Rock/Gravel					X	Numerous
	Snail shell - depressed ≥ 1 mm				1		
	Snail shell - depressed < 1 mm				X	X	Few
	Snail shell - oblong ≥ 0.5 mm				2	8	
NC-R16	Liters Floated						2.10 L
Unit 2c2A	Light Fraction Weight						3.046 g
Max P2	FLORAL REMAINS:						
	Roots					X	Numerous
	Rootlets					X	Few
	Sclerotia				X	X	Numerous
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.5 mm						0.0134 g
	Conifer	Charcoal		8			0.0027 g
	Pseudotsuga menziesii	Charcoal		6			0.0016 g
	Quercus	Charcoal		7			0.0010 g
	Unidentified hardwood twig	Charcoal		2			0.0033 g
	Unidentified hardwood - small	Charcoal		6			0.0013 g
	Unidentified hardwood - vitrified	Charcoal		1			0.0027 g
	Unidentifiable - small	Charcoal		2			0.0008 g
	NON-FLORAL REMAINS:						
	Rock					X	Numerous
	Snail shell - depressed ≥ 1 mm					1	
NC-R02	Sample Weight						0.008 g
Unit CHA	CHARCOAL/WOOD:						
Min CH	Total charcoal ≥ 0.25 mm						0.0015 g
	Conifer	Charcoal		3			0.0005 g
	Pseudotsuga menziesii	Charcoal		2			0.0002 g
	Unidentified hardwood - small	Charcoal		1			0.0006 g
	Unidentifiable - small	Charcoal		3			0.0002 g

TABLE 5 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
NC-R32	Liters Floated						1.00 L
Unit CHA	Light Fraction Weight						1.090 g
Min CH	FLORAL REMAINS:						
	Parenchymous tissue ≥ 1 mm			3			0.0029 g
	Roots					X	Moderate
	Rootlets					X	Moderate
	Sclerotia				X	X	Few
	CHARCOAL/WOOD:						
	Total charcoal ≥ 1 mm						0.0280 g
	Conifer	Charcoal		6			0.0066 g
	Juniperus	Charcoal		1			0.0020 g
	Pseudotsuga menziesii	Charcoal		4			0.0057 g
	Quercus	Charcoal		10			0.0083 g
	Rosaceae - twig	Charcoal		1			0.0016 g
	Unidentified hardwood - small	Charcoal		4			0.0038 g
	NON-FLORAL REMAINS:						
	Rock/Gravel					X	Moderate
	Snail shell - depressed ≥ 1 mm				2		
	Snail shell - depressed < 1 mm				1		
	Worm castings					X	Moderate
NC-R01	Sample Weight						0.007 g
Unit 2c2A	CHARCOAL/WOOD:						
Min CH	Unidentified hardwood	Charcoal		4			0.0032 g
NC-R03	Sample Weight						0.003 g
Unit 2c2A	FLORAL REMAINS:						
Max CH	Parenchymous tissue			3			0.0009 g
	NON-FLORAL REMAINS:						
	Rock/Sand					X	Few
NC-R31	Liters Floated						1.00 L
Unit 2c2A	Light Fraction Weight						1.008 g
Max CH	FLORAL REMAINS:						
	Roots					X	Moderate
	Rootlets					X	Moderate
	Sclerotia				X	X	Moderate

TABLE 5 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
NC-R31	CHARCOAL/WOOD:						
Unit 2c2A	Total charcoal ≥ 1 mm						0.0091 g
Max CH	Asteraceae	Charcoal		2			0.0008 g
	Conifer	Charcoal		1			< 0.0001 g
	Juniperus	Charcoal		1			0.0037 g
	Quercus	Charcoal		1			0.0001 g
	Quercus - Leucobalanus group	Charcoal		2			0.0028 g
	Salicaceae	Charcoal		2			0.0017 g
	NON-FLORAL REMAINS:						
	Bone ≥ 1 mm					3	
	Bone < 1 mm					X	Few
	Insect	Egg			X	X	Numerous
	Rock/Gravel					X	Moderate
	Snail shell - depressed ≥ 1 mm					3	
	Snail shell - depressed < 1 mm					X	Few
	Worm castings				X	X	Moderate
NC-R23	Liters Floated						1.90 L
Unit C3A	Light Fraction Weight						2.434 g
Min P3,	FLORAL REMAINS:						
Max P2	Poaceae B	Caryopsis		1			0.0001 g
	Roots					X	Moderate
	Rootlets					X	Few
	Sclerotia				X	X	Moderate
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.5 mm						0.0116 g
	Conifer	Charcoal		10			0.0017 g
	Juniperus	Charcoal		4			0.0035 g
	Pseudotsuga menziesii	Charcoal		4			0.0010 g
	Quercus	Charcoal		8			0.0016 g
	Quercus - Leucobalanus group	Charcoal		1			< 0.0001 g
	Salicaceae	Charcoal		1			0.0001 g
	Unidentified hardwood - small	Charcoal		13			0.0026 g
	Unidentifiable - small	Charcoal		8			0.0011 g

TABLE 5 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
NC-R23	Total wood ≥ 2 mm						0.1091 g
Unit C3A	*Artemisia*	Wood				5	0.0131 g
Min P3,	Conifer	Wood				25	0.0960 g
Max P2	NON-FLORAL REMAINS:						
	Insect	Chitin				X	Few
	Rock					X	Numerous
	Snail shell - depressed ≥ 1 mm				2		
	Snail shell - depressed < 1 mm				X	X	Few
NC-R18	Liters Floated						2.00 L
Unit C3A	Light Fraction Weight						2.392 g
Min P3	FLORAL REMAINS:						
	Roots					X	Moderate
	Rootlets					X	Moderate
	Sclerotia				X	X	Numerous
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.5 mm						0.0015 g
	Conifer	Charcoal		4			0.0008 g
	Unidentified hardwood - small	Charcoal		2			0.0004 g
	Unidentifiable - small	Charcoal		2			0.0003 g
	NON-FLORAL REMAINS:						
	Rock/Gravel					X	Numerous
	Snail shell - depressed ≥ 0.5 mm				2	4	
	Snail shell -oblong ≥ 0.5 mm				10	22	
NC-R29	Liters Floated						1.50 L
Unit C4A	Light Fraction Weight						2.723 g
Min P4,	FLORAL REMAINS:						
Max P3	Roots					X	Moderate
	Rootlets					X	Few
	Sclerotia				X	X	Moderate

TABLE 5 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
NC-R29	CHARCOAL/WOOD:						
Unit C4A	Total charcoal ≥ 0.5 mm						0.0134 g
Min P4,	Conifer	Charcoal		16			0.0013 g
Max P3	*Juniperus*	Charcoal		2			0.0101 g
	Pseudotsuga menziesii	Charcoal		1			0.0001 g
	Quercus	Charcoal		9			0.0012 g
	Unidentified hardwood - small	Charcoal		2			0.0007 g
	Total wood ≥ 4 mm						0.2235 g
	Conifer	Wood				6	0.2235 g
	NON-FLORAL REMAINS:						
	Insect	Chitin				X	Few
	Rock					X	Numerous
	Snail shell - oblong ≥ 0.5 mm				1		
NC-R13	Sample Weight						0.008 g
Unit C4	FLORAL REMAINS:						
Min P4	Periderm					X	Few
	Sclerotia				2		
	CHARCOAL/WOOD:						
	Unidentified hardwood - vitrified	Charcoal		9			0.0021 g
	NON-FLORAL REMAINS:						
	Sand					X	Few
NC-R19	Liters Floated						1.50 L
Unit 2bA	Light Fraction Weight						4.420 g
Min P4	FLORAL REMAINS:						
	Unidentified	Fruit		16			0.0090 g
	Roots					X	Moderate
	Rootlets					X	Moderate
	Sclerotia				X	X	Numerous
	CHARCOAL/WOOD:						
	Total charcoal ≥ 1 mm						0.0072 g
	Conifer	Charcoal		2			0.0009 g
	Unidentified hardwood - small	Charcoal		14			0.0057 g
	Unidentifiable - small	Charcoal		3			0.0006 g

TABLE 5 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
NC-R19	NON-FLORAL REMAINS:						
Unit 2bA Min P4	Rock/Gravel					X	Numerous
	Snail shell - depressed ≥ 1 mm				59	32	
	Snail shell - depressed < 1 mm				X	X	Moderate
	Snail shell - oblong ≥ 0.5 mm				44	15	
NC-R05	Sample Weight						0.042 g
Unit 1bA Max P4	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.5 mm						0.0093 g
	Unidentified hardwood - small	Charcoal		20			0.0093 g
	NON-FLORAL REMAINS:						
	Sediment					X	Few
NC-R07	Sample Weight						0.011 g
Unit 1bA Max P4	CHARCOAL/WOOD:						
	Quercus	Charcoal		9			0.0035 g
NC-R09	Sample Weight						0.016 g
Unit 1bA Max P4	CHARCOAL/WOOD:						
	Quercus	Charcoal		10			0.0042 g
NC-R12	Liters Floated						2.00 L
Unit 1c4A? Max P4	Light Fraction Weight						0.701 g
	FLORAL REMAINS:						
	Roots					X	Moderate
	Rootlets					X	Few
	Sclerotia				X	X	Numerous
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.25 mm						0.0008 g
	Unidentifiable - small	Charcoal		X			0.0008 g
	NON-FLORAL REMAINS:						
	Rock					X	Numerous
	Snail shell - oblong ≥ 0.5 mm				1	1	

TABLE 5 (Continued)

Sample No.	Identification	Part	Charred W	Charred F	Uncharred W	Uncharred F	Weights/ Comments
NC-R11	Bulk Sample Liters Floated						3.00 L
Unit 1c4A? Max P4	Bulk Sample Light Fraction Weight						2.764 g
	Charcoal Sample Weight						0.003 g
	FLORAL REMAINS:						
	Periderm ≥ 0.25 mm					6	0.0017 g
	Roots					X	Few
	Rootlets					X	Numerous
	Sclerotia				X	X	Numerous
	CHARCOAL/WOOD:						
	Total charcoal ≥ 0.5 mm						0.0025 g
	Conifer	Charcoal		6			0.0021 g
	Unidentifiable - small	Charcoal		7			0.0004 g
	NON-FLORAL REMAINS:						
	Insect	Chitin				X	Few
	Rock/Gravel					X	Numerous
	Snail shell - depressed ≥ 1 mm				1	1	
	Snail shell - oblong ≥ 0.5 mm				1	1	

W = Whole
F = Fragment
g = grams
L = liters
X = Presence noted in sample
mm = millimeters

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APPENDIX D
SUMMARY OF ^{14}C DATED CHARCOAL FOR THE SPRING LAKE SITE

Sample Name	NOSAMS[1] Accession No.	Trench Wall			Sample	Unit Sampled	Notes	Macrofloral remains (total weight in mg)[2]	Pre-treatment[3]	Laboratory age (^{14}Cyr)[4]			Calibrated age (cal yr BP)[5]		Calibrated age (rounded) (ka)	
		Horiz. (m)	Vert. (m)	Wall						Age	Age error	D^{13}C	Mean	1σ	Mean	2σ
SLN-R01	OS-105419	38.32	1.21	S	charcoal	S3d	Charcoal in massive silt/loess	1-PT (1.8)	ABA	6,620	110	-25.18	7507	90	7.5	0.2
SLN-R02	OS-104798	32.47	2.43	S	charcoal	S3bA	Charcoal from A horizon on AF sediments	31-UVC (1.2)	A	6680	40	-24.55	7547	36	7.6	0.1
SLN-R03	OS-105243	36.03	1.94	S	charcoal	S3d	Charcoal in massive silt/loess	1-UHT (1.2)	A	6260	80	-23.41	7164	105	7.2	0.2
SLN-R04	OS-105241	38.07	1.71	S	charcoal	S3g4	Charcoal in alluvial-fan sediments	UC (0.9)	A	6110	40	-26.18	7006	79	7.0	0.2
SLN-R05	-	33.71	3.81	S	charcoal	S3h1	Charcoal in alluvial-fan sediments	6-UC (<0.1)	-	-	-	-	-	-	-	-
SLN-R06	-	33.73	3.87	S	charcoal	S3h1	Charcoal in alluvial-fan sediments	2-UT (<0.1)	-	-	-	-	-	-	-	-
SLN-R07	-	38.14	1.29	S	bulk	S3d	Massive silt/loess	-	-	-	-	-	-	-	-	-
SLN-R08	-	33.20	2.23	S	bulk	S3bA	A horizon on AF sediments	-	-	-	-	-	-	-	-	-
SLN-R09	-	27.92	3.43	N	bulk + char.	C6	Top of C6	5-UC (<0.1)	-	-	-	-	-	-	-	-
SLN-R10	OS-104444	28.86	3.14	N	bulk	C6	Top of C6 (slightly more distal)	**5-VT(0.7)**, 5-PT(<0.1)	NP	13800	130	25	16920	144	16.9	0.3
SLN-R11	OS-104738	33.67	3.92	S	bulk	S3h1	Alluvial-fan sediments (charcoal fragments)	UC(2.2)	ABA	6170	35	-24.66	7074	57	7.1	0.1
SLN-R12	-	25.23	7.82	S	bulk	S3j	Slopewash above C1	-	-	-	-	-	-	-	-	-
SLN-R13	-	26.15	7.28	S	bulk	S3j	Slopewash above C1 (slighly more distal)	**2-A(1.6)**, 23-MHD(2.6)	ABA	-	-	-	-	-	-	-
SLN-R14	-	25.44	7.51	S	bulk	C1	Soil organics in uppermost C1	-	-	-	-	-	-	-	-	-
SLN-R15	OS-104825	26.55	6.94	S	bulk	C1	Soil organics in uppermost C1	UC (1.1)	A	790	25	-25.28	708	18	0.7	0.04
SLN-R16	OS-104739	25.86	7.06	S	bulk	C1A	Soil organics in C1	UC (1.9)	ABA	2390	25	-25.57	2420	65	2.4	0.1
SLN-R17	OS-104449	25.49	6.83	S	bulk	C2	Soil organics in uppermost C2	36-S (7.4)	ABA	2320	30	-17.6	2333	41	2.3	0.1
SLN-R18	OS-104824	26.09	6.49	S	bulk	C2	Soil organics in C2	UC(1.4)	A	3740	25	-23.05	4089	55	4.1	0.1
SLN-R19	OS-104829	26.22	6.19	S	bulk	C3	Soil organics in uppermost C3	**UC(1.0)**, 4-PT(0.8)	A	3280	40	-21.3	3509	50	3.5	0.1
SLN-R20	OS-105242	27.28	5.43	S	bulk	C4	C4 colluvial sediment	UC(0.8)	A	3930	35	-21.7	4365	62	4.4	0.1
SLN-R21	OS-104831	26.2	7.34	N	bulk + char.	C1	Base of C1 colluvial wedge	14-UC (0.9) ***	A	770	30	-25.76	700	19	0.7	0.04
SLN-R22	OS-104826	26.55	6.96	N	bulk	C2	Top of C2 colluvial wedge	10-UC(0.2), 1-UVT(0.8)	A	1150	30	-24.68	1060	53	1.1	0.1
SLN-R23	-	27.18	6.69	N	bulk + char.	C2	Top of C2 colluvial wedge	15-UC(0.5)	NP	sample lost during processing				-	-	-
SLN-R24	OS-104823	12.28	13.84	S	bulk	S2cA	A horizon on alluvial-fan sediments	9-UC (1.2)	A	5280	40	-21.11	6067	70	6.1	0.1
SLN-R25	OS-104740	11.34	14.08	S	bulk	CF3	Basal CF3	3-UC (<0.1), **MC(34.5)**	ABA	3380	30	-26.91	3624	43	3.6	0.1
SLN-R26	OS-104445	10.24	13.94	S	bulk	S2bA	A horizon within alluvial-fan sediments	5-VT(0.5)	NP	11850	95	-22.91	13684	120	13.7	0.2
SLN-R27	OS-104832	27.85	6.05	N	bulk	N3g	A horizon on AF deposits below C2 wedge	UC(1.0)	A	4960	45	-23.76	5697	65	5.7	0.1
SLN-R28	-	21.1	10.1	S	bulk	CF1	CF1 colluvial sediment	-	-	-	-	-	-	-	-	-

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

[2] Number of fragments of charcoal and their weight (in parentheses) following sample sorting by PaleoResearch Institute (Golden, Colorado). Unidentified charcoal: MC - microcharcoal, MHD - monocot/Herbaceous dicot, PT - Parenchymous tissue (charred), UC - unidentified charcoal, UHT - unidentified hardwood twig (charred), UVT - unidentified twig (vitrified), UVC - unidentified charcoal (vitrified), UT - unidentified tissue (charred), VT- vitrified tissue. Identified charcoal: A - Asteraceae (sunflower family), S - Sagebrush (Artemisia). Bold text indicates subset of charcoal dated.

[3] Pretreatment methods: A - acid wash only, ABA - acid-base-acid washes, NP - no pretreatment.

[4] Delta ^{13}C for SLN-R10 is assumed; all other values were measured.

[5] Calibrated using OxCal version 4.2 (Bronk Ramsey, 1995, 2001) and the terrestrial calibration curve of Reimer and others (2009).

APPENDIX E

SUMMARY OF ^{14}C DATED CHARCOAL FOR THE NORTH CREEK SITE

Sample Name	NOSAMS[1] Accession No.	Trench Wall			Sample	Unit Sampled	Notes	Macrofloral remains (total weight in mg)[2]	Pre-treatment[3]	Laboratory age (^{14}Cyr)[4]			Calibrated age (cal yr BP)[5]		Calibrated age (rounded) (ka)	
		Horiz. (m)	Vert. (m)	Wall						Age	Age error	D^{13}C	Mean	1σ	Mean	2σ
NC-R01	-	7.7	3.78	South	charcoal	2cA2/CgA	Thin soil A horizon on AF unit 2c	4-UH(3.2)	-	-	-	-	-	-	-	-
NC-R02	OS-103474	8.42	3.56	South	charcoal	2cA2/CgA	Thin soil A horizon on Cg1 (graben colluvial wedge)	**3-C(0.5)**, 2-DF(0.2), **UH(0.6)**, **3-UC(0.2)**	A	915	25	-25.61	845	43	0.9	0.1
NC-R03	-	8.92	3.35	South	charcoal	2cA	A horizon on 2c below Cg1	3-PT(0.9)	-	-	-	-	-	-	-	-
NC-R04	-	33.80	10.75	South	charcoal	1bA	A horizon within footwall AF sediments	-	-	-	-	-	-	-	-	-
NC-R05	-	33.40	10.70	South	charcoal	1bA	A horizon within footwall AF sediments	20-UH(9.3)	-	-	-	-	-	-	-	-
NC-R06	-	30.25	10.75	South	bulk/charcoal	1bA	A horizon within footwall AF sediments	-	-	-	-	-	-	-	-	-
NC-R07	OS-104336	36.30	11.15	South	charcoal	1bA	A horizon within footwall AF sediments	9-Q(3.5)	ABA	7,090	120	-25.62	7913	123	7.9	0.3
NC-R08	-	33.28	10.70	North	charcoal	1bA	A horizon within footwall AF sediments	-	-	-	-	-	-	-	-	-
NC-R09	OS-103168	36.25	11.17	South	charcoal	1bA	A horizon within footwall AF sediments	10-Q(4.2)	ABA	4590	30	-24.1	5311	103	5.3	0.2
NC-R10	-	27.60	9.75	North	bulk	1bA	A horizon within footwall AF sediments	-	-	-	-	-	-	-	-	-
NC-R11	OS-103263	20.80	0.90	North	bulk/charcoal	C5A	A horizon on hanging wall AF sediments	**6-C(2.1)**, 7-UC(0.4)	ABA	2010	40	-23.6	1965	51	2.0	0.1
NC-R12	OS-103475	20.78	1.10	South	bulk	C5A	A horizon on hanging wall AF sediments	UC(0.8)	A	3680	30	-24.48	4019	52	4.0	0.1
NC-R13	OS-103166	20.63	1.62	South	bulk/charcoal	C4A	Thin soil lense within C4 colluvium	9-UH(2.1)	ABA	4700	30	-26.5	5424	77	5.4	0.2
NC-R14	-	21.13	5.20	South	bulk/charcoal	C1A	Soil organics and slopewash overlying C1	UC(2.6)	ABA							
NC-R15	OS-103167	20.14	4.10	South	bulk	C2A	Weak A horizon on C2 colluvium	UC(2.0)	ABA	5220	30	-23.55	5974	50	6.0	0.1
NC-R16	OS-103264	20.75	3.68	South	bulk	2cA	Well developed A horizon on C3/2c	8-C(2.7), 6-DF(1.6), 7-Q(1.0), **2-UHT(3.3)**, 7-UHC(4.0), 2-UC(0.8)	ABA	1280	30	-25.44	1223	38	1.2	0.1
NC-R17	-	19.9	3.36	South	bulk	2cA	Well developed A horizon on 2c	-	-	-	-	-	-	-	-	-
NC-R18	OS-103265	19.57	2.76	South	bulk	C3	Weak A horizon on C3 colluvium, below 2c	4-C(0.8), 2-UHC(0.4), 2-UC(0.3)	ABA	2110	30	-23.43	2084	55	2.1	0.1
NC-R19	OS-103266	18.38	1.14	South	bulk	2b2	Organics-rich debris flow inter-fingered with C4	**16-UF(9)**, 2-C(0.9), 14-UHC(5.7), 3-UC(0.6)	ABA	3710	40	-25.96	4052	62	4.1	0.1
NC-R20	OS-103476	22.23	5.32	North	bulk	C1	Silt/organic lense in C1 colluvium	**MH(1.0)**, 12-C(0.9), 13-UC(0.5)	A	315	20	-25.12	382	41	0.4	0.1
NC-R21	OS-103477	22.44	4.72	North	bulk	C2A	Well developed A horizon on C2	**3-UF(0.8)**, 13-J(6.9), Q(0.7)	A	245	20	-24.56	257	74	0.3	0.2
NC-R22-c	OS-103267	17.96	3.49	North	charcoal	2d1	Silt/organic lense likely in C1 colluvium	7-J (4.6)	ABA	160	25	-23.9	157	85	0.2	0.2
NC-R22-b	-	17.96	3.49	North	bulk	2d1	Silt/organic lense likely in C1 colluvium	-	-	-	-	-	-	-	-	-
NC-R23	OS-103169	21.46	3.22	North	bulk	C3A	A horizon on C3 (massive organic-rich sediments)	10-C(1.7), 4-J(3.5), 4-DF(1.0), **8-Q(1.6)**, W(0.1), 21-UHC/UC(3.7)	ABA	590	20	-24.6	599	31	0.6	0.1
NC-R24	-	12.6	2.37	North	bulk/charcoal	Cg2	Base of Cg2/top of 2cA (relation to contact uncertain)	-	-	-	-	-	-	-	-	-
NC-R25	-	16.82	2.26	North	bulk	2b2	Organic-rich gravel below C3	-	-	-	-	-	-	-	-	-
NC-R26	-	15.32	1.35	North	bulk	2b2	Organic-rich gravel below C3	-	-	-	-	-	-	-	-	-
NC-R27	-	14.58	1.08	North	bulk	2bA	A horizon on alluvial-fan gravel 2b1	-	-	-	-	-	-	-	-	-
NC-R28	OS-103170	20.26	4.58	South	bulk/charcoal	C1A	Thin soil lense within C1 colluvium	**A(0.7)**, J(2.4), DF(1.6), UC(0.4)	NP	5450	30	-25	6250	30	6.3	0.1
NC-R29	OS-103405	21.70	2.63	North	bulk	C4A	A horizon on C4, below C3	16-C(1.3), 2-J(10.1), DF(0.1), **9-Q(1.2)**, 2-UH(0.7)	A	180	25	-24.85	163	89	0.2	0.2
NC-R30	-	8.84	2.66	North	bulk	2cA	A horizon on 2c below Cg1	-	-	-	-	-	-	-	-	-
NC-R31	OS-103478	12.33	2.3	North	bulk	2cA	A horizon on 2c below Cg1	**2-A(0.8)**, J(3.7), Q(2.9), 2-W(1.7)	A	365	20	-25.59	415	57	0.4	0.1
NC-R32	OS-103171	12.25	2.53	North	bulk	Cg	Cg1 colluvium	6-C(6.6), 1-J(2.0), 4-DF(5.7), 10-Q(8.3), **1-RT(1.6)**, 4-UHC(3.8)	ABA	215	20	-24.03	183	97	0.2	0.2

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

[2] Number of fragments of charcoal and their weight (in parentheses) following sample sorting by PaleoResearch Institute (Golden, Colorado). Unidentified charcoal: MC - microcharcoal, MHD - monocot/Herbaceous dicot, PT - Parenchymous tissue (charred), UC - unidentified charcoal, UHC - unidentified hardwood charcoal, UHT - unidentified hardwood twig (charred), UT - unidentified tissue (charred), UVC - unidentified charcoal (vitrified), UVT - unidentified twig (vitrified), VT- vitrified tissue. Identified charcoal: A - Asteraceae (sunflower family), C - conifer, DF - Douglas Fir (Pseudotsuga menziesii), J - Juniperus, RT - Roseacaea twig, S - Sagebrush (Artemisia), Q - Quercus (oak), W - Willow family (Salicaceae). Bold text indicates subset of charcoal dated.

[3] Pretreatment methods: A - acid wash only, ABA - acid-base-acid washes, NP - no pretreatment.

[4] Delta ^{13}C for NC-R28 is assumed; all other values were measured.

[5] Calibrated using OxCal version 4.2 (Bronk Ramsey, 1995, 2001) and the terrestrial calibration curve of Reimer and others (2009).

APPENDIX F
OPTICALLY STIMULATED LUMINESCENCE AGES FOR THE SPRING LAKE SITE

Sample[1]	**% Water content**[2]	**K** (%)[3]	**U** (ppm)[3]	**Th** (ppm)[3]	**Cosmic dose**[4] **additions** (Gy/ka)	**Total Dose Rate** (Gy/ka)	**Equivalent Dose** (Gy)	**n**[5]	**Age (yr)**[6]		**Age (rounded) (ka)**	
									mean	**1σ**	mean	2σ
SL-L1	6 (13)	1.60 ± 0.03	3.53 ± 0.11	9.40 ± 0.33	0.19 ± 0.01	3.28 ± 0.07	17.2 ± 0.43	21 (34)	5240	170	5.2	0.3
SL-L2	5 (14)	0.88 ± 0.06	1.78 ± 0.19	4.29 ± 0.45	0.18 ± 0.01	1.77 ± 0.11	14.1 ± 0.97	21 (28)	7980	740	8.0	1.5
SL-L3	6 (21)	1.26 ± 0.06	2.35 ± 0.20	3.75 ± 0.47	0.18 ± 0.01	2.19 ± 0.12	17.1 ± 0.52	30 (42)	7810	490	7.8	1.0
SL-L4	7 (27)	2.14 ± 0.06	2.57 ± 0.18	10.4 ± 0.48	0.18 ± 0.01	3.49 ± 0.11	21.3 ± 2.044	21 (32)	6100	610	6.1	1.2
SL-L5	4 (18)	2.24 ± 0.06	2.34 ± 0.16	10.0 ± 0.75	0.17 ± 0.01	3.58 ± 0.16	24.9 ± 0.62	12 (20)	6970	360	7.0	0.7
SL-L6	7 (44)	1.50 ± 0.04	2.88 ± 0.16	6.67 ± 0.57	0.23 ± 0.02	2.64 ± 0.13	15.1 ± 0.73	19 (24)	5720	390	5.7	0.8
SL-L7	3 (25)	2.08 ± 0.06	2.93 ± 0.20	8.77 ± 0.76	0.24 ± 0.02	3.48 ± 0.17	>1	2 (20)	>300	-	>0.3	-
SL-L8	2 (26)	2.33 ± 0.06	3.51 ± 0.19	12.4 ± 0.85	0.23 ± 0.02	3.66 ± 0.17	36.5 ± 1.44	25 (48)	9970	580	10.0	1.2
SL-L9	4 (29)	1.94 ± 0.05	2.33 ± 0.15	10.9 ± 0.75	0.19 ± 0.01	3.04 ± 0.15	52.6 ± 1.95	28 (30)	17,300	970	17.3	1.9
SL-L10	9 (25)	1.83 ± 0.04	3.00 ± 0.15	10.7 ± 0.69	0.22 ± 0.02	3.38 ± 0.14	15.2 ± 0.56	26 (30)	4500	240	4.5	0.5

[1] Analyses by the U.S. Geological Survey Luminescence Dating Laboratory (Denver, Colorado).
[2] Field moisture, with figures in parentheses indicating the complete sample saturation percent. Ages calculated using approximately 25% of total saturation value, except SL-8 and -9, at 50%.
[3] Analyses obtained using in-situ gamma spectrometry (NaI detector) and lab gamma spectrometry (Ge detector).
[4] Cosmic doses and attenuation with depth were calculated using the methods of Prescott and Hutton (1994).
[5] Number of replicated equivalent dose (De) estimates used to calculate the equivalent dose. Figures in parentheses indicate total number of measurements included in calculating the represented equivalent dose and age using radial plots (weighed mean). Not all samples had adequate sand-sized grains for analyses; dispersion varied between 10-40%.
[6] Dose rate and age for fine-grained 125-90 microns or 150-125 microns sized quartz. Exponential + linear fit used on equivalent dose, errors to one sigma.

APPENDIX G
OPTICALLY STIMULATED LUMINESCENCE AGES FOR THE NORTH CREEK SITE

Sample[1]	**% Water content**[2]	**K** (%)[3]	**U** (ppm)[3]	**Th** (ppm)[3]	**Cosmic dose**[4] **additions** (Gy/ka)	**Total Dose Rate** (Gy/ka)	**Equivalent Dose** (Gy)	**n**[5]	**Age (yr)**[6] **mean**	**1σ**	**Age (rounded) (ka)** mean	2σ
NC-L1	6 (51)	0.99 ± 0.04	1.79 ± 0.08	3.00 ± 0.26	0.18 ± 0.01	1.63 ± 0.07	9.77 ± 0.50	17 (20)	6000	390	6.0	0.8
NC-L2	1 (55)	0.84 ± 0.06	1.56 ± 0.22	4.04 ± 0.36	0.24 ± 0.02	1.56 ± 0.09	2.26 ± 0.22	24 (30)	1450	170	1.5	0.4

[1] Analyses by the U.S. Geological Survey Luminescence Dating Laboratory (Denver, Colorado).

[2] Field moisture, with figures in parentheses indicating the complete sample saturation percent. Ages calculated using approximately 25% of total saturation value.

[3] Analyses obtained using in-situ gamma spectrometry (NaI detector) and lab gamma spectrometry (Ge detector).

[4] Cosmic doses and attenuation with depth were calculated using the methods of Prescott and Hutton (1994).

[5] Number of replicated equivalent dose (De) estimates used to calculate the equivalent dose. Figures in parentheses indicate total number of measurements included in calculating the represented equivalent dose and age using radial plots (weighed mean). Not all samples had adequate sand-sized grains for analyses; dispersion varied between 25-45%.

[6] Dose rate and age for fine-grained 125-90 microns or 150-125 microns sized quartz. Exponential + linear fit used on equivalent dose, errors to one sigma.

APPENDIX H

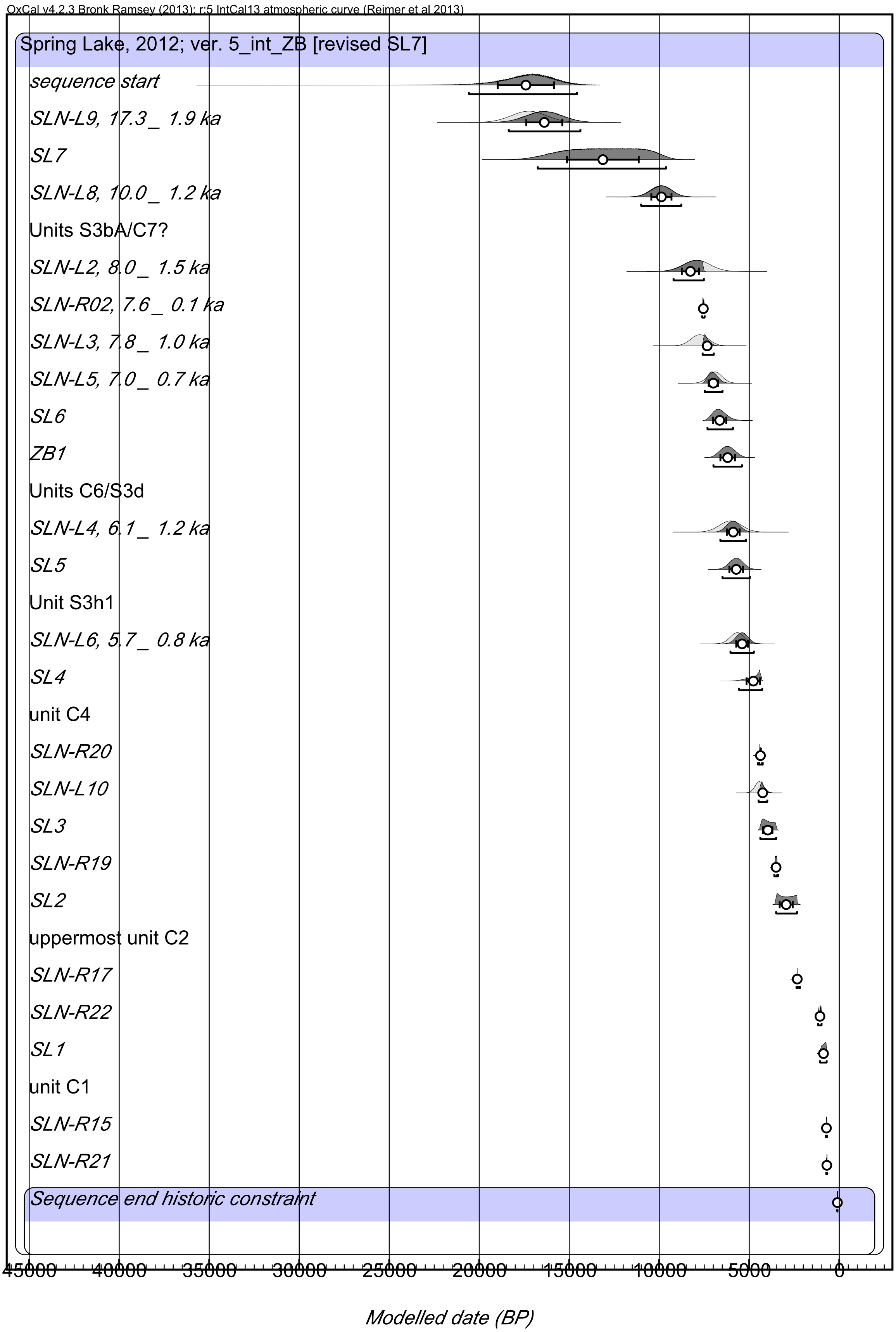
OXCAL MODELS FOR THE SPRING LAKE AND NORTH CREEK SITES

OxCal models for the Spring Lake and North Creek sites were created using OxCal calibration and analysis software (version 4.2; 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). 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. Ages following two forward slashes (//) are not considered during model analysis. The models are presented here in reverse stratigraphic order, following the order in which the ages and events are evaluated in OxCal.

Spring Lake Site

```
Plot()
 {
  Sequence("Spring Lake, 2012; ver. 5_int_ZB")
  {
   Boundary("sequence start");
   C_Date("SLN-L9, 17.3 ± 1.9 ka", -15288, 970);
   Date("SL7");
   C_Date("SLN-L8, 10.0 ± 1.2 ka", -7958, 580);
   Phase("Units S3bA/C7?");
   {
    C_Date("SLN-L2, 8.0 ± 1.5 ka", -5968, 740);
    R_Date("SLN-R02, 7.6 ± 0.1 ka", 6680, 40);
    C_Date("SLN-L3, 7.8 ± 1.0 ka", -5798, 490);
    C_Date("SLN-L5, 7.0 ± 0.7 ka", -4958, 390);
   };
   Boundary("SL6");
   Zero_Boundary("ZB1");
   Phase("Units C6/S3d");
   {
    C_Date("SLN-L4, 6.1 ± 1.2 ka", -4088, 610);
    //R_Date("SLN-R01, 7.5 ± 0.1 ka", 6620, 110); [detrital?]
    //R_Date("SLN-R03, 7.2 ± 0.2 ka", 6260, 80); [detrital?]
    //C_Date("SLN-L1, 5.2 ± 0.3 ka", -3228, 170); [stratigraphically inverted]
   };
   Boundary("SL5");
   //R_Date("SLN-R04", 6110, 40); [relation to P5 unclear]
   Phase("Unit S3h1");
```

```
  {
   //R_Date("SLN-R11, 7.1 ± 0.1 ka", 6170, 35); [detrital?]
   C_Date("SLN-L6, 5.7 ± 0.8 ka", -3708, 390);
  };
  //R_Date("SLN-R24", 5280, 40); [unknown relation]
  Boundary("SL4");
  Phase("unit C4");
  {
   R_Date("SLN-R20", 3930, 35);
   C_Date("SLN-L10", -2488, 240);
  };
  Boundary("SL3");
  R_Date("SLN-R19", 3280, 40);
  //R_Date("SLN-R25", 3380, 30); [unknown relation]
  //R_Date("SLN-R27", 4960, 45); [detrital?]
  Boundary("SL2");
  //R_Date("SNL-R18", 3740, 25);
  Phase("uppermost unit C2");
  {
   //R_Date("SLN-R18", 4089, 55); [likely sourced from C3A]
   R_Date("SLN-R17", 2320, 30);
   R_Date("SLN-R22", 1150, 30);
  };
  Boundary("SL1");
  Phase("unit C1");
  {
   //R_Date("SLN-R16", 2390, 25); [likely sourced from C2A]
   R_Date("SLN-R15", 790, 25);
   R_Date("SLN-R21", 770, 30);
  };
  Boundary("Sequence end historic constraint", 1847);
 };
 Difference("SL7-SL6","SL6","SL7");
 Difference("SL6-SL5","SL5","SL6");
 Difference("SL5-SL4","SL4","SL5");
 Difference("SL4-SL3","SL3","SL4");
 Difference("SL3-SL2","SL2","SL3");
 Difference("SL2-SL1","SL1","SL2");
 Difference("SL7-SL1","SL1","SL7");
 Difference("SL6-SL1","SL1","SL6");
 Difference("SL5-SL1","SL1","SL5");
 Difference("SL4-SL1","SL1","SL4");
 Difference("SL3-SL1","SL1","SL3");
};
```


OxCal v4.2.3 Bronk Ramsey (2013); r:5 IntCal13 atmospheric curve (Reimer et al 2013)
Spring Lake, 2012; ver. 5_int_ZB [revised SL7]
sequence start
SLN-L9, 17.3 _ 1.9 ka
SL7
SLN-L8, 10.0 _ 1.2 ka
Units S3bA/C7?
SLN-L2, 8.0 _ 1.5 ka
SLN-R02, 7.6 _ 0.1 ka
SLN-L3, 7.8 _ 1.0 ka
SLN-L5, 7.0 _ 0.7 ka
SL6
ZB1
Units C6/S3d
SLN-L4, 6.1 _ 1.2 ka
SL5
Unit S3h1
SLN-L6, 5.7 _ 0.8 ka
SL4
unit C4
SLN-R20
SLN-L10
SL3
SLN-R19
SL2
uppermost unit C2
SLN-R17
SLN-R22
SL1
unit C1
SLN-R15
SLN-R21
Sequence end historic constraint
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
Modelled date (BP)

	Unmodelled (cal yr BP)				Modelled (cal yr BP)				
Spring Lake, 2012; ver. 5_int_ZB	central 95%		mean	sigma	central 95%		mean	sigma	Agreement
sequence start					20577	14569	17410	1565	
SLN-L9, 17.3 ± 1.9 ka	19174	15304	17239	970	18362	14379	16384	1001	81.6
SL7					**16751**	**9623**	**13132**	**1992**	
SLN-L8, 10.0 ± 1.2 ka	11067	8751	9909	580	11007	8771	9880	561	101.4
Units S3bA/C7?									
SLN-L2, 8.0 ± 1.5 ka	9395	6442	7919	740	9207	7522	8266	484	112.1
SLN-R02, 7.6 ± 0.1 ka	7615	7476	7547	36	7617	7479	7551	35	99.5
SLN-L3, 7.8 ± 1.0 ka	8727	6770	7749	490	7592	6971	7337	174	98.7
SLN-L5, 7.0 ± 0.7 ka	7688	6129	6909	390	7476	6485	6995	260	114.6
SL6					**7320**	**5907**	**6640**	**364**	
ZB1					6989	5403	6200	403	
Units C6/S3d									
SLN-L4, 6.1 ± 1.2 ka	7256	4821	6039	610	6605	5177	5890	358	119.2
SL5					**6487**	**4966**	**5722**	**380**	
Unit S3h1									
SLN-L6, 5.7 ± 0.8 ka	6438	4879	5659	390	6044	4743	5396	327	94.7
SL4					**5563**	**4277**	**4773**	**377**	
unit C4									
SLN-R20	4510	4248	4365	61	4515	4252	4377	60	100.2
SLN-L10	4919	3959	4439	240	4483	3998	4254	120	102.2
SL3					**4385**	**3508**	**3971**	**260**	
SLN-R19	3607	3402	3509	47	3606	3402	3510	47	99.8
SL2					**3506**	**2348**	**2948**	**362**	
uppermost unit C2									
SLN-R17	2378	2184	2334	37	2377	2184	2333	38	97.6
SLN-R22	1174	979	1066	57	1175	982	1073	57	97.6
SL1					**1077**	**700**	**876**	**109**	
unit C1									
SLN-R15	739	674	708	18	744	680	713	17	99.8
SLN-R21	734	668	700	19	722	667	690	14	110
Sequence end historic constraint	104	103	104	0	104	103	104	0	100

Intervals:	central 95%		mean	sigma
SL7-SL6	2867	10232	6492	2027
SL6-SL5	106	1758	918	438
SL5-SL4	1	1799	950	502
SL4-SL3	-2	1766	802	518
SL3-SL2	82	1860	1023	478
SL2-SL1	1413	2728	2072	380
SL7-SL1	8733	15904	12256	1995
SL6-SL1	4994	6479	5764	380
SL5-SL1	4057	5638	4846	395
SL4-SL1	3290	4731	3897	392
SL3-SL1	2569	3591	3095	281

All values are in calendar years before 1950 (cal yr BP)

Indices:

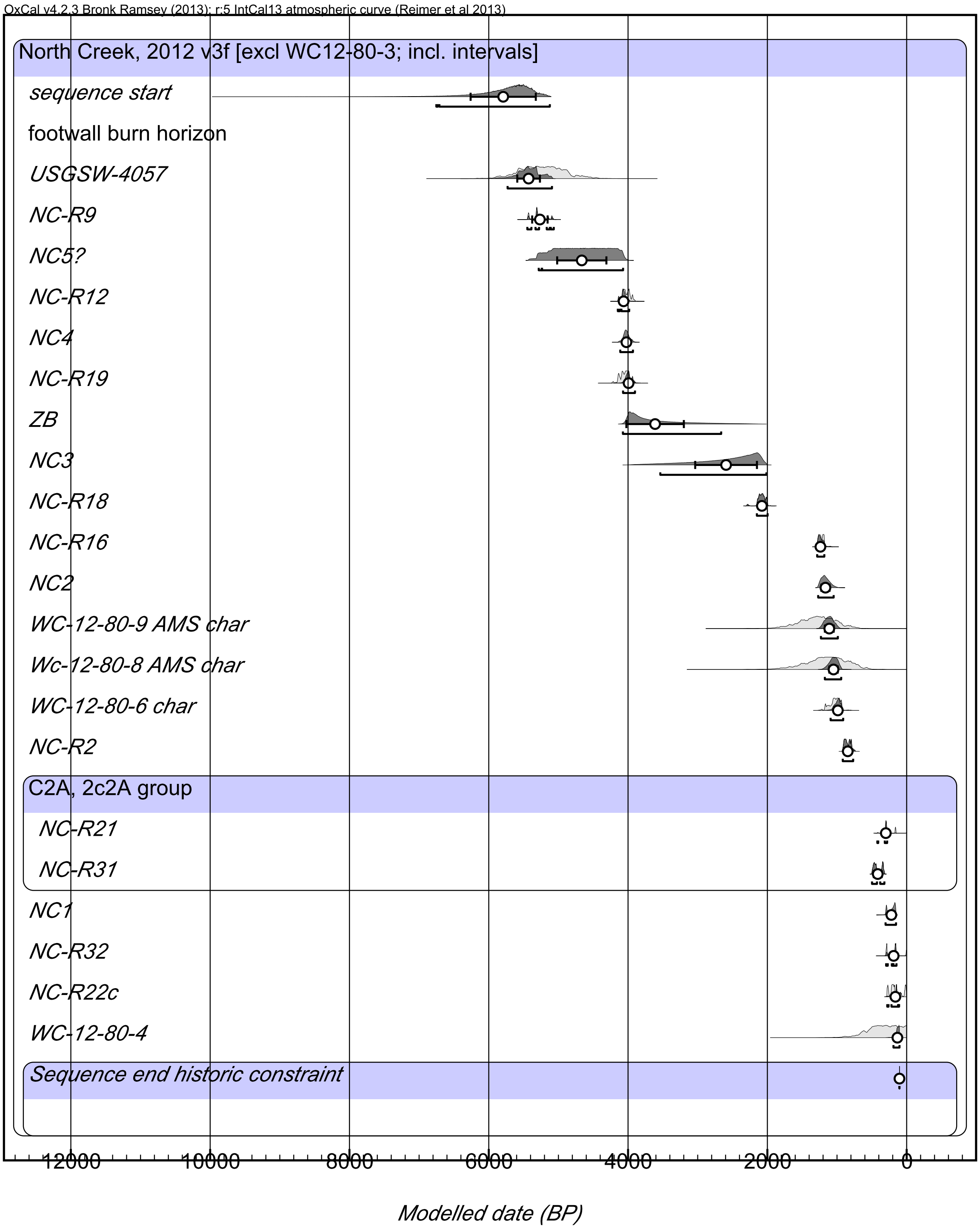
Amodel 106.8

Aoverall 106

North Creek Site

```
Plot()
 {
  Sequence("North Creek, 2012 v3f")
  {
   Boundary("sequence start");
   Phase("footwall burn horizon");
   {
    R_Date("USGSW-4057", 4580, 250);
    R_Date("NC-R9", 4590, 30);
   };
   Date("NC5?");
   R_Date("NC-R12", 3680, 30);
   //R_Date("NC-R11", 2010, 40);
   //R_Date("NC-R13", 4700, 30);
   Boundary("NC4");
   R_Date("NC-R19", 3710, 40);
   //R_Date("NC-R29", 180, 25);
   //Delta_R("MRT correction1", 200, 200);
   //R_Date("WC-12-80-3 soil AMRT", 2180, 80);
   Zero_Boundary("ZB");
   Boundary("NC3");
   Delta_R("no MRT correction", 0, 0);
   R_Date("NC-R18", 2110, 30);
   //R_Date("NC-R23", 590, 20);
   R_Date("NC-R16", 1280, 30);
   Boundary("NC2");
   R_Date("WC-12-80-9 AMS char", 1350, 250);
   R_Date("Wc-12-80-8 AMS char", 1200, 300);
   //R_Date("WC-12-80-5 char", 1350, 70); [relation to NC2 is unclear]
   R_Date("WC-12-80-6 char", 1110, 60);
   R_Date("NC-R2", 915, 25);
   Phase("C2A, 2c2A group")
   {
    //R_Date("NC-R15", 5220, 30);
    R_Date("NC-R21", 245, 20);
    R_Date("NC-R31", 365, 20);
   };
   Boundary("NC1");
   //R_Date("NC-R20", 315, 20); [poor agreement with R21]
   //R_Date("NC-R28", 5450, 30);
   R_Date("NC-R32", 215, 20);
   R_Date("NC-R22c", 160, 25);
   R_Date("WC-12-80-4", 250, 300);
   Boundary("Sequence end historic constraint", 1847);
```

```
 };
 Difference("NC5?-NC4","NC4","NC5?");
 Difference("NC4-NC3","NC3","NC4");
 Difference("NC3-NC2","NC2","NC3");
 Difference("NC2-NC1","NC1","NC2");
 Difference("NC5?-NC1","NC1","NC5?");
 Difference("NC4-NC1","NC1","NC4");
 Difference("NC3-NC1","NC1","NC3");
};
```


OxCal v4.2.3 Bronk Ramsey (2013); r:5 IntCal13 atmospheric curve (Reimer et al 2013)
North Creek, 2012 v3f [excl WC12-80-3; incl. intervals]
sequence start
footwall burn horizon
USGSW-4057
NC-R9
NC5?
NC-R12
NC4
NC-R19
ZB
NC3
NC-R18
NC-R16
NC2
WC-12-80-9 AMS char
Wc-12-80-8 AMS char
WC-12-80-6 char
NC-R2
C2A, 2c2A group
NC-R21
NC-R31
NC1
NC-R32
NC-R22c
WC-12-80-4
Sequence end historic constraint
12000
10000
8000
6000
4000
2000
0
Modelled date (BP)

	Unmodelled (cal yr BP)				Modelled (cal yr BP)				
North Creek, 2012 v3f [excl WC12-80-3; incl. intervals]	95% range		mean	sigma	95% range		mean	sigma	Agreement
sequence start					6753	5123	5793	468	
footwall burn horizon									
USGSW-4057	5891	4582	5234	312	5730	5093	5428	163	110.2
NC-R9	5448	5075	5312	101	5447	5067	5266	111	88.4
NC5?					**5283**	**4072**	**4665**	**353**	
NC-R12	4139	3914	4019	51	4147	3984	4064	38	101.1
NC4					**4112**	**3930**	**4023**	**43**	
NC-R19	4219	3926	4052	62	4072	3901	3992	43	92.3
ZB					4074	2663	3612	413	
NC3					**3537**	**2014**	**2593**	**443**	
no MRT correction	-0.5	0.5	0	0	-0.5	0.5	0	0	100
NC-R18	2153	1995	2084	54	2151	1996	2079	51	100.1
NC-R16	1288	1176	1226	36	1285	1182	1238	31	100.7
NC2					**1271**	**1048**	**1166**	**60**	
WC-12-80-9 AMS char	1820	783	1282	260	1231	988	1111	63	117.8
Wc-12-80-8 AMS char	1780	562	1152	293	1175	940	1050	61	134.8
WC-12-80-6 char	1176	930	1038	72	1092	912	988	47	107.8
NC-R2	919	767	847	42	918	768	846	42	99.3
C2A, 2c2A group									
NC-R21	312	151	262	67	421	280	299	30	108.6
NC-R31	498	320	415	57	498	320	415	57	99.5
NC1					**303**	**153**	**220**	**50**	
NC-R32	304	...	190	92	295	146	187	46	99
NC-R22c	285	...	157	85	279	109	162	35	98.1
WC-12-80-4	731	...	340	219	190	103	133	26	110.1
Sequence end historic constraint	104	103	104	0	104	103	104	0	100

Intervals:	95% range		mean	sigma
NC5?-NC4	36	1245	641	354
NC4-NC3	460	2030	1431	446
NC3-NC2	812	2396	1426	449
NC2-NC1	792	1091	946	79

NC5?-NC1	3842	5080	4445	357
NC4-NC4	3664	3925	3803	66
NC3-NC4	1762	3345	2373	446

All values are in calendar years before 1950 (cal yr BP)

Indices:

Amodel 114

Aoverall 115.3

APPENDIX I

SUMMARY OF EARTHQUAKE-TIMING, RECURRENCE, AND FAULT-SLIP-RATE ESTIMATES FOR THE SPRING LAKE SITE

Earthquake timing *(cal yr B.P.)*

Event	mean	1σ	2σ	central 95%	
SL7	13,132	1992	3984	9623	16,751
SL6	6643	364	728	5911	7321
SL5	5722	380	760	4966	6488
SL4	4779	387	774	4279	5562
SL3	3971	260	520	3509	4386
SL2	2948	362	724	2348	3506
SL1	876	109	218	700	1077

OxCal model: Spring_Lake_N/SpringLake_ver_5_int_ZB.
central 95% range is based on the OxCal time distribution with the highest probability density.

Inter-event recurrence

Events	Mean	1σ	2σ	central 95%	
SL7-SL6	6492	2027	4054	2867	10232
SL6-SL5	920	438	876	109	1759
SL5-SL4	950	502	1004	1	1799
SL4-SL3	802	517	1034	0	1766
SL3-SL2	1023	478	956	82	1859
SL2-SL1	2072	380	760	1414	2728

Inter-event intervals (e.g., between SL7 and SL6) calculated using the "Difference" command in OxCal.

Coefficient of variation (COV)

events	mean	stdev	COV
SL7-SL1	2043	2228	1.09
SL6-SL1	1153	520	0.45

COV is the standard deviation (stdev) of inter-event recurrence times divided by their mean.

Mean recurrence

Events	Total time interval					Intervals	Mean recurrence				
	mean	1σ	2σ	central 95%			mean	1σ	2σ	central 95%	
SL7-SL1	12,256	1995	3990	8733	15,904	6	2043	333	665	1456	2651
SL6-SL1	5766	380	760	4995	6480	5	1153	76	152	999	1296
SL5-SL1	4846	396	792	4058	5639	4	1212	99	198	1015	1410
SL4-SL1	3897	392	784	3293	4734	3	1299	131	261	1098	1578
SL3-SL1	3095	281	562	2569	3592	2	1548	141	281	1285	1796

Total time intervals between events (eg., SL7 and SL1) calculated using the "Difference" command in OxCal.
Mean recurrence is elapsed time divided by the number of intervals.

Slip rate

Event	Mean time	Ind. displacement			Total displacement				Total time interval				Slip rate		
		midpt	min	max	events	midpt	min	max	events	mean	95th range		mean	min	max
SL7	13,132	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SL6	6643	1.1	0.8	1.4	SL6-SL1	5.9	4.4	7.4	SL7-SL1	12,256	8733	15904	0.48	0.28	0.85
SL5	5722	0.95	0.7	1.2	SL5-SL1	4.8	3.6	6.0	SL6-SL1	5766	4995	6480	0.83	0.56	1.20
SL4	4779	0.9	0.7	1.1	SL4-SL1	3.85	2.9	4.8	SL5-SL1	4846	4058	5639	0.79	0.51	1.18
SL3	3971	1.05	0.8	1.3	SL3-SL1	2.95	2.2	3.7	SL4-SL1	3897	3293	4734	0.76	0.46	1.12
SL2	2948	0.8	0.6	1.0	SL2-SL1	1.9	1.4	2.4	SL3-SL1	3095	2569	3592	0.61	0.39	0.93
SL1	876	1.1	0.8	1.4	SL1	1.1	0.8	1.4	SL2-SL1	2072	1414	2728	0.53	0.29	0.99

Slip rate is total displacement (e.g., for earthquakes SL6 to SL1) divided by the total time interval (e.g., SL7 to SL1).

APPENDIX J

SUMMARY OF EARTHQUAKE-TIMING, RECURRENCE, AND FAULT-SLIP-RATE ESTIMATES FOR THE NORTH CREEK SITE

Earthquake timing *(cal yr B.P.)*

Event	mean	1σ	2σ	central 95%		
NC5	4665	353	706	4072	5283	
NC4	4023	43	86	3930	4112	
NC3	2593	443	886	2014	3537	*(mode: 2150)*
NC2	1166	60	120	1048	1271	
NC1	220	50	100	153	303	

OxCal model: North Creek, 2012 v3f [excl WC12-80-3; incl. intervals] (appendix E).
Central 95% range is based on the OxCal time distribution with the highest probability density.

Inter-event recurrence

Events	Mean	1σ	2σ	central 95%		
NC5-NC4	641	354	708	36	1245	
NC4-NC3	1431	446	892	460	2030	*(mode: 1845)*
NC3-NC2	1426	449	898	812	2396	*(mode: 1015)*
NC2-NC1	946	79	158	792	1091	

Inter-event intervals (e.g., between NC4 and NC1) calculated using the "Difference" command in OxCal.

Coefficient of variation (COV)

Events	mean	stdev	COV
NC5-NC1	1111	387	0.35
NC4-NC1	1268	279	0.22

COV is the standard deviation (stdev) of inter-event recurrence times divided by their mean.

Mean recurrence

Events	Total time interval					Intervals	Mean recurrence				
	mean	1σ	2σ	central 95%			mean	1σ	2σ	central 95%	
NC5-NC1	4445	357	714	3842	5080	4	1110	90	180	960	1270
NC4-NC1	3803	66	132	3664	3925	3	1270	20	40	1220	1310
NC3-NC1	2373	446	892	1762	3345	2	1190	220	450	880	1670

Total time intervals between events (eg., NC4 and NC1) calculated using the "Difference" command in OxCal.
Mean recurrence is elapsed time divided by the number of intervals.

Slip rate

Total displacement				Total time interval				Slip rate		
events	midpt	min	max		mean	central 95%		mean	min	max
Units 1c/2a	10.4	6.0	14.8	soil 1bA	5268	5048	5433	2.0	1.1	2.9
NC4-NC1	8.3	3.9	12.7	NC5-NC1	4445	3842	5080	1.9	0.8	3.3

The slip rate for NC5 is the total displacement for earthquakes NC5-NC1 divided by the mean time of footwall soil 1bA.
For NC4, the slip rate is the displacement in NC4-NC1 divided by the elapsed time between NC5 and NC1.

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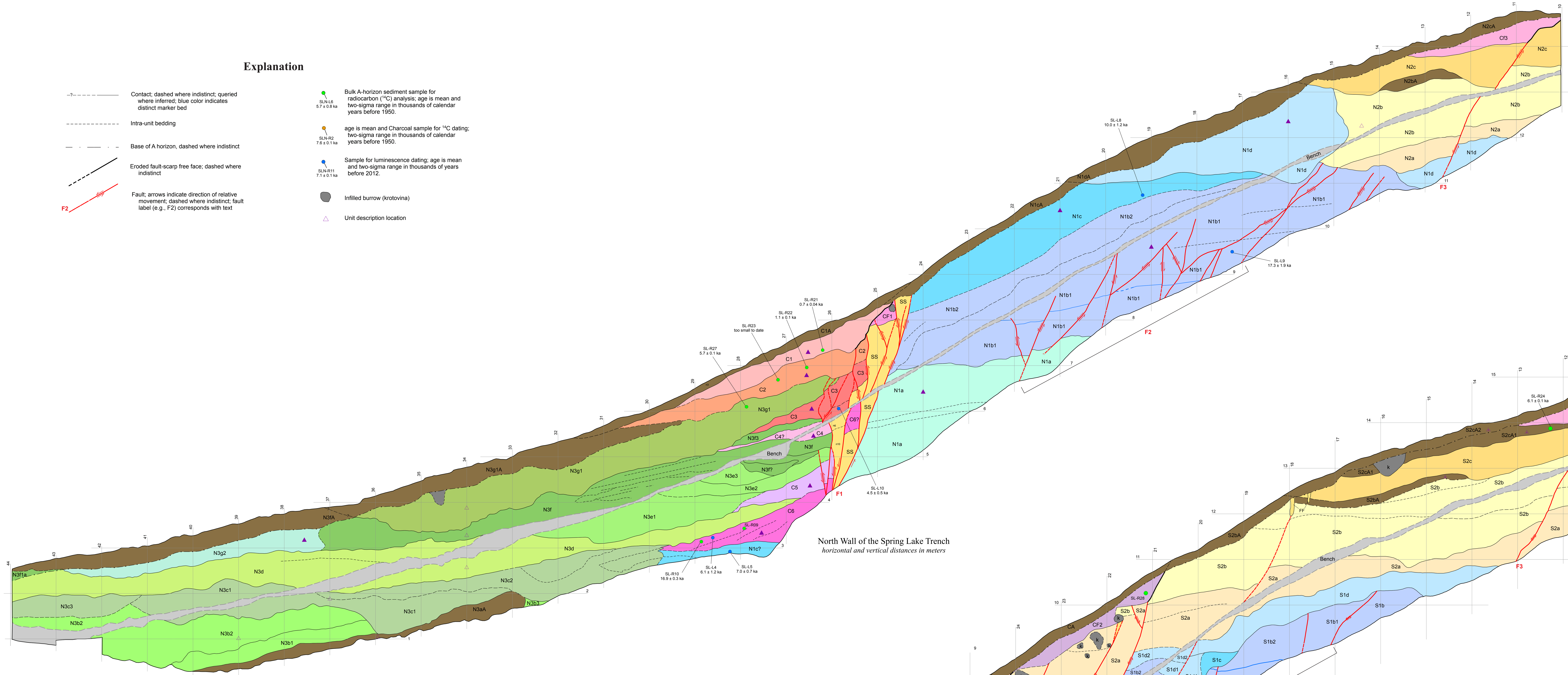
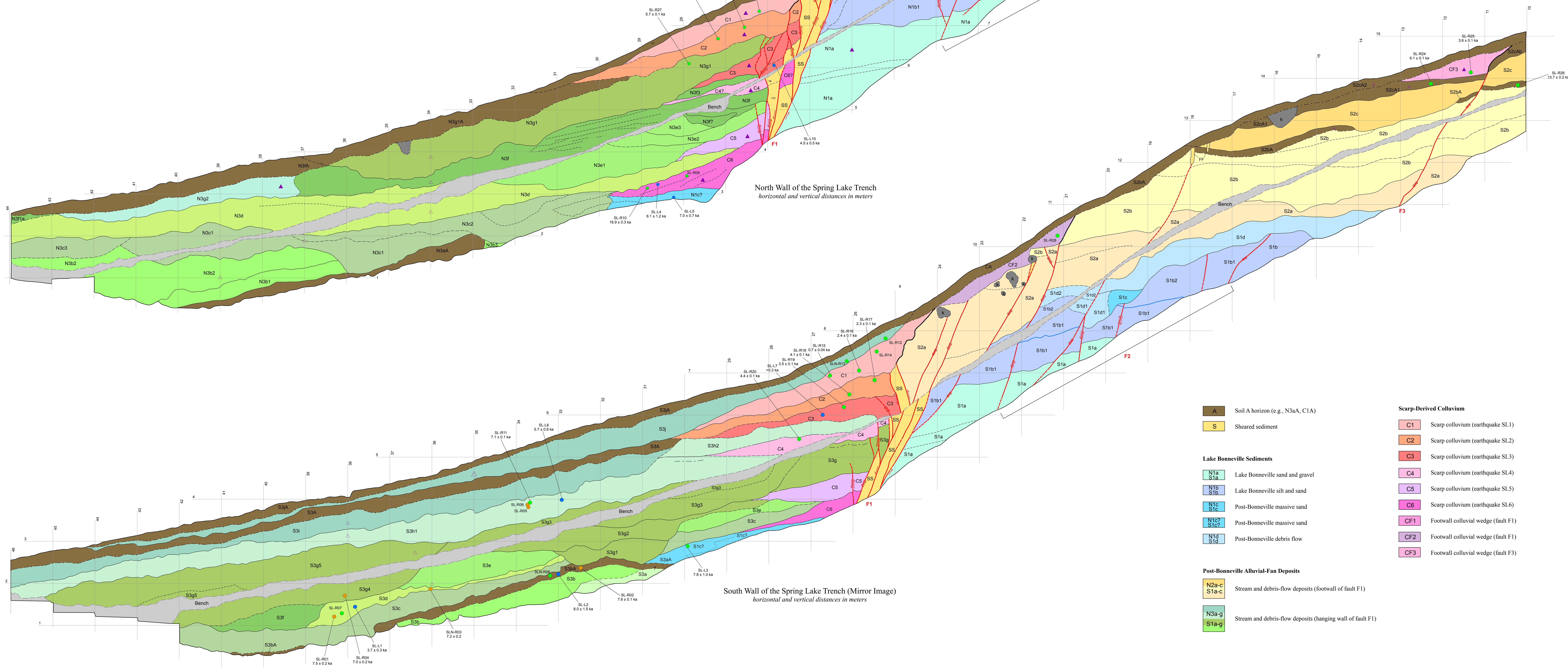
Explanation

- Contact; dashed where indistinct; queried where inferred; blue color indicates distinct marker bed
- Intra-unit bedding
- Base of A horizon, dashed where indistinct
- Eroded fault-scarp free face; dashed where indistinct
- F2 — Fault; arrows indicate direction of relative movement; dashed where indistinct; fault label (e.g., F2) corresponds with text
- SLN-L6 5.7 ± 0.8 ka — Bulk A-horizon sediment sample for radiocarbon (^{14}C) analysis; age is mean and two-sigma range in thousands of calendar years before 1950.
- SLN-R2 7.6 ± 0.1 ka — age is mean and Charcoal sample for ^{14}C dating; two-sigma range in thousands of calendar years before 1950.
- SLN-R11 7.1 ± 0.1 ka — Sample for luminescence dating; age is mean and two-sigma range in thousands of years before 2012.
- Infilled burrow (krotovina)
- Unit description location



North Wall of the Spring Lake Trench
horizontal and vertical distances in meters



South Wall of the Spring Lake Trench (Mirror Image)
horizontal and vertical distances in meters

Unit	Description
A	Soil A horizon (e.g., N3aA, C1A)
S	Sheared sediment

Lake Bonneville Sediments

Unit	Description
N1a S1a	Lake Bonneville sand and gravel
N1b S1b	Lake Bonneville silt and sand
N1c S1c	Post-Bonneville massive sand
N1c? S1c?	Post-Bonneville massive sand
N1d S1d	Post-Bonneville debris flow

Post-Bonneville Alluvial-Fan Deposits

Unit	Description
N2a-c S1a-c	Stream and debris-flow deposits (footwall of fault F1)
N3a-g S1a-g	Stream and debris-flow deposits (hanging wall of fault F1)

Scarp-Derived Colluvium

Unit	Description
C1	Scarp colluvium (earthquake SL1)
C2	Scarp colluvium (earthquake SL2)
C3	Scarp colluvium (earthquake SL3)
C4	Scarp colluvium (earthquake SL4)
C5	Scarp colluvium (earthquake SL5)
C6	Scarp colluvium (earthquake SL6)
CF1	Footwall colluvial wedge (fault F1)
CF2	Footwall colluvial wedge (fault F1)
CF3	Footwall colluvial wedge (fault F3)

STRATIGRAPHIC AND STRUCTURAL RELATIONS AT THE SPRING LAKE TRENCH SITE

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A — Soil A horizon (e.g., 2bA, C1A)
S — Sheared sediment

Footwall Alluvial-Fan Sediments

1a-c — Stream and debris-flow deposits

Hanging-Wall Alluvial-Fan Sediments

4 — Cultural fill (Hanson and others [1981] trench)
3 — Historical debris flow
2e — Stream and debris-flow deposits
2d — Stream and debris-flow deposits
2c — Stream deposits (well-sorted gravel)
2b — Stream and debris-flow deposits
2a — Silt (loess)

Scarp-Derived Colluvium

C1 — Scarp colluvium (earthquake NC1)
C2 — Scarp colluvium (earthquake NC2)
C3 — Scarp colluvium (earthquake NC3)
C4 — Scarp colluvium (earthquake NC4)
C5? — Scarp colluvium (earthquake NC5)
Cg1 — Hanging-wall colluvial wedge (fault F6)
Cg2 — Hanging-wall colluvial wedge (faults F3 and F4)
Cg3 — Hanging-wall colluvial wedge (fault F2)

South Wall of the North Creek Trench (Mirror Image)
horizontal and vertical distances in meters

North Wall of the North Creek Trench
horizontal and vertical distances in meters

Explanation

Contact; dashed where indistinct; queried where inferred; blue color indicates distinct marker bed

Intra-unit bedding

Base of A horizon, dashed where indistinct

Eroded fault-scarp free face; dashed where indistinct

F2 — Fault; arrows indicate direction of relative movement; dashed where indistinct; fault label (e.g., F2) corresponds with text

NC-R21 0.3 ± 0.2 — Bulk A-horizon sediment sample for radiocarbon (^{14}C) analysis; age is mean and two-sigma range in thousands of calendar years before 1950.

NC-R19 4.1 ± 0.1 — Charcoal sample for ^{14}C dating; age is mean and two-sigma range in thousands of calendar years before 1950.

NC-L2 1.5 ± 0.8 — Sample for luminescence dating; age is mean and two-sigma range in thousands of years before 2012.

k — Infilled burrow (krotovina)

Unit description location

d — Sediment disturbed during trench excavation

STRATIGRAPHIC AND STRUCTURAL RELATIONS AT THE NORTH CREEK TRENCH SITE