FINAL TECHNICAL REPORT

Paleoseismology of Faults Submerged Beneath Utah Lake

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Abstract

High-resolution seismic reflection profiles covering all of Utah Lake at spacings of 1.5 kilometers and with typical depth penetration of about 25 meters allowed us to delineate the lengths, orientations, and paleoseismic history of two major auxiliary normal faults to the Provo segment of the Wasatch fault, the Main Saratoga Springs fault and the Lincoln Point West fault. Twenty-one additional subsidiary normal faults and monoclines, shorter and with smaller displacements, but all displaying latest Holocene activity, were mapped across two or more profiles, and several more are traceable on only one profile.

The upper stratigraphic section in the lake comprises two major lake cycles, Lakes A and B, separated by an erosional, locally angular unconformity, U2. Earthquake event horizons identified in these strata include scarp-fill wedges that onlap the pre-earthquake lakefloor in proximal fault hanging walls, stratigraphically limited liquefaction collapse structures including fractures and sags, seismite strata caused by wholesale, basinwide liquefaction of the lake bed to a depth of 2 meters, and probable seismically triggered debris flows. Six distinct event horizons are recognized, and provisionally correlated to major earthquakes on the Provo segment determined by trenching.

The most important seismic hazards discovered in the lake are two enormous debris flows, probably triggered by the same large earthquake, as they are intercalated between the same two lacustrine strata. The American Fork flow underlies 28 km^2 in the northeast basin and reaches a thickness of 16 meters. Its probable source is American Fork Canyon. The Provo Canyon/Orem debris flow is of similar aerial extent and has a maximum preserved thickness of 7 meters. Its presumed source is Provo Canyon. Older large debris flows are also present in deeper strata in the same locations. If similar flows are triggered by a future large earthquake, American Fork, Orem, and surrounding communities will be devastated, and the lake tsunami produced could inundate lakeshore developments such as Saratoga Springs.

Introduction

Utah Lake lies in north central Utah, in the hanging wall of the arcuate, west-dipping Provo segment of the Wasatch normal fault (Fig. 1). This segment has a tip-to-tip scarp length of ~58 kilometers and generates earthquakes as large as M_w7.5 at a closed mean recurrence interval of 1300 ± 200 years. The most recent event (MRE) was 580 ± 50 years ago (Christopher DuRoss, personal communication, 2014).

The eastern Utah Valley Interstate-15 urban corridor, including the cities of Lehi, American Fork, Orem, Provo, Springville, Spanish Fork, and Payson, is situated on the proximal hanging wall of the Provo segment. Total population exceeded 516,000 as of the 2010 Census. Utah Lake occupies the more distal hanging wall further west, submerging the west central part of Utah Valley. The Provo and Spanish Fork Rivers, entering the lake from the east and southeast, respectively, are its current primary tributaries, although additional streams and rivers were important water and sediment sources during earlier, wetter climatic periods. The Jordan River is its sole outlet, flowing from the lake's northwest corner northward into the Great Salt Lake. Utah Lake is very shallow, averaging only 3.2 meters deep. It has a north-south elongate kidney shape with a length of 39 kilometers and maximum width of 21 kilometers.

This report documents active faults and faulting-related tectonostratigraphy beneath Utah Lake, and also summarizes the record of paleoearthquakes preserved in the upper 25 meters of lacustrine sediment. Features related to active faulting and seismicity include surface-rupturing earthquake event horizons, seismite strata and other liquefaction-induced deformation, major debris flows, and hot springs and related collapse structures and travertine deposits. These were identified and studied on 84 high-resolution seismic reflection profiles collected in the summer of 2010 using the Scripps Oceanographic Institute custom-built Chirp seismic system. 24 profiles cross the entire basin on east-west tracks, approximately perpendicular to the strike of most faults present, at spacings of about 1.5 kilometers (Fig. 2).

Previous Work

Cook and Berg (1961) postulated an east-dipping "Utah Lake Fault Zone" based on a steep, north-striking gravity gradient that extends northward through the center of the lake from the eastern slope of West Mountain (Figure 1). Two high-resolution seismic reflection surveys in Utah Lake, both with the goal of locating and characterizing sublacustrine springs and associated travertine deposits, imaged faults cutting lakebed deposits. The traces of faults beneath Utah Lake shown on all published Utah fault maps (e.g., Goter, 1990; Hecker et al., 2003) are based on data from a 1975 reflection survey, which consists of sparse, low-quality, analog 7-kHz records with a maximum subbottom penetration of about 20 m collected using dead-reckoning navigation with location uncertainties greater than 0.1 km (Brimhall et al., 1976; Brimhall and Merritt, 1981). This reconnaissance survey established the existence and rough locations of normal faults displacing mid- to late Holocene deposits in the lake basin, and suggested that faults in the center of the basin dip predominantly west, not east, as postulated by Cook and Berg (1961). Unfortunately, the results of that survey cannot be evaluated or reconstructed, as no trackline map appears in either of the two reports that resulted from that project, and the original trackline map and seismic data have been lost and probably destroyed (Willis H. Brimhall, personal communication, 2006). Nonetheless, the current state of knowledge on Utah Lake faults is based primarily on that survey and is summarized in the Utah Quaternary Fault and Fold Data Base (2006) as follows:

"[Utah Lake] fault and fold locations, based on widely spaced seismic reflection transects, are uncertain. Acoustical profiles show from < 2 to 5 m of displacement across individual faults and folds beneath the lake in a persistent 8- to 15-m-deep layer identified as the Provo Formation. Machette et al. (1992) interpreted the layer as lake-bottom sediments probably deposited during the regressive phase of Lake Bonneville. The reflection profiles suggest that displacements decrease upward in strata above the marker horizon and occur within several meters of the lake bottom."

In a study focused narrowly on hot springs beneath the south central part of the lake, Baskin and Berryhill (1998) collected some 40 km of boomer reflection data with a maximum subbottom penetration of 75 m in a zone about 4 km wide (E-W) by 5 km long (N-S) due north of West Mountain (Fig. 2). These profiles confirmed the existence of normal faults cutting Holocene lake deposits. They presumed that east-dipping faults near the eastern ends of their east-west lines are antithetic ruptures auxiliary to the Provo segment of the Wasatch fault. A prominent west-dipping fault with 6-8 meters of Holocene displacement near the western end of their study area was surmised to have a displacement history possibly independent of the Provo segment.

Data Collection

The seismic reflection equipment used for this 2010 survey was a custom-built Chirp system on loan from the Scripps Institute of Oceanography and designated as an Edgetech SB512SC (see Baskin, 2014). The Chirp towfish contains both the seismic source and receiver. Two transducers on the towfish supply an outgoing Chirp signal in two overlapping frequency ranges, with one producing a signal from 500 Hz to 6 kHz and the other from 2-16 kHz. In this survey, the system was configured to sweep a 1-15 kHz frequency range in 0.03 s, with a time interval of 0.5 s between sweeps and a recording time of 0.133 s. The receiver in the towfish consists of four hydrophone arrays in a near vertical orientation, the output of which is summed to produce a single record from each outgoing source pulse. The known Chirp source signal is deconvolved from each record as part of the data acquisition process. Under optimal conditions, the SB512SC Chirp system can obtain interpretable data to ~30 m below the lakebed. Positioning was supplied by a GPS receiver supplemented with a Wide Area Augmentation System (WAAS) capable of providing ±3 m accuracy 95% of the time.

The Edgetech SB512SC differs from commercial units in that the signal digitization and source deconvolution processes are done in an on-fish pressured bottle instead of in a computer on the boat. This configuration minimizes interference from electromagnetic sources and reduces variations in signal quality resulting from environmental conditions. The data are recorded on hard disk in an Edgetech format. We converted the data to SEG-Y format, and imported into the HIS Kingdom Suite software package, which we used for viewing and interpreting the profiles.

Stratigraphy

The Utah Lake stratigraphic section relevant to this study overlies a prominent reflector, U1, which along the basin margins is an erosional unconformity in some places, a delta top/transgressive flooding surface in others. It dips basinward and becomes a conformity in the deeper, central basin, where it is overlain by approximately 25 meters of sedimentary strata representing two lake cycles, here designated Lake A (LA) and Lake B (LB), pending coring, dating, and correlation of these sequences with regional late Quaternary lake cycles (e.g., Oviatt, 1997). All thicknesses and depths below the lakebed cited here are calculated assuming a sedimentary P-wave velocity of 1700 meters/second. No measurements of P-wave velocity are yet available from Utah Lake, so the chosen value is based on typical velocities measured on lacustrine deposits at similar depths at GLAD1 Core Site 4 in the Great Salt Lake (http://www.ngdc.noaa.gov/mgg/curator/data/kerry_kelts/glad1/data/).

Surface U1 as it appears near the basin margin in the northwest corner of the lake is shown in Figure 3. It overlies a foreset unit less than a meter thick, and is overlain by the lowermost strata of the Lake A sequence, Units LA1-LA5. These and overlying strata are interpreted as lacustrine in origin because, in general, they persist in remarkably uniform thicknesses throughout the basin and display thin, planar, subhorizontal, internal bedding, identical to acoustic signatures of known lacustrine deposits profiled in numerous other lakes (e.g., Dinter and Pechmann, 2005). Units LA2 and LA3 are exceptions. LA2 has a mounded or hummocky-topped morphology throughout the lake basin and a nonuniform thickness of 0.3-1.2 meters. Individual mounds are 5 - 30 meters wide and swales between mounds have relief up to 0.5 meters. Internal bedding is only rarely and spottily preserved. By contrast, LA3 has a uniform thickness of 0.6-0.7 meters and well-preserved internal bedding, but is folded into antiforms above prominent LA2 mounds and into synforms above prominent LA2 swales. Small-relief and closely spaced mound-and-swale morphology on the top of LA2 is commonly not mimicked in the folding of LA3 (Fig. 3). The deformation of LA2 and LA3 and its significance will be discussed in a later section. The lowest beds of LA4 infill LA3 synforms, whereas its upper internal beds are planar and subhorizontal.

The complete post-U1 sedimentary section is depicted in Figure 4 on a profile slightly deeper into the basin than Figure 3. Units LA4 to LA10 are all similar in character, thickening slightly basinward and preserving thin internal bedding. The toe of an enormous debris flow, described below, overlies Unit LA8 and is draped and mantled by Unit LA9. Units LA11-LA14, poorly imaged on this profile, were partially removed by subaerial erosion following the end of the Lake A phase, evidenced by the channel cut on this section. Unconformity U2, commonly an angular unconformity near basin margins, lies at the base of the Lake B section (LB), which is not subdivided here, but is seen to consist of 4 distinct beds at this location.

Unit LA11, well imaged in Figure 5, has a mound-and-swale morphology similar to LA2, but the mounds are more closely spaced on the average, and have greater relief. Swales between mounds commonly penetrate to the base of unit. No internal bedding is preserved. The overlying Unit LA12 is, unlike LA3, highly nonuniform in thickness. Swales and gaps between LA11 mounds were mostly filled by the lower beds of LA12 prior to the draping of upper LA12 beds over the mound crests. Units LA13 and LA14 represent the final stages of the Lake A phase. They are similar to Units LA4-LA10, but planar internal beds are not as strongly reflective.

Surface U2, present throughout the Utah Lake Basin, is typically an angular unconformity near basin margins. In more central parts of the basin, fluvial channels eroded into upper Lake A beds are common beneath U2 (Fig. 4). Lake B Units LB1-LB4, overlying the U2 unconformity, are bounded by relatively strong reflectors that correspond to earthquake event horizons, discussed below (Fig. 6). The Lake B section is up to several meters thicker on the hanging walls of major faults in the basin than on the footwalls, illustrating growth on those structures.

Faults

Active normal faults disrupt late Holocene Utah Lake sedimentary strata in five broad areas: near the northwest lakeshore east of Saratoga Springs, along the northeast lakeshore south of American Fork, in the central basin west and south of Utah Lake State Park, north and east of West Mountain near Bird Springs and Lincoln Point, and in Goshen Bay and along the west shoreline of West Mountain (Fig. 7). Saratoga Springs faults strike north-northwest, American Fork faults strike northwest, and most central and southern faults strike roughly north-south. In general, faults in the central and northern parts of the basin persist for 2 to 7.5 kilometers along strike, whereas those surrounding West Mountain in the southern basin can be traced for only 1-2 kilometers. Both east- and west-dipping faults are present. Most disrupt sediments within a meter or two below the lakebed, displaying either a buried scarp of a surface rupture or a monoclinal warp above a fault that did not rupture the lakebed.

Saratoga Springs faults

Four east-dipping faults in the northwest/north-central basin east of Saratoga Springs rupture strata within a meter of the lakebed (Fig. 7). Two are traceable for only 1.5 km along strike near the northern lakeshore. Cumulative post-U1 vertical displacement on each is about one meter, with displacement increasing northward. The main Saratoga Springs fault has a tip-to-tip length of 8.0 km and maximum cumulative post-U1 vertical displacement of 3.75 meters. At least four post-U1 surface-rupturing earthquake event horizons are recognized in the hanging wall of this fault, with strong evidence for a fifth (discussed below). A smaller fault with ~one meter of post-U1 vertical displacement parallels the northern part of the main fault for 4 km along strike, 0.6 km to the west.

American Fork faults

Lacustrine strata within 1-2 km of the eastern lakeshore commonly contain biogenic gas that significantly degrades seismic profiles. As a result, only two structures are mappable across two or more profiles in the northeast Utah Lake basin along the American Fork shoreline, a southwest-dipping normal fault at least 2.5 km long and a minor northeast-dipping monocline facing it 300 meters to the northwest (Fig. 7). The fault displaces Unconformity U2 approximately 0.8 meters. Deeper correlative horizons are not visible owing to gas. At least two additional west-dipping faults with post-U2 displacements exist about 0.7 and 1.0 km southwest of the mapped fault, but are only visible on one profile, again because of gas wipeouts.

Central basin faults

Active extensional structures in the central Utah Lake basin include the west-dipping State Park fault and five east-dipping monoclines (Fig. 7). The State Park fault is at least 1.5 km long, but neither its full length nor displacement can be determined owing to severe gas degradation of profiles. The monoclines strike north-south and range 3 to 5 km in length. The two easternmost monoclines are closely spaced and form a low-relief graben with the State Park fault. The remaining three are spaced at 0.8-1.5 km, and each step westward into the basin is associated with a 1.5-2.5-km step southward, defining an en echelon-like pattern. Each monocline has a meter or less displacement of Lake B strata within 1-2 meters of the lakebed, usually with a clearly defined event horizon. Growth is evident in deeper strata, but gas wipeouts preclude identification of deeper event horizons.

Bird Springs/Lincoln Beach faults

The Bird Springs fault is a minor northwest-dipping structure only 1.5 km long, notable principally owing to its spatial association with a travertine mound some 2 km in diameter, centered on Bird Island (Fig. 7). Units L6-L11 are displaced at most one meter on this fault. Older units are not present because they onlap the travertine mound west of the fault. Between Bird Island and Lincoln Point a pre-U1, east-dipping monocline is traceable for 1 km, and four similar structures are present north of Lincoln Beach to the east. These monoclines displace pre-U1 strata up to 3 meters, but displace post-U1 strata at most 0.3 meters, if at all.

Goshen Bay faults

The most important fault in this zone is the west-dipping Lincoln Point West fault, which strikes north-northeast for 5 kilometers in northeast Goshen Bay (Fig. 7). Its southern end has two, locally three, splays, with a cumulative NTVD of Units LA1-LA10 of about 4.7 meters, and of Unconformity U2 of 3.4 meters. The east-dipping Northwest Goshen Bay fault persists for 7 kilometers along strike and appears to intersect the west lakeshore at its north end. Units LA10 and older are displaced 1.2 meters vertically. Younger strata through LB3 are warped into a monocline. The Southwest Goshen Bay fault also dips east and displaces strata as young as LB3. The NTVD of Lower Lake B units is 2.1 meters, with displacement increasing southward. The Southeast Goshen Bay fault also dips east and has similar displacements at similar stratigraphic levels. Its southern end appears to project onshore into a linear travertine spring along the shoreline west of West Mountain.

Seismite Strata

Units LA2 and LA11, the strata characterized throughout the Utah Lake basin by mound-and-swale morphology and by the absence or sparse, poor preservation of internal bedding (see above), are interpreted here as seismites, layers that experienced wholesale (LA11) or nearly complete (LA2) liquefaction during paleoearthquakes. Unit LA3 has a uniform thickness and is folded into antiforms and synforms that overlie the larger mounds and swales, respectively, of Unit LA2 (Figs. 3 and 4). We interpret this morphology to indicate that LA3 was present during the earthquake that liquefied LA2, and was folded passively during the liquefaction event. The basal beds of Unit LA4 infill LA3 synforms, and so postdate the earthquake. The top of Unit LA3 is an earthquake event horizon.

Unit LA11 has greater relief than LA2. Some swales penetrate nearly to the base of the unit (Fig. 5). Mound tops are more rounded and no internal bedding is preserved. Basal Unit LA12 beds infill the swales, such that this unit up to three times thicker above LA11 swales than above mound crests. These morphologies imply that LA11 was the stratum immediately underlying the lakebed when the liquefaction event occurred, and LA12 draped the liquefaction-created relief afterward. The top of Unit LA11 is another earthquake event horizon.

Debris Flows

Two types of debris flows are intercalated within the Lake A stratigraphic section in at least four areas of the lake (Fig. 7). The larger flows have extrabasinal sources, almost certainly major canyons draining the Wasatch Mountains to the east. Smaller flows are intrabasinal and appear to have originated by partial liquefaction and downslope movement of lacustrine strata near the basin margins. Remarkably, all four debris flows illustrated in Figure 7 are at least roughly the same age, and probably exactly the same age, most likely resulting from liquefaction induced by a single earthquake. However, debris flows into the lake are not a one-off event. Large flows are also present at deeper stratigraphic levels beneath the most recent American Fork and Provo Canyon/Orem flows.

American Fork debris flow

The American Fork flow is the largest present in the imaged section of the Utah Lake basin, underlying ~28 km^2 in the northeast part of the lake (Fig. 7). Its distal toe overlies Unit LA8 and underlies Unit LA9, the lower beds of which infill irregular relief at the top of the flow (Figs. 4 and 8). The flow thickens northeastward to a maximum of 16 meters near the American Fork lakeshore, and was once even thicker, as pre-U2 subaerial erosion removed part of the top of the flow mass. Mechanical erosion by the debris flow removed all or part of underlying Unit LA8 and incorporated it into the flow beneath much of its extent. In the region within about 1 kilometer of the lakeshore, the entire L1-L8 section was removed by the same process and incorporated into the flow. The most likely source region of the American Fork flow is the American Fork Canyon drainage 10 kilometers to the northeast.

Provo Canyon/Orem debris flow

The Provo Canyon/Orem debris flow has a similar areal extent to that of the American Fork flow and also overlies Unit LA8 and underlies Unit LA9 (Figs. 2 and 8). It is thinner, reaching a maximum thickness of some 7 meters in the lake. However, its thickness and extent were originally greater, as pre-U2 subaerial erosion thinned the flow mass over much of its extent, and entirely removed it in places along the eastern lakeshore (Fig. 2).

Saratoga Springs intrabasinal debris flow

The Saratoga Springs debris flow underlies the northwest basin margin in an area about 0.5 km wide by 4.5 km long (Fig. 2). It did not originate onshore, but by the liquefaction, downslope transport, and thickening of this part of Unit LA8 (Fig. 98). The short, west-dipping reflectors within the flow mass near its toe probably represent compressional shingling or duplexing resulting from the gravitational load of the bulk of the flow mass upslope. Its maximum thickness is 3.5 meters. Like the two extrabasinal flows described above, the intrabasinal Saratoga Spring flow is overlain by an undisrupted Unit LA9, and is, therefore, the same age as those flows (Fig. 9).

West Mountain intrabasinal debris flow

A small intrabasinal debris flow underlies an area of the eastern Goshen Bay margin 0.2-0.5 kilometers wide by 2 kilometers long west of West Mountain (Fig. 7). Seismic images of this flow are of marginal quality, but it also appears to have originated by the partial liquefaction and downslope transport of a section of Unit LA8. Its maximum preserved thickness is 2 meters, but its upslope extent has been removed by pre-U2 subaerial erosion.

Earthquake Event Horizons

Tectonostratigraphic geometries imaged within Lake A and Lake B deposits in Utah Lake preserve direct evidence of multiple late Quaternary surface-rupturing events on the two most significant structures in the lake, the east-dipping Main Saratoga Springs fault and west-dipping Lincoln Point West fault. Seismic event horizons associated with surface ruptures of these faults are recognized on the basis of (1) tectonically produced proximal hanging wall bedding rotations overlain by onlapping “scarp-fill wedges”, analogous to colluvial wedges that bury terrestrial normal fault scarps, and (2) stratigraphically limited “reliquefaction fractures” (Figs. 6 and 8).

Reliquefaction fractures look superficially like stratigraphically limited auxiliary or subsidiary faults, and they have the same utility in dating paleoearthquakes: The uppermost horizon offset by the fractures is an earthquake event horizon (Figs. 6 & 8). However, these fractures are not deeply rooted faults. All of those illustrated in Figures 6 and 8 displace the top of the American Fork debris flow up to 0.5 meters vertically, but do not displace its base. Note in particular the westernmost fracture in the Saratoga Springs fault footwall on Figure 8. These fractures root into the debris flow, and are therefore inferred to be collapse structures caused by local reliquefaction of the flow mass during large earthquakes.

The American Fork debris flow is not the only stratum in the lake that has locally reliquefied during earthquakes subsequent to its emplacement or deposition. Fractures similar to those illustrated in Figures 6 and 8, and closely related features we term “liquefaction sags”, also root variously into Unit LA11 (the upper seismite), into the Provo Canyon debris flow, into Unit LA2 (the lower seismite), or into an unknown pre-Lake A stratum deeper than the depth limit of our seismic profiles. Moreover, earthquake event horizons defined by stratigraphically limited reliquefaction structures are found in numerous areas of the Utah Lake basin far from any tectonic faults.

Two additional types of earthquake event horizons not related to any specific intralake fault are also recognized in Utah Lake, those associated with seismites, and those associated with debris flows. As discussed above, Unit LA3 had already been deposited when LA2 was liquefied, so that the LA3/LA4 contact is an event horizon (Figs. 3, 4 and 5). Unit LA11 was liquefied when it was itself the youngest stratum in the lake. Thus, its contact with overlying Unit LA12 is another event horizon (Figs. 5, 6, and 8). Finally, all four debris flows illustrated in Fig. 2 either overlie or incorporate Unit LA8 and underlie Unit LA9 (Figs. 4, 5 and 8). We therefore consider it highly likely that the LA8/LA9 contact is an event horizon.

Paleoearthquake Chronology of Utah Lake

At least six large paleoearthquakes are recorded in the tectonostratigraphy of post-Unconformity U1 deposits in Utah Lake. Three surface-rupturing event horizons, SS1, SS2, and SS3, are recognized within Lake B strata in the hanging wall of the Main Saratoga Springs fault in the northwestern lake basin (Figs. 6 and 8). Typical net vertical tectonic displacements are on the order of 0.3-0.7 meters/event, with the result that Lake B strata are about 1.5 meters thicker in the hanging wall than in the footwall. Each of these earthquakes rotated proximal hanging wall strata down to the west, such that beds within each post-earthquake scarp-fill wedge onlap the pre-earthquake lakebed (Figs. 6 and 8). Reliquefaction fractures also delineate event horizons SS2 and SS3 on these profiles. Stratigraphically limited reliquefaction fractures and sags correlative to all three of the youngest events are common in many areas of the lake.

The top of the upper seismite, Unit LA11, is designated as event horizon SS4 (Figs. 5, 6 and 8). A reliquefaction fracture coincident with this event soles into the American Fork debris flow (Fig. 8). Gas degradation precludes identification of an SS4 scarp-fill wedge, and indeed, the mound-and-swale morphology created by the liquefaction event may have obscured any associated scarp. However, the LA11-L14 section is ~0.5 meters thicker in the hanging wall of the fault than in the footwall, consistent with the clearer record of growth in Lake B strata (Figs. 6 and 8).

Where present, the tops of the four debris flows depicted in Figure 7 and the base of overlying Unit LA9 approximate event horizon SS5. Elsewhere, SS5 is the LA8/LA9 contact (Fig. 4). Any fault surface ruptures or reliquefaction structures associated with event SS5 would presumably have formed some minutes to perhaps an hour prior to the arrival of the large extrabasin-sourced debris flows, if they were indeed earthquake-triggered. However, no such SS5 structures have yet been identified. Likewise, no such structures have yet been identified associated with the oldest event horizon, SS6, which lies at the top of Unit LA3 as discussed in the previous section.

Most of the faults in Utah Lake, at least those north of West Mountain, are interpreted here as auxiliary faults that probably sole into the Provo segment of the Wasatch fault and are coseismic with it, analogous to the West Valley faults that bear a similar relationship to the Salt Lake City segment of the Wasatch fault to the north (Fig. 1). Therefore, the simplest provisional chronologic interpretation is that events SS1-SS5 in Utah Lake may correlate 1:1 with events P1-P5 delineated by trenching of the Provo segment (e.g., DuRoss, 2014). In order of increasing age, these earthquakes occurred at approximately 580, 1480, 2240, 4710, and 5640 calendar years B.P. SS6 would then be an event older than those so far recognized in Provo segment trenches. Alternatively, some of the Utah Lake event horizons might represent earthquakes that occurred within the P1-P5 age range, but have not been recognized in trenches. Coring and dating the sharply defined Utah Lake event horizons has the potential to greatly increase both the accuracy and precision of the trench-based earthquake chronology of the Provo segment utilizing a completely independent data set.

Seismic Hazard Implications

Sublacustrine, coseismic surface ruptures of up to 0.7 meters along the 8-km-long Main Saratoga Springs fault and 6-km-long Lincoln Point West fault would contribute significantly to the ground acceleration associated with major Provo segment earthquakes, and would also likely create lake tsunamis. By far the greatest seismic hazard illuminated by the Utah Lake record, however, is that associated with the enormous American Fork and Provo Canyon debris flows (Fig. 7). If repeated during a future Provo segment earthquake, such flows would devastate American Fork, Orem, and surrounding population centers, and likely produce a very large lake tsunami that could inundate lakeshore developments such as Saratoga Springs. An additional hazard, particularly relevant to any structures proposed within the lake, such as a bridge crossing, is that the entire lakefloor has liquefied to a depth up to two meters at least twice in the past. Moreover, reliquefaction of seismite and debris flow strata during every large Prove segment earthquake produces lakefloor ruptures and sags with up to a meter of relief in unpredictable locations throughout much of the basin.

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Bibliography of Publications Resulting from Work Performed Under this Award

This document constitutes the first complete, written summary of our analysis of the data collected under this award. We have, however, presented preliminary results in three invited lectures, to the Utah Quaternary Fault Parameters Working Group convened by the Utah Geological Survey, and for seminars at the British BG Group and to Professor Gerard Schuster's research consortium at KAUST (King Abdullah University of Science and Technology).

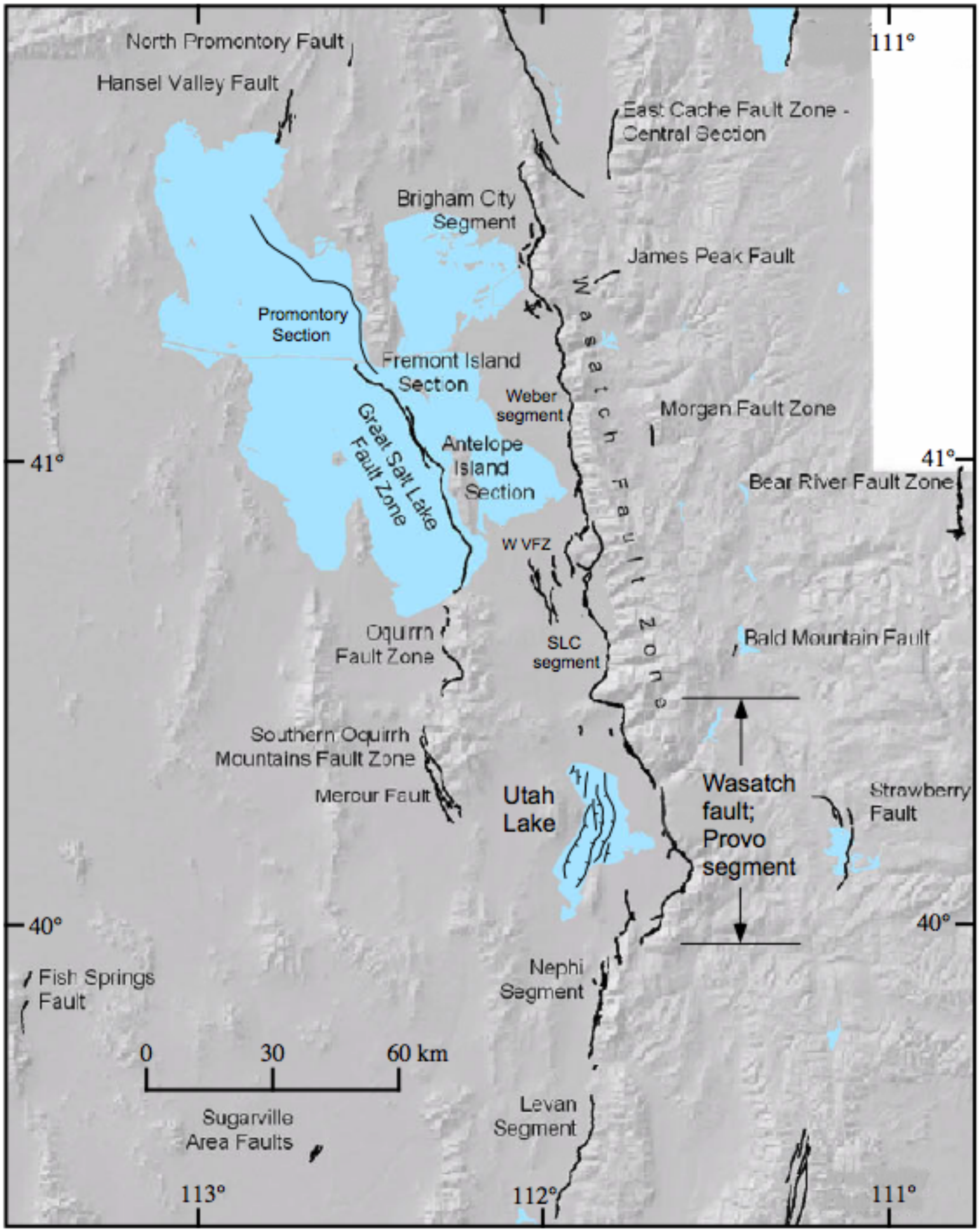

Figure 1. Normal faults with known late Quaternary activity in north central Utah. Faults shown in Utah Lake modified from Brimhall and Merritt (1981). Regional faults after Lund et al. (2005). WVFZ - West Valley fault zone.

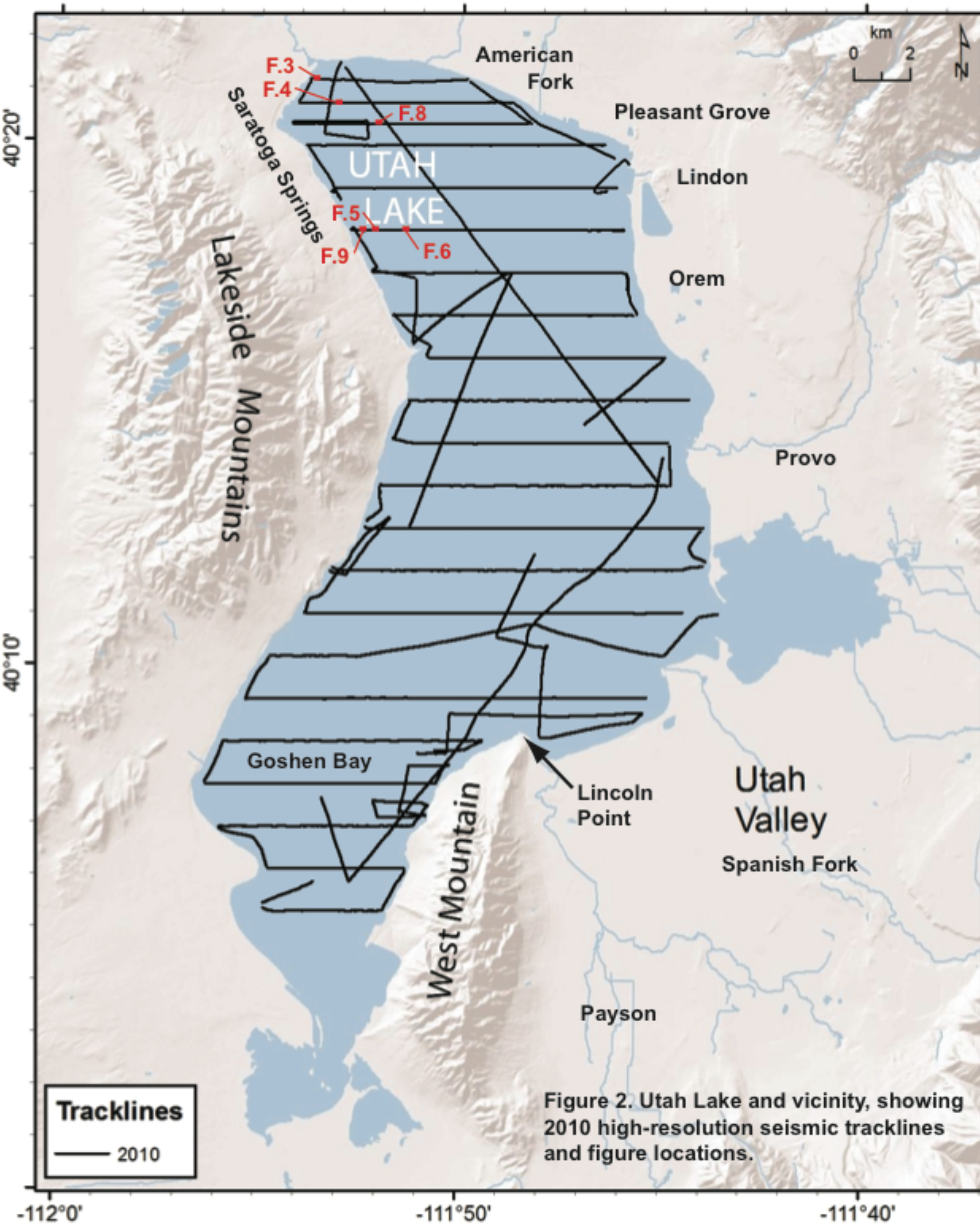

Figure 2. Utah Lake and vicinity, showing 2010 high-resolution seismic tracklines and figure locations.

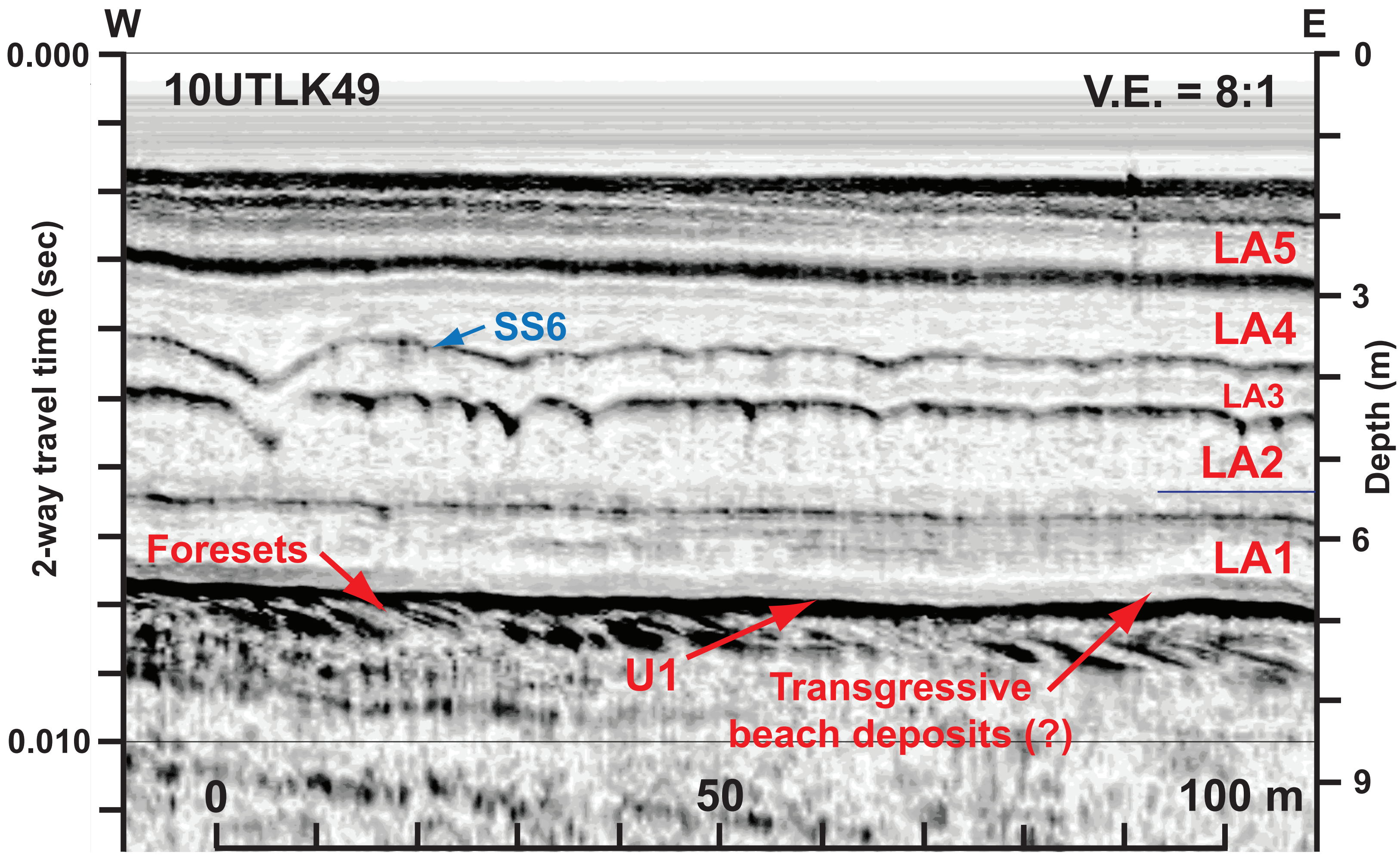

Figure 3. Chirp profile showing Unconformity U1, underlying foresets, and overlying lower strata of Lake A lacustrine sequence. LA2 is the “Lower Seismite” (see text), SS6 is earthquake event horizon SS6 (Saratoga Springs 6, see text). Note possible transgressive beach deposits at base of Unit LA1. See Fig. 2 for location.

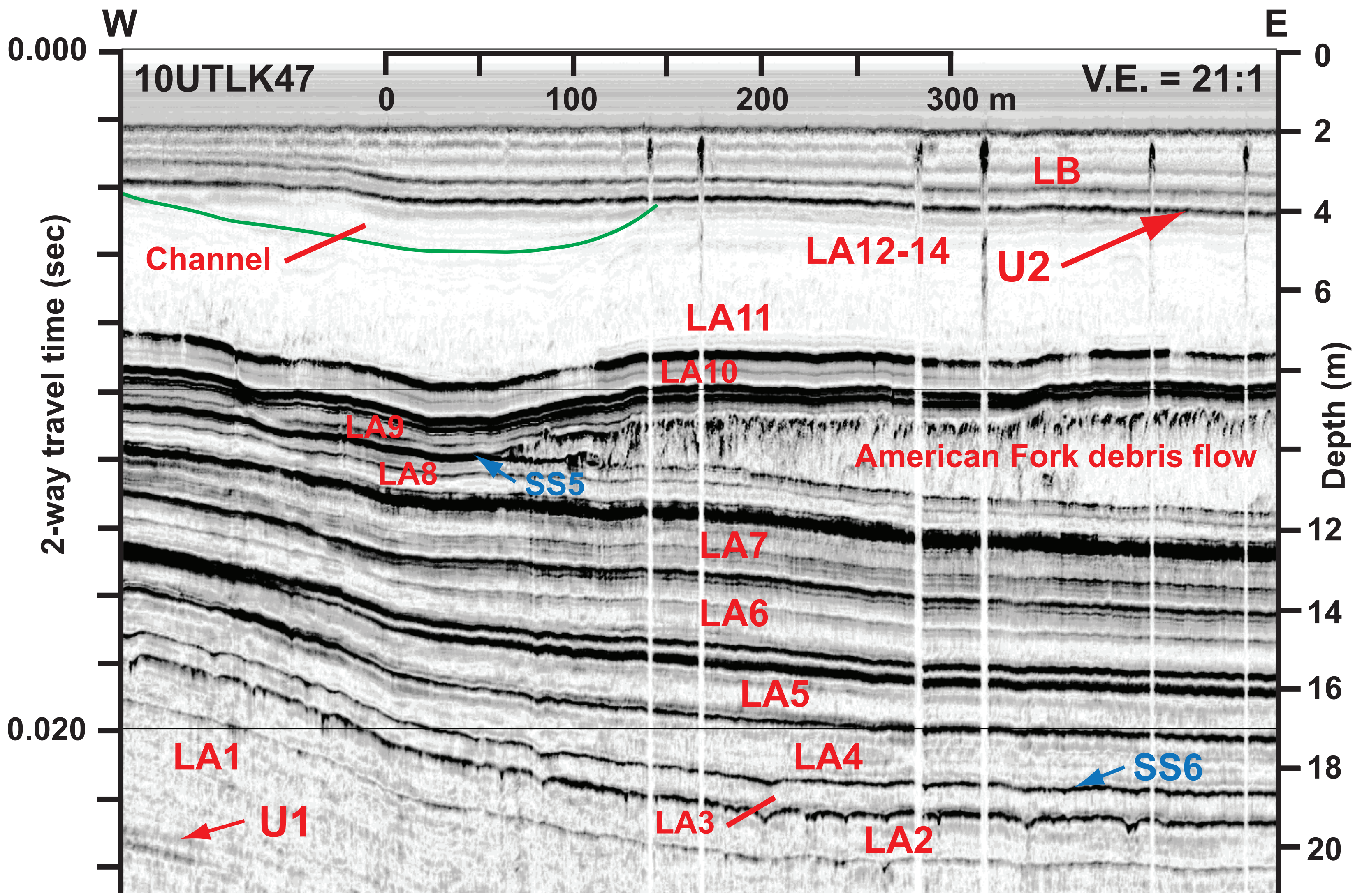

Figure 4. Chirp profile showing entire Lake A stratigraphic section between unconformities U1 & U2, and Lake B strata overlying U2. Note debris flow intercalated between LA8 & LA9 and fluvial channel below U2. SS5 & SS6 are earthquake event horizons (see text). See Fig. 2 for location.

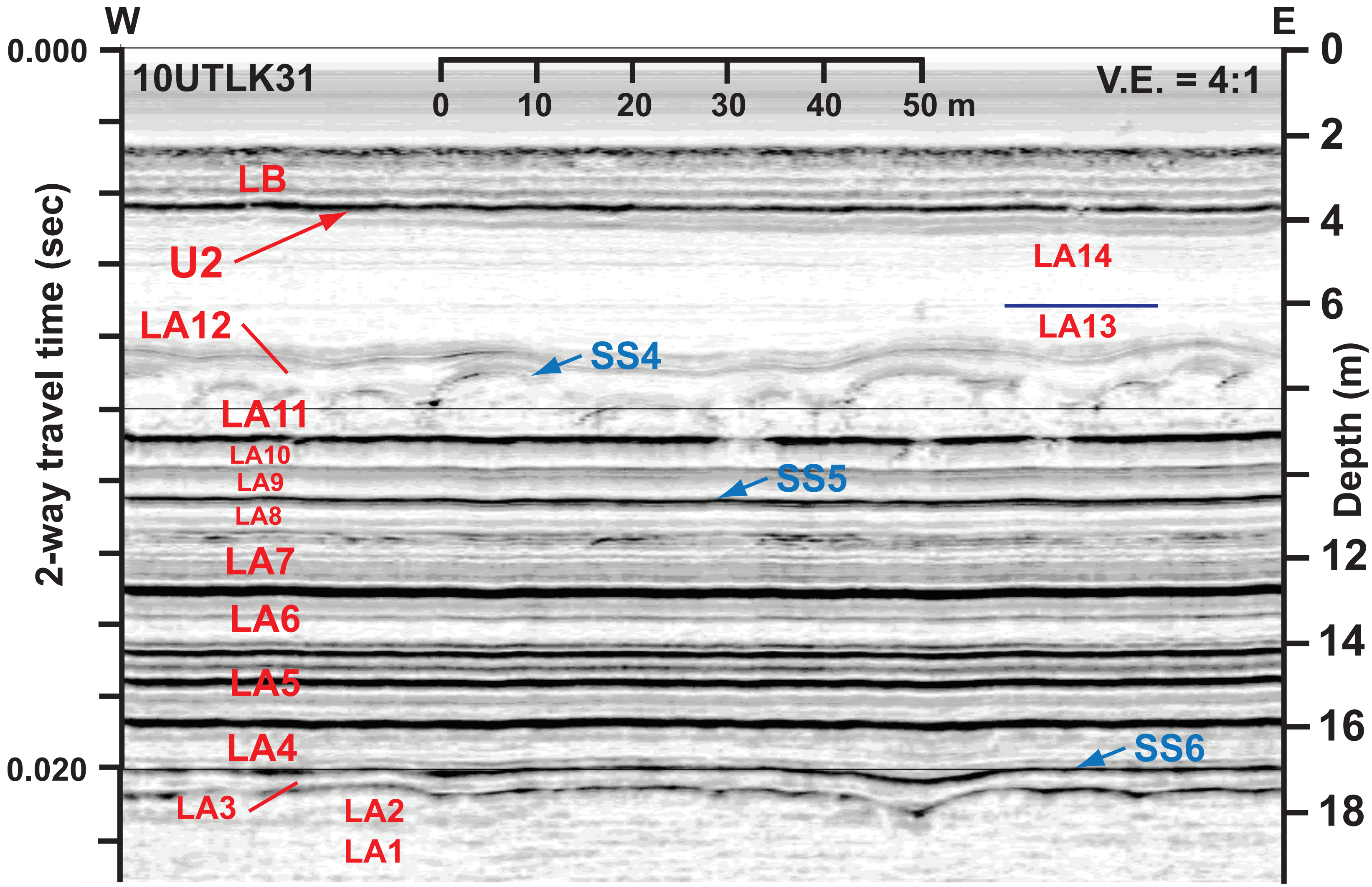

Figure 5. Chirp profile showing good imagery of upper Lake A beds LA11-LA14. LA11 is the “Upper Seismite”, characterized by mound-and-swale morphology and lack of internal bedding. LA12 drapes it, infilling swales. SS4, SS5, and SS6 are earthquake event horizons (see text). See Fig. 2 for location.

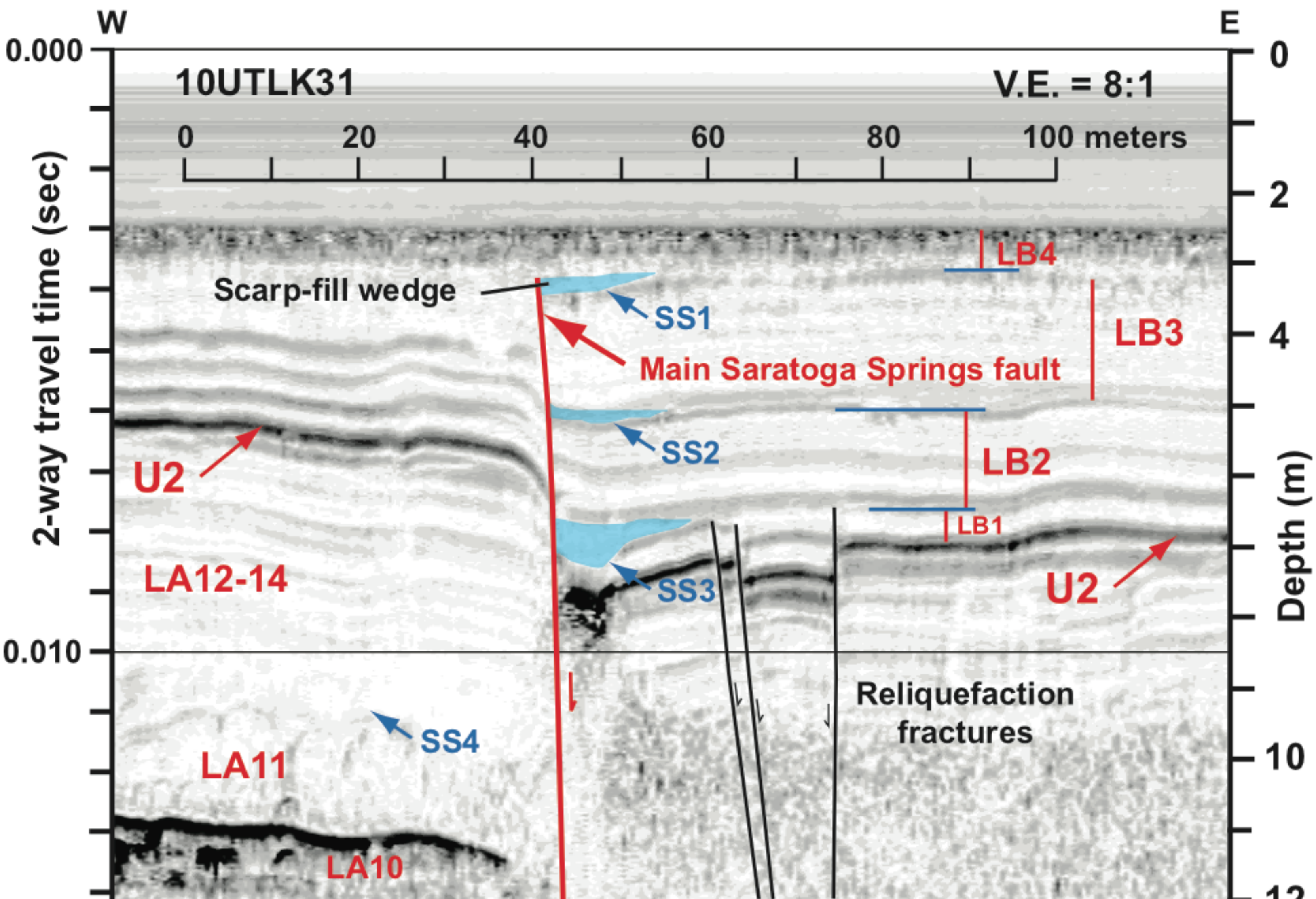

Figure 6. Chirp profile showing detailed Lake B stratigraphy, Main Saratoga Springs fault, event horizons SS1-SS3 delineated by onlapping scarp-fill wedges and stratigraphically limited reliquefaction fractures, and SS4 at top of upper seismite, Unit LA11. See Fig. 2 for location.

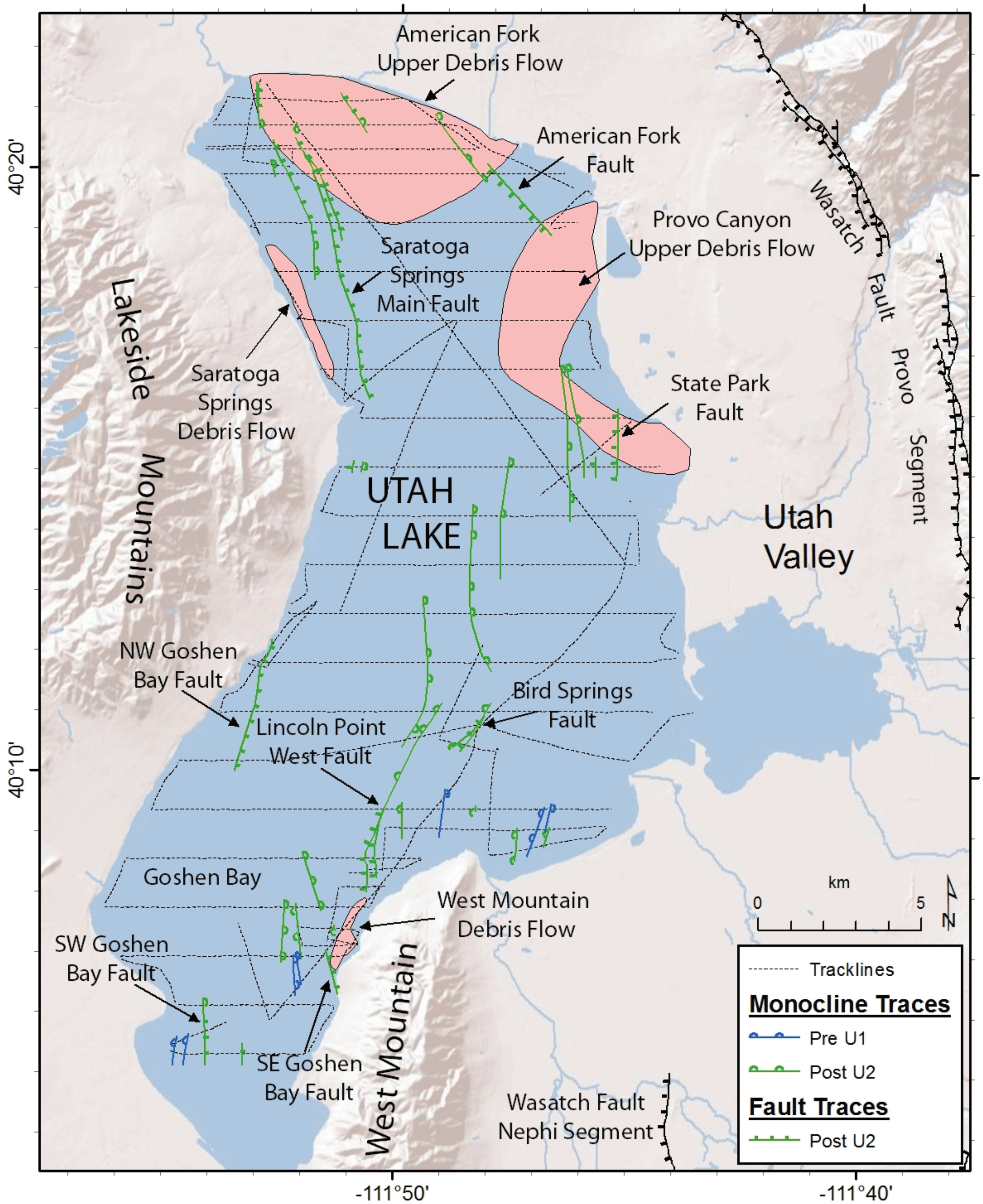

Figure 7. Map showing late Holocene faults and monoclines and four debris flows, all the same age, in Utah Lake. Green structures deform Lake B strata, typically up to LB3. Blue structures are pre-U1. See text for discussion.

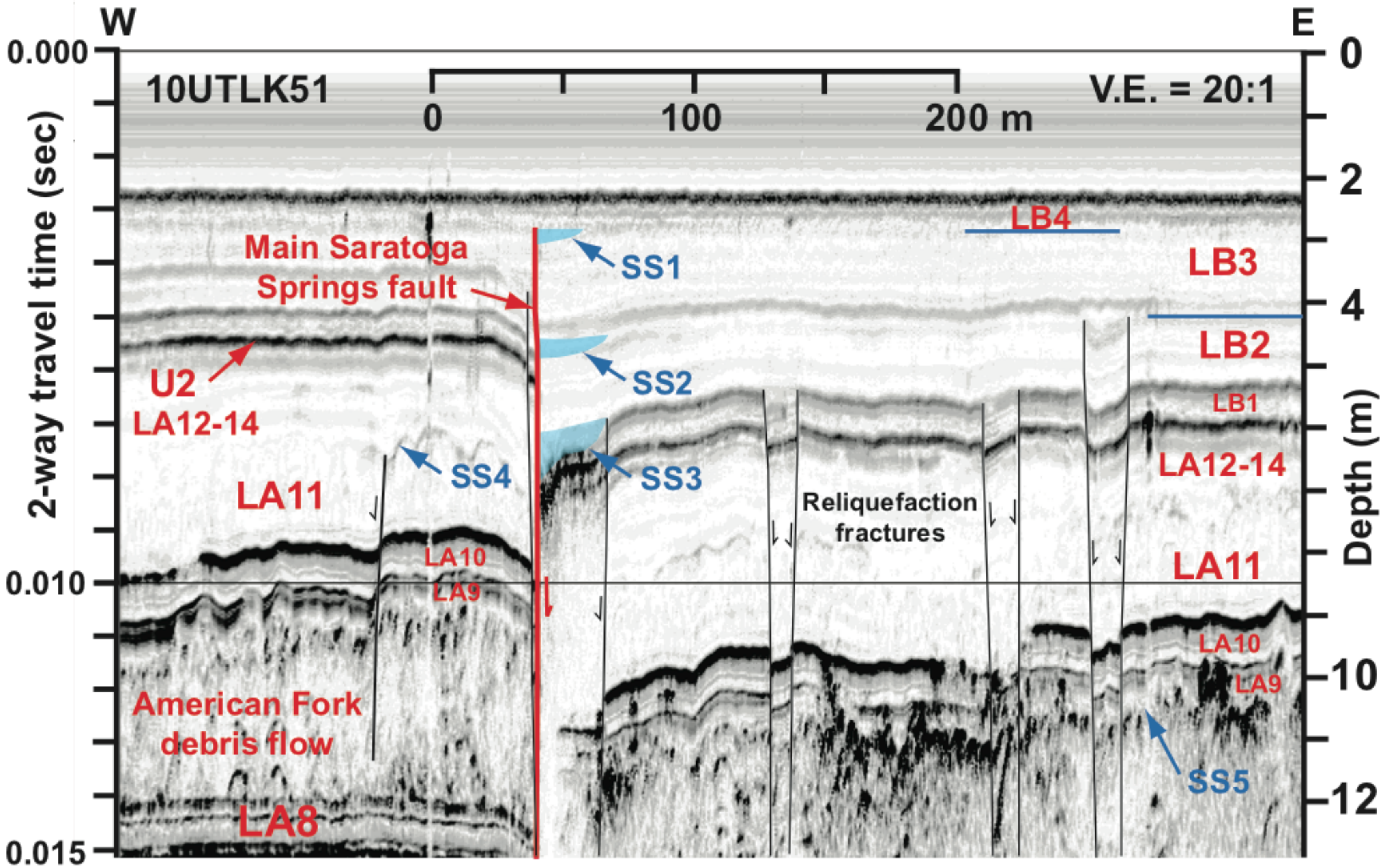

Figure 8. Chirp profile showing Main Saratoga Springs fault, event horizons SS1, SS2, & SS3 with overlying, onlapping scarp-fill wedges, reliquefaction fractures relating to events SS2, SS3, and SS4 (top of upper seismite, LA11), and soling into American Fork debris flow. See text for discussion, Figure 2 for location.

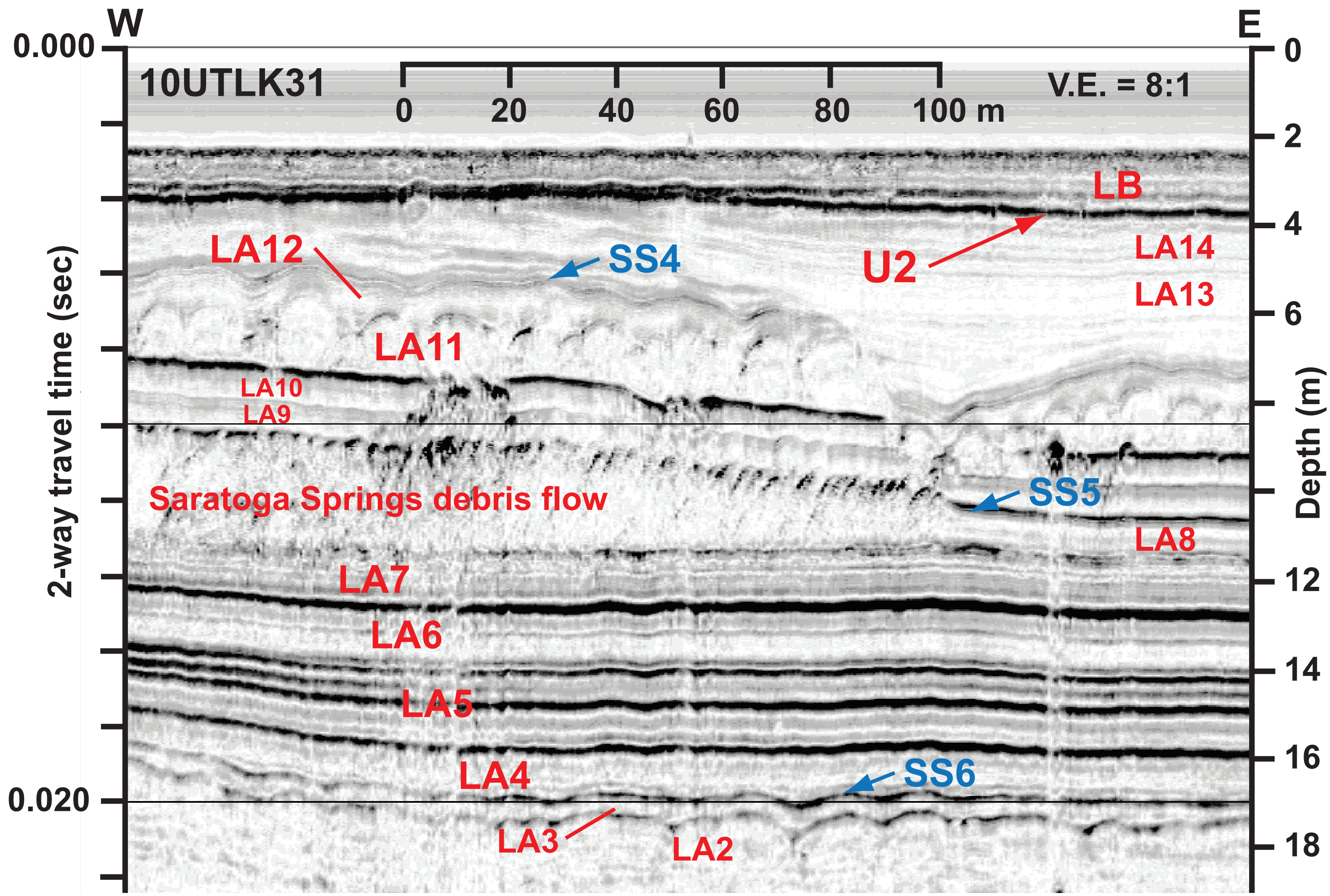

Figure 9. Chirp profile showing intrabasinal Saratoga Springs debris flow, derived from localized liquefaction and downslope movement of Unit LA8. Note west-dipping shingling at toe of flow. SS4, SS5, and SS6 are earthquake event horizons. See discussion in text, Figure 2 for location.