Seismic profiling in downtown Salt Lake City: Mapping the Wasatch fault with seismic velocity and reflection methods from a land streamer

Project Award Number: # G15AP00054

Award Dates: May 2015 through April 2016

Submission date: July 14, 2016

Project dates: April 15, 2015 through April 14, 2016

Lee M. Liberty

Research Professor

Center for Geophysical Investigation of the Shallow Subsurface (CGISS)

Department of Geosciences

Boise State University

Boise, Idaho 83725-1536

Phone: 208-426-1419

lliberty@boisestate.edu

http://cgiss.boisestate.edu/~lml

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number G12AP20078. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Contents

Summary

This report summarizes new seismic data collected across the Wasatch fault zone (WFZ) in the vicinity of downtown Salt Lake City (Figure 1). Specifically, this report focuses on the location and slip history of the active Warm Springs and East Bench faults that are mapped, but poorly constrained (Figure 2). A Boise State University seismic crew collected 14 km of new land streamer accelerated weight drop seismic data over a three day survey. West to east seismic profiles along North Salt Lake City streets totaling 4 km were acquired to image known and inferred strands of the Warm Springs fault. Two 5 km long profiles (200 South and 700 South Streets) through downtown Salt Lake City were acquired to assess the southern limits of the Warm Springs fault and to characterize deformation related to the East Bench fault. Via police escort and flagger crews, we (PI Liberty, two graduate students and one undergraduate student) collected near continuous profiles to image strata up to 200 m depth and Vp/Vs profiles to 30 m depth, with data gaps only at the intersections of US highways and rail crossings.

The resulting images point to: 1) offset and folded strata related to both known and inferred active faults; 2) a transition from generally low to high Vs velocities from west to east related to the transition from Bonneville lacustrine and overbank deposits to stiffer alluvial fan dominated deposits to the east; 3) high average shear wave velocities within shallow (30m) footwall rocks; 4) a transition from high Vp velocity near surface water saturated sediments to low velocity near surface dry sediments from west to east across most profiles. The seismic results suggest a transition from a clear surface and subsurface expression of the Warm Springs fault beneath north Salt Lake City to a diffuse fault zone with related folding of Bonneville age strata beneath the downtown corridor. There is no surface topographic expression of the Warm Springs fault within the downtown corridor and the seismic results are consistent with the Leeflang (2008) cone penetrometer interpretation for active faults related to the Warm Springs fault along a 400 South transect. The East Bench fault shows a clear topographic expression near the University of Utah campus and the results of this survey point to a refined fault location along 200 South. The reflection results point to folded and offset strata and Vp images point to well-developed colluvium in the hanging wall of the fault. Products in this report include a new fault map and Vs30 high frequency site response map for Salt Lake City and seismic reflection, Vp and Vs results in profile.

Wasatch fault

The active, 343-km-long WFZ defines the eastern boundary of the Basin and Range Province in north-central Utah. The urbanized portion of the WFZ is composed of the Brigham City, Weber, Salt Lake City, Provo, and Nephi segments (Figure 1). Segment boundaries are based on geological discontinuities (Wheeler and Krystinik, 1992) as well as a detailed earthquake record (e.g., Machette et al., 1992; McCalpin and Nishenko, 1996; Lund, 2005). These segments have evidence for three or more large-magnitude earthquakes since about 6,500 calendar years B.P. (DuRoss, 2008). The segments range in length from 26 km (Levan segment) to 59 km (Provo segment) (Machette et al., 1992; Black et al., 2003) and are each considered capable of generating large magnitude (M ~7) surface-faulting earthquakes (Swan et al., 1980; Schwartz and Coppersmith, 1984). This study focuses on the Salt Lake City segment of the Wasatch fault and hazards related to the most densely populated region of Utah.

Salt Lake City segment of the Wasatch fault

The Salt Lake City (SLC) segment can be divided into three en-echelon faults; the Warm Springs, East Bench, and Cottonwood faults (Personius and Scott, 1992; Figure 2). Here, I focus discussions on the Warm Springs and East Bench faults near downtown Salt Lake City with published descriptions and interpretations from new high resolution seismic data.

The 7 km long Warm Springs fault forms a prominent escarpment along the eastern flank of the Salt Lake salient, then splits into subparallel fault strands and trends south into basin fill to some unknown locale (Figures 2 and 3). The fault shows evidence for at least three post-Bonneville events, with displacements totaling 9 m (Hunt, 1982). Personius and Scott (1992) identified six to eight latest Quaternary events with displacements totaling 14-16 m at the Washington School site (Figure 3). Clear evidence of faulting was found in an excavation for the Salt Palace expansion in 1999 (Figure 2 and 3). However, while some investigators interpreted the deformation to be tectonic in origin (Simon and Schlemon, 1999), others (Korbay and McCormick, 1999) interpreted the deformation to be the result of lateral spreading caused by liquefaction. Based on these excavations, the surface trace for the Warm Springs fault was extended through the Salt Palace Convention Center and as far south as 400 South Street (McKean, 2014) to accommodate offsets noted from a cone penetrometer testing (CPT) survey (Leflang, 2008). In contrast to the McKean (2014) interpretation, the map of Personius and Scott (1992) shows the Warm Springs fault as ending 2 ½ km farther to the north near the Washington school, consistent with the interpretation of lateral spreading through downtown Salt Lake City. This report, in part, addresses these competing interpretations by summarizing the results of seismic profiles within north and downtown Salt Lake City regions.

In northeastern Salt Lake Valley, the East Bench fault forms prominent northwest- to southwest-facing intrabasin fault scarps from Salt Lake City (about 2 km east of the southern end of the Warm Springs fault) along about 1100 East Street and Highland Drive south to Big Cottonwood Creek (Figure 2). A trench site at the north end of the East Bench fault revealed evidence for 7 m of deformation in transgressive Lake Bonneville deposits, including 3 m of monoclinal folding that occurred prior to 12.5 ka and 4 m of Holocene-age brittle faulting (Machette et al., 1992). The subsurface presence, geometry, and vertical offsets of these two faults is poorly understood outside of a few key trench sites. Two seismic profiles described in this report further characterize the location and slip history of the East Bench fault.

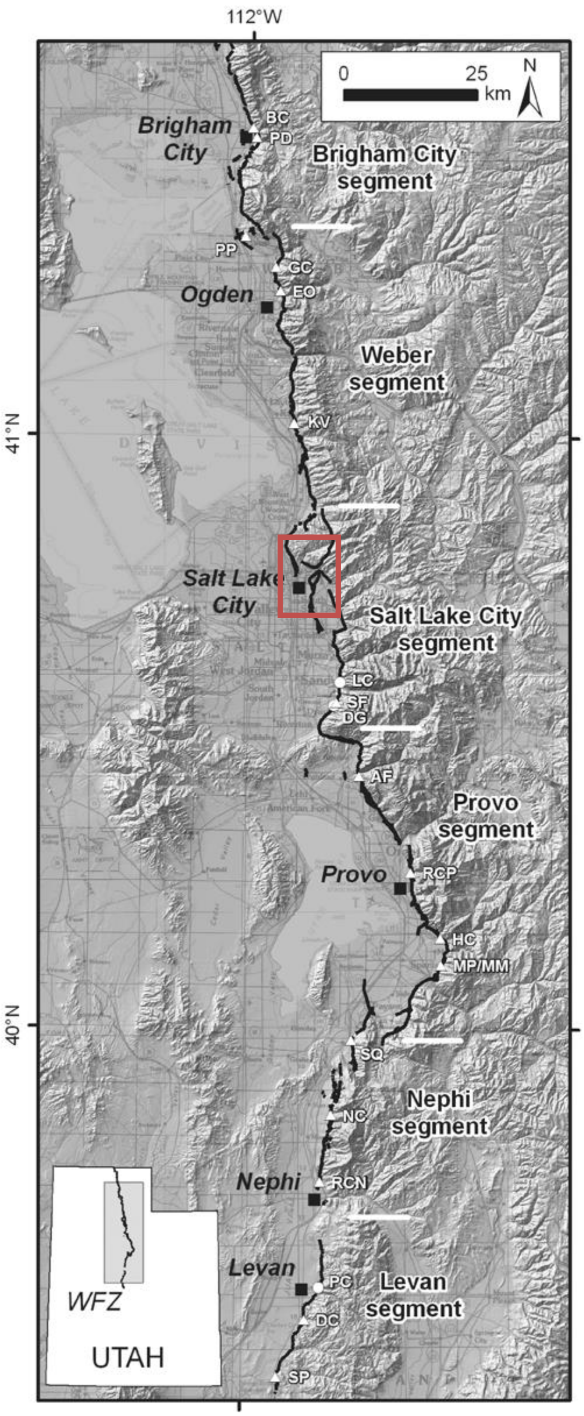


Figure 1. From Duross (2008) showing six segments of the WFZ in north-central Utah. The black line is the Quaternary trace from Black et al. (2003). Horizontal white lines indicate segment boundaries. White triangles are paleoseismic sites. White circles indicate paleoseismic sites having earthquake-timing information but no displacement data. The box represents the area shown in Figure 2 for the downtown Salt Lake City area.

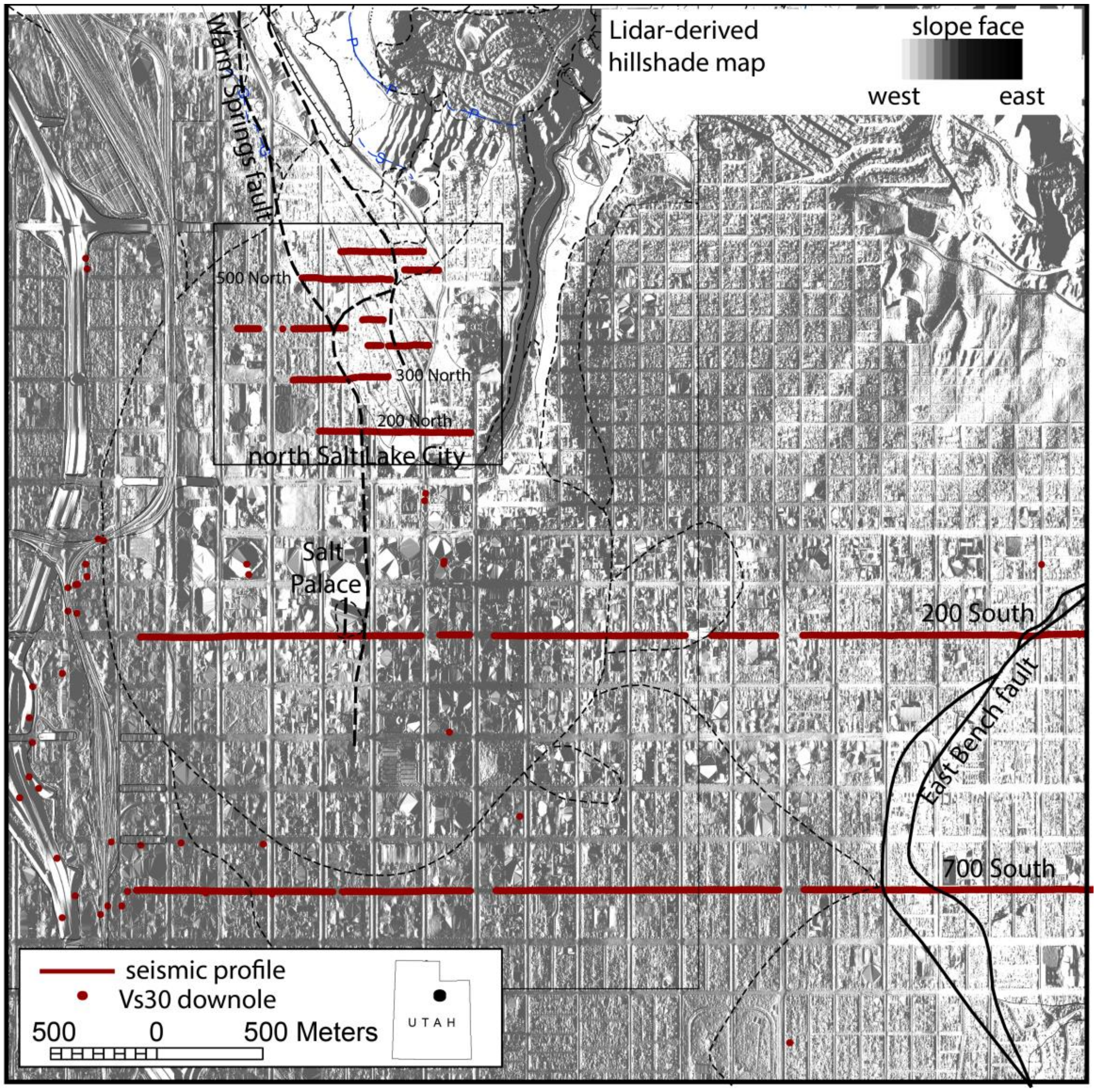


Figure 2. Seismic profile locations (red lines) in downtown and north Salt Lake City across known and inferred strands (black lines) of the Warm Springs and East Bench faults (from Personious and Scott, 2009 and McKean, 2014). Long profiles are along 200 South and 700 South. Background image represents lidar-derived hillshading where white areas represent west-facing slopes and dark areas represent east-facing slopes. Note the relationship between slope directions and the mapped location of faults. Alluvial fan deposits are outlined as faint dashed lines (from McKean, 2014). Line location details are shown in

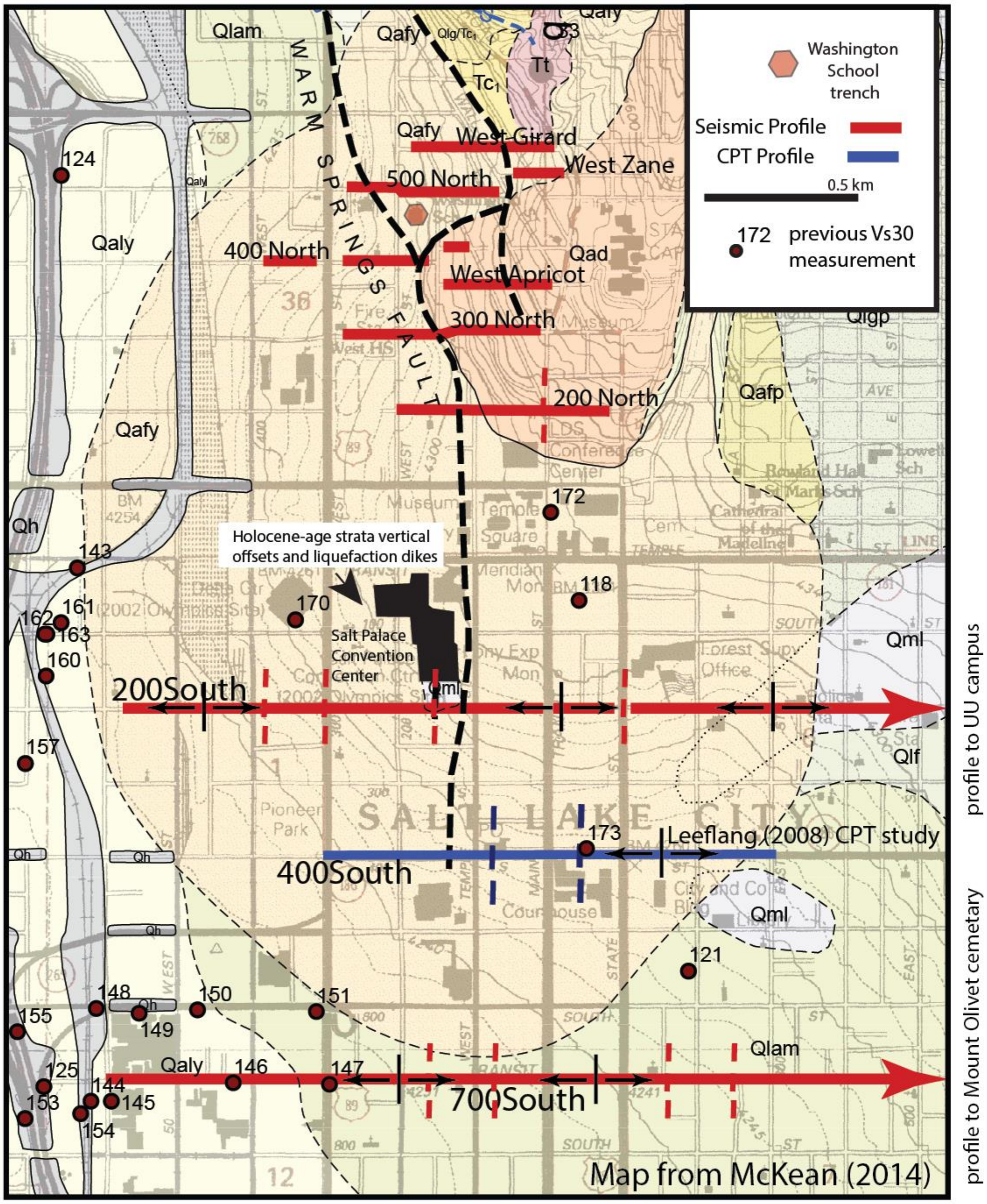


Figure 3. Seismic profile locations (red lines) in downtown Salt Lake City across known and inferred strands of the Warm Springs fault. Mapped fault strands (black dashed lines) and geologic unit boundaries are from McKean (2014). The seismic profiles lie mostly above alluvial fan deposits. Interpreted faults (blue dashed lines) from a cone penetrometer survey (blue line) are from Leeflang (2008) and identified faults from this report (red dashed lines) come from offset seismic reflectors.

Seismic Land Streamer Approach

We acquired approximately 14 km of new seismic data over three field days in 2015 at a nominal 2 m shot spacing using a 200 kg accelerated weight drop source and a 2-component (vertical and in-line), 1.25 m spaced, 48-channel seismic land streamer system that contained 4.5 Hz baseplate-coupled geophones embedded in fire hose (Figure 4). The weight drop source operates directly on city streets with no surface damage while pulling the streamer at a distance of 5 m between source and nearest geophone. Timing between 2 m shots (single hammer hit per location) was approximately 15 s, resulting in about 480 m/hour rate of data acquisition or 4-5 km per day. We extracted first arrivals to obtain Vp measurements to about 20 m depth, Rayleigh wave dispersion curves to obtain Vs profiles to 30 m depth, and reflected signals to map subsurface horizons within the upper few hundred meters below land surface. We utilized a differential GPS system to obtain decimeter scale position measurements and replaced measured elevations with Lidar derived values. The north Salt Lake City profiles were obtained with the assistance of a certified road survey crew to control traffic while the downtown profiles were acquired with the assistance of Salt Lake City off-duty police officers.

First arrival p-waves from the land streamer recording system were clear and easy to pick using Halliburton's SeisSpace/ProMAX® seismic processing software (https://www.landmark.solutions/SeisSpace-ProMAX). These measurements, utilizing a two-dimensional wavepath eikonal traveltime inversion approach (Schuster, 1993), help constrain stacking velocities for p-wave reflection processing and provide depth estimates to saturated sediments and to lateral changes in lithology. The clearest signal from the Vp profiles point to the depth to water saturated sediments (>1,500 m/s) that are consistent with nearby water well logs (e.g., Figure 5). Lateral changes in water elevation may be related to changes in lithology and/or active faulting. Additionally, high velocity bedrock of north Salt Lake City and low velocity colluvium within the hanging wall of the East Bench fault are identified from Vp inversions using Intelligent Resources Rayfract® software. The only place where Vp measurements were not accurately obtained was where high velocity concrete road material masked first arrivals. Asphalt road surfaces, along most surveyed roads, did not limit p-wave refracted arrival analyses.

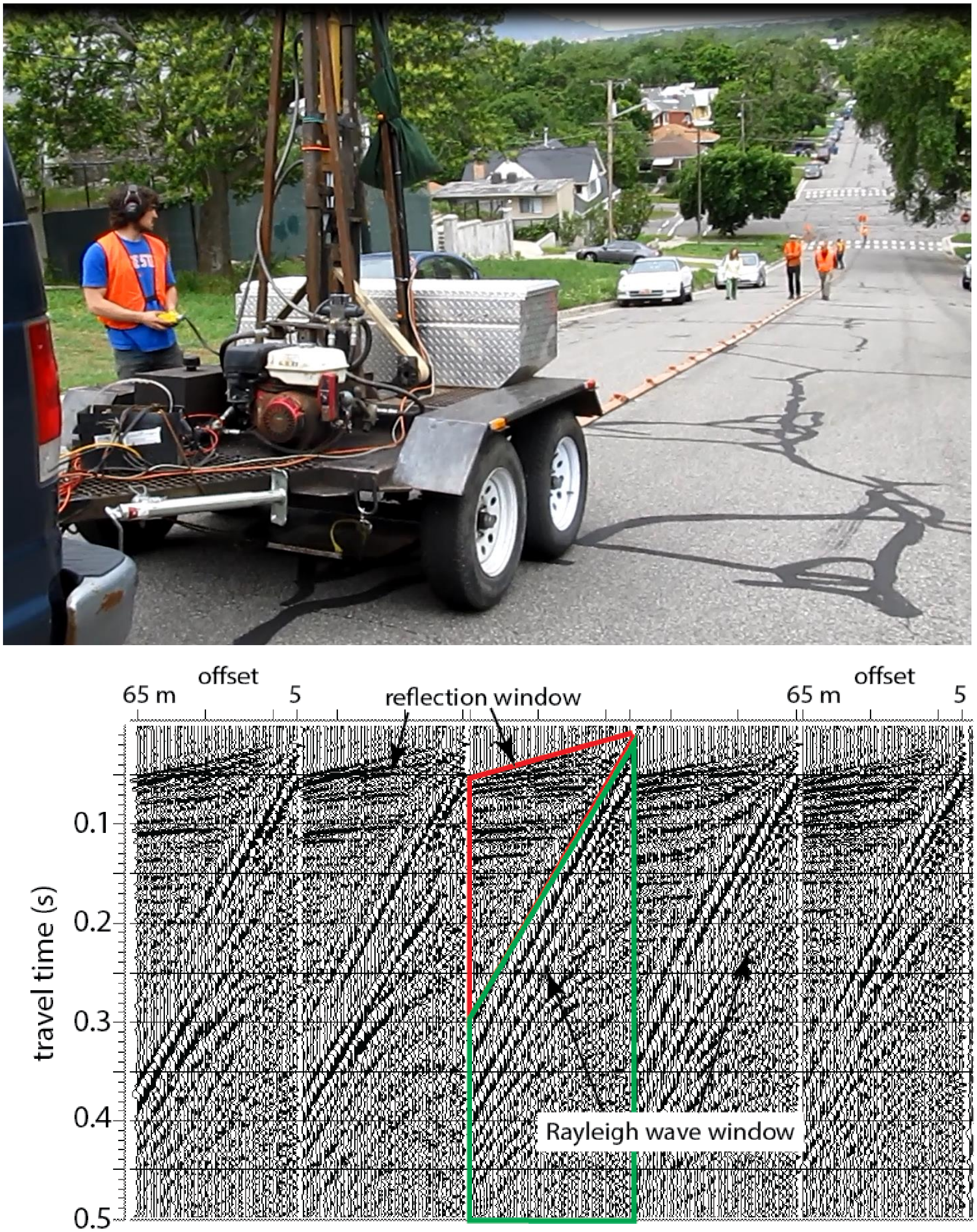


Figure 4. Land streamer vertical component shot gathers from Salt Lake City 700 South profile during 2015 field campaign (spectral whitening filter applied). Note the hyperbolic reflections to 0.25 s (~250 m depth), limited in depth by Rayleigh wave interference. I will lengthen the streamer from this 2015 survey to obtain reflections and refractions to greater depths, while still recording surface waves for Vs profiling.

The Rayleigh wave signals were extracted and processed via the multichannel analysis of surface wave (MASW) approach (Park et al., 1999) using both Kansas Geological Survey Surfseis software (http://www.kgs.ku.edu/software/surfseis/) and in-house Matlab code (Gribler et al., in press). This approach provides estimates of subsurface elastic (stiffness) conditions using surface wave measurements with the impulsive (accelerated hammer) source and the array of p-wave 4.5 Hz sensors. Frequency-phase velocity dispersion plots were generated for each shot gather and peak semblance picks from these plots were inverted to generate Vs profiles for the upper ~30 m. Rayleigh wave frequencies that are recorded with the land streamer system typically range from 3-60 Hz. Once Vs profiles were calculated, 1-D profiles were combined to obtain Vs values with depth in profile. Vs30 values were then calculated for each shot/receiver spread midpoint location (e.g., Boore et al. 1993). We combined all new Vs30 measurements with existing regional point measurements compiled by McDonald and Ashland (2008) to provide a new Vs30 map for the downtown Salt Lake City region. This map can be used to estimate soil response during earthquake ground shaking. A direct comparison between MASW and cone penetrometer downhole Vs measurements (McDonald and Ashland, 2008) near the west end of the SLC 700 South profile show comparable Vs measurements between the two approaches (Figure 5). Additional comparisons are shown below when profile descriptions are presented.

P-wave reflection images were obtained by examining signals between first arrival and surface wave windows (Figure 4), where reflections up to 200 m depth are observed. Reflection data quality are variable, due mostly to changes in lithology (acquisition conditions and geometries were fixed). We processed the data using Halliburton's ProMAX® seismic processing software with a standard processing approach outlined by Yilmaz (2001). Geometry was applied to each source and receiver location from differentially corrected GPS positions recorded each shot record and via lidar-derived elevation values. Processing steps included datum statics, spiking deconvolution, bandpass filter, iterative velocity analyses with dip moveout corrections, amplitude gains, and a post-stack time migration for each profile. Depths were estimated using a smoothed stacking velocity and refraction model. Water well and engineering (Vs30) logs help constrain lithology and depth to water table for interpretation and to obtain the depth to high velocity contrasts.

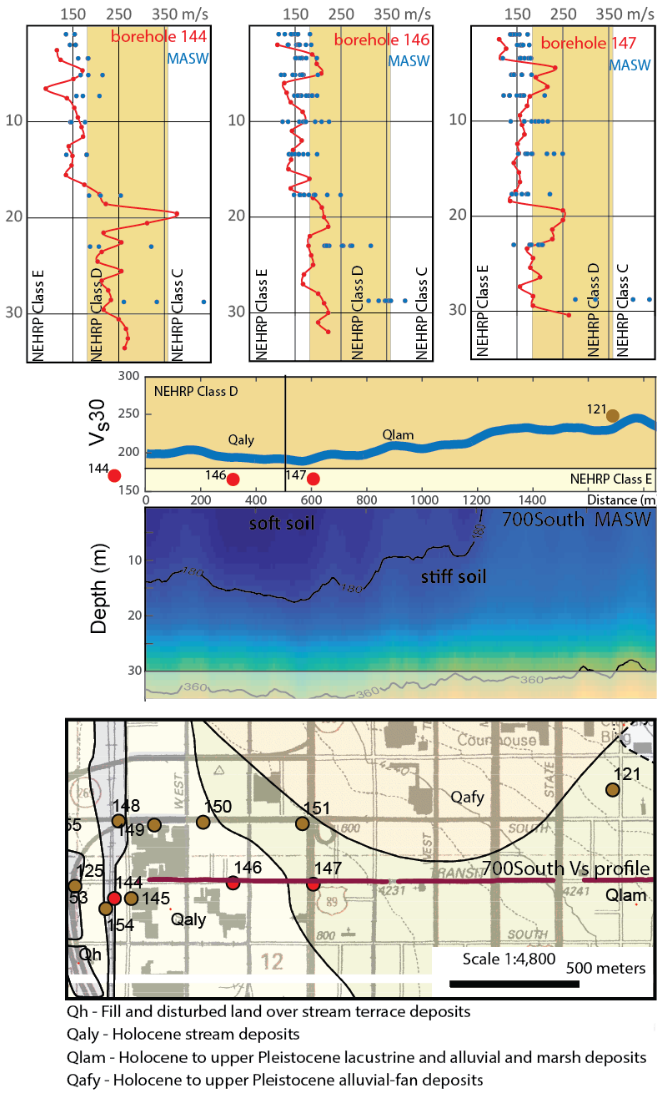


Figure 5. (top) Comparison of land streamer MASW results (blue dots) with published downhole Vs measurements (red dots) from McDonald and Ashland (2008). (middle) Vs profile for a portion of 700 South with Vs30 calculation. Note the Vs30 values are within 10% of the downhole measurements for the 4 borehole surveys along the profile (bottom) McKean (2014) map with downhole Vs measurement locations (dots) and 700 South profile location (red line). The red circle cone penetrometer Vs measurements were directly compared to adjacent land streamer MASW picks.

Results - North Salt Lake City

West Girard Street profile

The 460 m long west-east West Girard Street profile extends from Center Street to Darwin Street in North Salt Lake City (Figure 3). The profile climbs a topographic slope that gains 40 m in elevation from west to east with a topographic inflection about 100 m from the end of profile. This line is the northernmost profile that we acquired during the 2015 field project. McKean (2014) mapped Holocene to Upper Pleistocene undifferentiated alluvial fan deposits along the profile and Tertiary rock exposures are mapped immediately north of the eastern portion of the profile (Figure 3). The eastern strand of the Warm Springs fault is mapped near the center of the profile.

Shear wave velocities for the upper 30 m average 320 m/s (Figure 6) or NEHRP Class D3 stiff soil (BSSC, 2001). At about 5 m depth along the eastern portion of the profile, we identify NEHRP Class C soft rock that is consistent with weathered bedrock mapped nearby (McKean, 2014; Figure 3). Near surface p-wave velocities of less than 1,500 m/s suggest unsaturated sediments in the upper 20 m along the length of the profile, with high velocity bedrock (>2,000 m/s) mapped at about 5 m depth beneath the eastern 1/3 of the profile. Depth to water table along the western portions of the profile is constrained by a strong amplitude reflector at about 20 m below land surface.

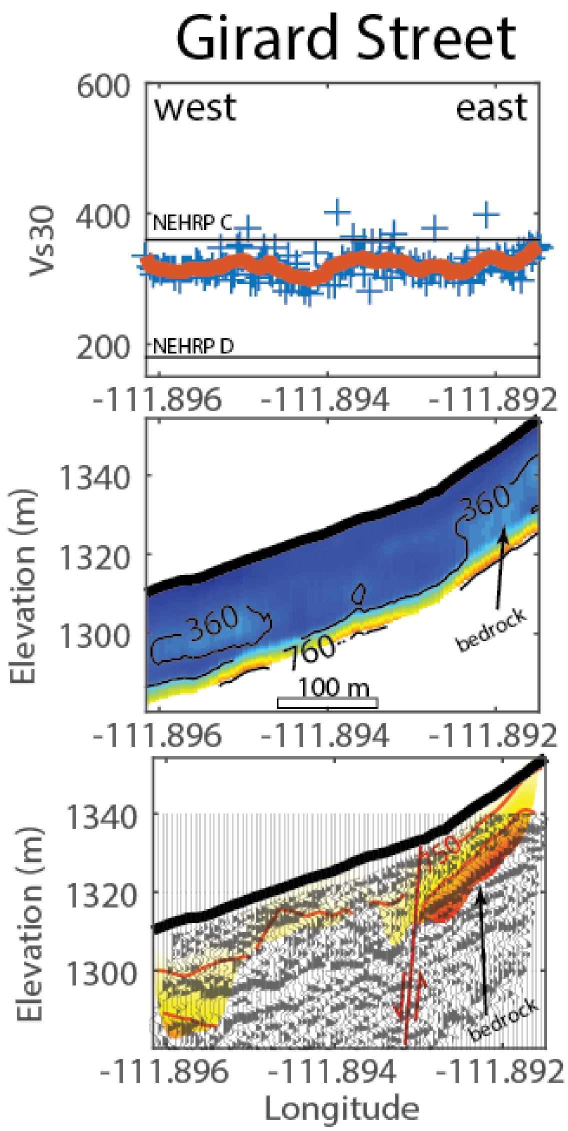


Figure 6. Girard seismic results that includes (top) Vs30 profile, (middle) Vs profile for upper 30 m and (bottom) Vp map with reflection image. I interpret a mapped strand of the Warm Springs fault at the western termination of shallow bedrock and a change in reflector dip. Bedrock is identified by a west-dipping reflector and high p-wave and s-wave velocities compared to the western portion of the profile.

I interpret a normal fault (down to the west) at the westward termination of the high velocity bedrock surface that is consistent with the inflection in topographic slope. This eastern strand of the Warm Springs fault (McKean, 2014) separates reflections of differing dip, but it is unclear from this profile the amount of slip across this fault due to the lack of reflector continuity across the fault.

500 North Street/Zane Street transect

The 500 m long 500 North Street and 190 m long Zane Street profiles begin near the intersection of 250 West and extends eastward to Darwin Street (Figure 3). The gap and northward step of the two profile segments is located at Wall Street. The 500 North profile contains a relatively gentle westward slope compared to the Girard Street and Zane Street profiles. Holocene to Upper Pleistocene younger undifferentiated alluvial fan deposits are mapped along this profile and the western strand of the Warm Springs fault is projected along the western portion of the 500 North profile while the eastern fault strand is mapped between the two profile segments (McKean, 2014; Figure 2). A fault identified in the Washington Elementary school trench is interepreted as a step over between the two north-south fault segments (McKean, 2014) and is located south of the transect center.

Shear wave velocities for the upper 30 m average 348 m/s (NEHRP Class D3) for the 500 North profile and 370 m/s (NEHRP Class C1) for the Zane Street profile (Figure 7), consistent with alluvial fan and lacustrine sediment deposits (Figure 3). NEHRP Class D (<360 m/s) stiff soil sediments appear in the upper 20 m for much of the 500 North profile, consistent with Bonneville lacustrine sediments that are mapped one block to the west. Vs velocities are highest near the western portion of the profile. A high amplitude reflector at about 10-40 m depth below land surface, along with a jump in refraction velocities to above 1,500 m/s, is consistent with the transition from dry to saturated sediments. This interpretation is supported by the nearby water well 57-8417 that shows a 35 m depth water table (http://www.waterrights.utah.gov/wellinfo/wellsearch.asp). I identify reflector truncations and folded strata beneath the water table, consistent with strands of the Warm Springs fault. The identified faults near the western portion of the 500 North profile do not offset the water table reflector, but appear at a prominent inflection in surface topography (Figure 2). The identified faults along the eastern portion of the 500 North profile and the western portion of the Zane Street profile appear at topographic breaks, and offset reflectors above the water table. High velocities are mapped beneath Zane Street that are likely related to shallow, fault controlled bedrock.

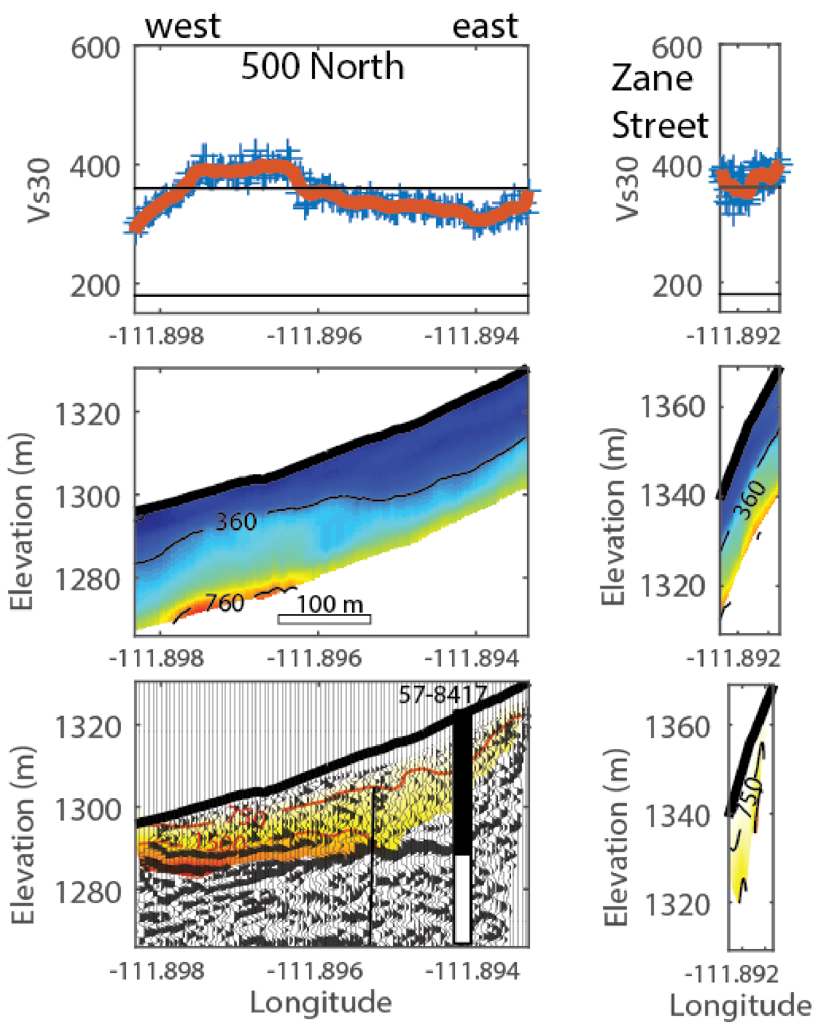
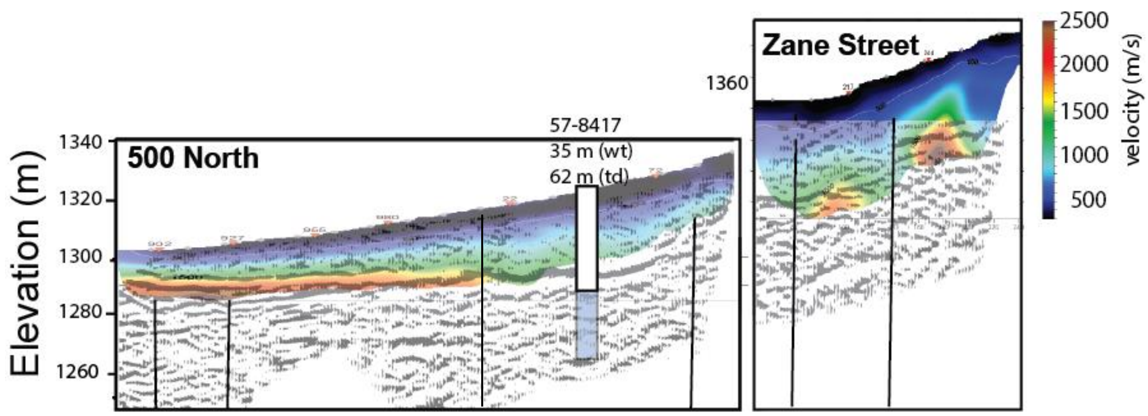


Figure 7. 500 North/Zane Street composite seismic images that includes (top) Vs30 profile, (middle) Vs profile for upper 30 m and (bottom) Vp map with reflection image. Mapped strands of the Warm Springs fault are interpreted between the two profiles and at the west end of the 500 North profile. The Washington school trench is located approximately 500 m south of this transect (Figure 3).



400 North/Apricot Street transect

The 400 North transect is comprised of three road segments (Figure 2). The flat lying portion of 400 North lies between 400 West and 300 West streets and sits upon younger Holocene to Upper Pleistocene undifferentiated alluvial fan deposits (Figure 2). The middle segment of this transect is located along 400 North between 300 West and Quince Streets. A slope break appears along the eastern portions of this segment. East of 400 North, the transect continues along Apricot Street east to within one block of the state capitol building where Upper Pleistocene lacustrine sand and gravel deposits are mapped (McKean, 2014). McKean maps the western strand of the Warm Springs fault along the eastern edge of the 400 North profile and the eastern strand beneath the central Apricot Street segment.

Seismic imaging shows a strong amplitude reflector and large seismic velocity increase at about 10-30 m depth, consistent with the water table depth from nearby water wells. This reflector roughly follows topography, but deepens from west to east. A decrease in seismic velocity, a break in the topographic slope, and a disrupted water table reflector along the eastern portion of the 400 North profile points to a strand of the Warm Springs fault system mapped by McKean (2014). I interpret a second strand of the Warm Springs fault at a second slope break beneath Apricot Street. A step in reflector depths and continuity between 400 North (center) and Apricot Street profiles may point to an additional fault strand. At the eastern fault location, reflectors beneath the water table are discontinuous. Although bedrock likely shallows to the east along this profile, refraction and reflection data not constrain the bedrock depth. This is consistent with gravity data that suggest a deepening of bedrock to beneath downtown Salt Lake City compared to the area to the north (http://irpsrvgis08.utep.edu/viewers/Flex/GravityMagnetic/GravityMagnetic_CyberShare/).

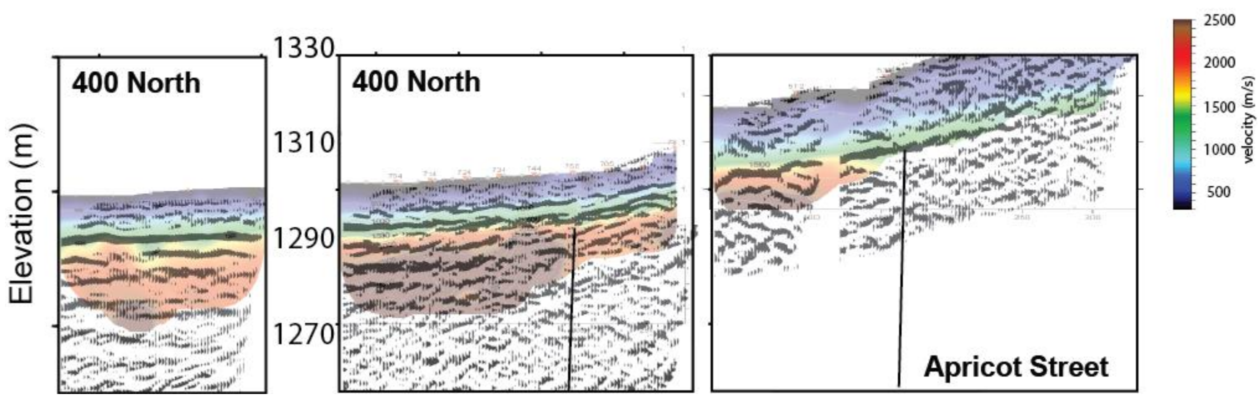


Figure 8. 400 North/Apricot Street seismic transect showing p-wave velocities and reflection images.

300 North profile

The 525 m long 300 North profile begins at 300 West Street and progresses east to Center Street with a slope break at Qunice Street. Holocene to Upper Pleistocene undifferentiated alluvial-fan deposits are mapped along the western portions of this profile (McKean, 2014) with Upper Pleistocene lacustrine sand and gravel along the eastern reaches of the profile (Figure 2). McKean (2014) mapped only the western strand of the Warm Springs fault beneath this profile, with the eastern strand terminating immediately to the north.

Shear wave seismic velocities range from 300-800 m/s with an average Vs30 value of 401 m/s (NEHRP Class C1 dense soil) for the profile (Figure). We map NEHRP Class D (<360 m/s) shear wave velocities in the upper 20 m along the western limits of the profile, consistent with Bonneville lake unconsolidated sediments. A a step in both shear wave and p-wave seismic velocities approximately 100 m to the east of the profile start suggest a change in lithology and is consistent in location with a strand of the Warm Springs fault. Dipping reflectors beneath the water table also support the interpretation. We map a sedond fault strand at the change in topographic slope near the center of the profile. At this location, slower p-wave and s-wave velocities are mapped to the east and there is a change in reflection character to denote the eastern strand of the Warm Springs fault.

200 North profile

The 200 North profile is located between 200 West and North State Street (Figure 3). Elevation increases along the length of the profile from west to east, with an inflection in topographic slope near West Temple Street (Figures 2 and 10). The Warm Springs fault is mapped between 200 W and West Temple near the western limits of the profile and Holocene to Upper Pleistocene undifferentiated alluvial-fan deposits are mapped beneath the profile (McKean, 2014). A Vs30 borehole measurement near the LDS Assembly Hall (#172) approximately one block south of this profile measured value of 348 m/s (McDonald and Ashland, 2008; Figure 3).

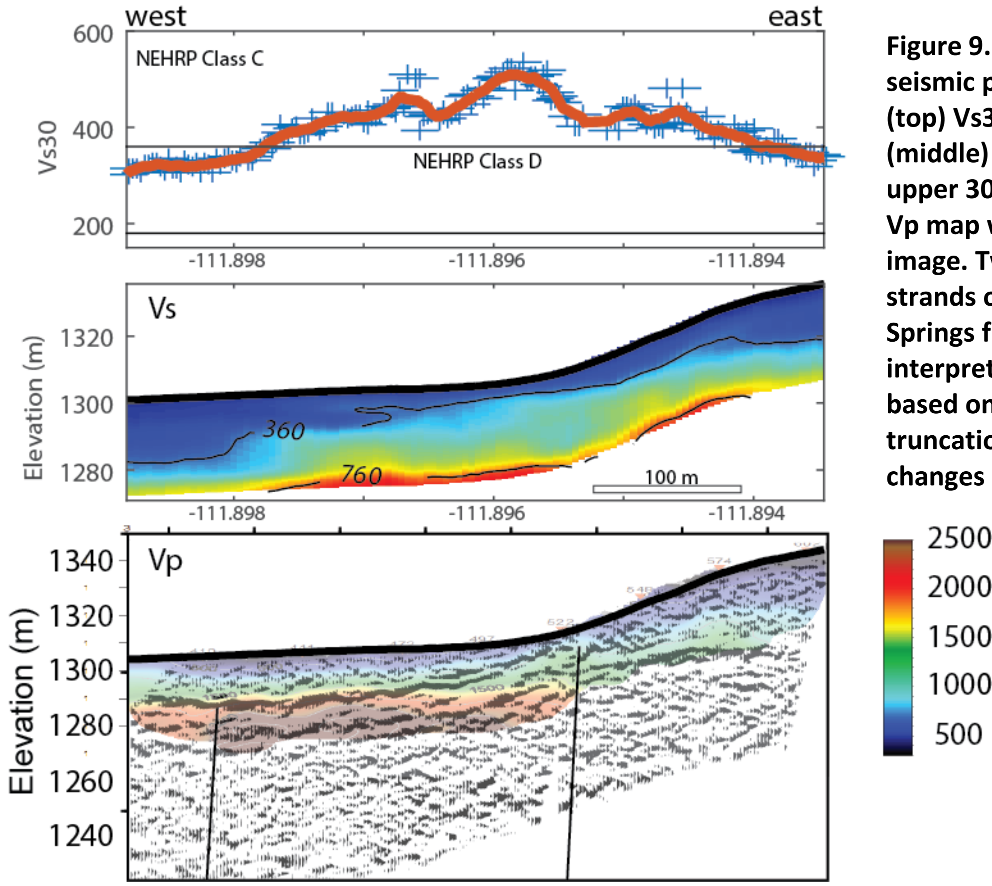


Figure 9. 300 North seismic profile showing (top) Vs30 profile, (middle) Vs profile for upper 30 m and (bottom) Vp map with reflection image. Two mapped strands of the Warm Springs fault are interpreted on this profile based on reflector truncations and lateral changes in velocity.

Shear wave seismic velocities for the 200 North profile range from 300-800 m/s with an average Vs30 value of 389 m/s (NEHRP Class C1 dense soil) for the profile (Figure 10). This bulk velocity value is consistent with the mapped alluvial fan deposits of McKean (2014). NEHRP Class D (<360 m/s) soils appear to a depth of about 20 m along the western portion of the profile, and this NEHRP class boundary shallows to the east.

We map three strands of the Warm Springs fault along this profile (Figure 10). The western strand is based on reflector truncations below the water table and an increase in p-wave and s-wave velocities. The center and eastern fault strand is based on an inflection of the surface topography, water table and deeper reflections and lateral changes in p-wave and s-wave velocities.

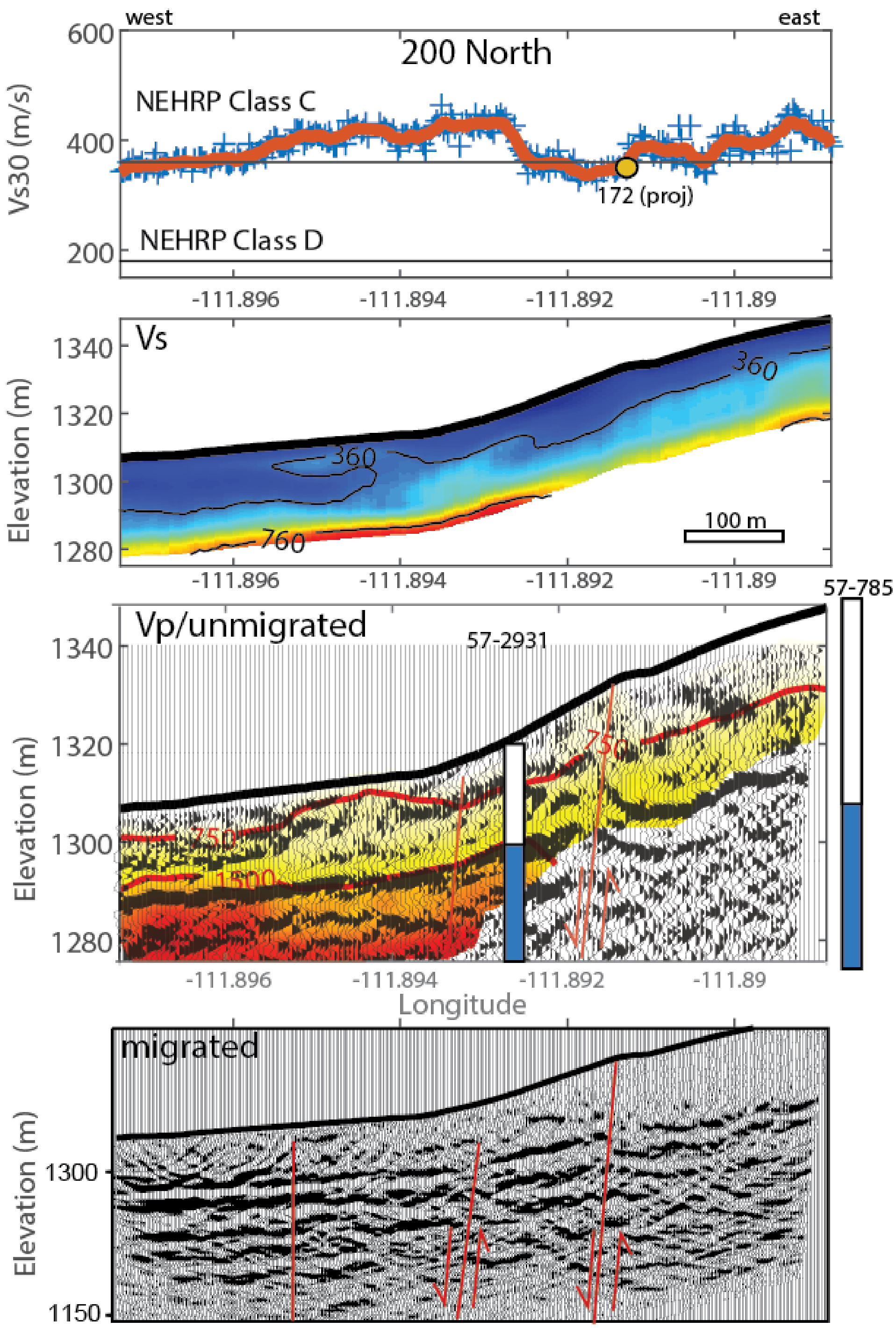


Figure 10. 200 North seismic profile showing (a) Vs30 profile, (b) Vs profile for upper 30 m, (c) Vp map with unmigrated reflection image and (d) migrated reflection image. Three strands of the Warm Springs fault are interpreted on this profile based on reflector truncations and lateral changes in velocity.

Downtown Salt Lake City

<u>200 South Street profile</u>

The 5 km long 200 South Street profile extends from between 600 W and 500 W east to University Street (Figures 2 and 3). Elevation generally increases along the length of the profile from west to east, with a small (1 km wide, 10 m high) hill between 200 West and State Street. Additionally, there is an inflection in topographic slope near 100 East Street and about 1150 East (Figure 11). The Warm Springs fault is mapped near the Salt Palace between 200 W and West Temple Streets (McKean, 2014) and the East Bench fault is mapped near the intersection of 1200 East Street (Personious and Scott, 1992).

Shear wave seismic velocities for the 200 North profile range from 160-700 m/s with an average Vs30 value of 290 m/s (NEHRP Class D2 stiff soil) for the profile (Figure 11). Vs values are generally lower along the western portion of the profile, consistent with mapped Bonneville lake sediments (Personious and Scott, 1992) and with past Vs30 surveys (McDonald and Ashland, 2008; Figure 5). To the east, mapped alluvial fan deposits are consistent with higher measured shear wave velocities with a notable drop in Vs values near a topographic low at 200 East Street. A large increase in Vs values appears near the eastern portion of the profile and close to the mapped location of the East Bench fault at about 1150 East. An increase in shear wave velocity at the location of well 10092 is consistent with a change from dominantly clays to gravels. This boundary may be the transition from upper Pleistocene Bonneville to middle Pleistocene Alpine Formation that Leeflang (2008) noted from a CPT survey along 400 South.

Seismic reflection results show folded and offset reflectors in the upper 100 m (0.15 s) below land surface. The shallowest reflectors are located at about 20 m depth, consistent with the top of gravels associated with the Alpine Formation (Leeflang, 2008). I identify two anticlines along the western portion of the profile (near Main Street and 300 East) that are likely tectonically controlled. Between 400 West 100 West, offset reflectors suggest faults cut the Alpine strata, consistent with interpretations of active faulting from Salt Palace and CPT reports. The shallowest reflector offsets across the identified faults range from 8-12 ms or 6-8 m of uplift. This uplift amount is consistent with the Leeflang (2008) observation of approximately 8.7 meters of vertical offset of late Pleistocene lacustrine and alluvial deposits at about 100 West Street.

Figure 12 shows the eastern half of the 200 South profile with a focus on the East Bench fault. Here, changing reflection character corresponds with the East Bench fault with faults identified at 850 East and 1100 East.

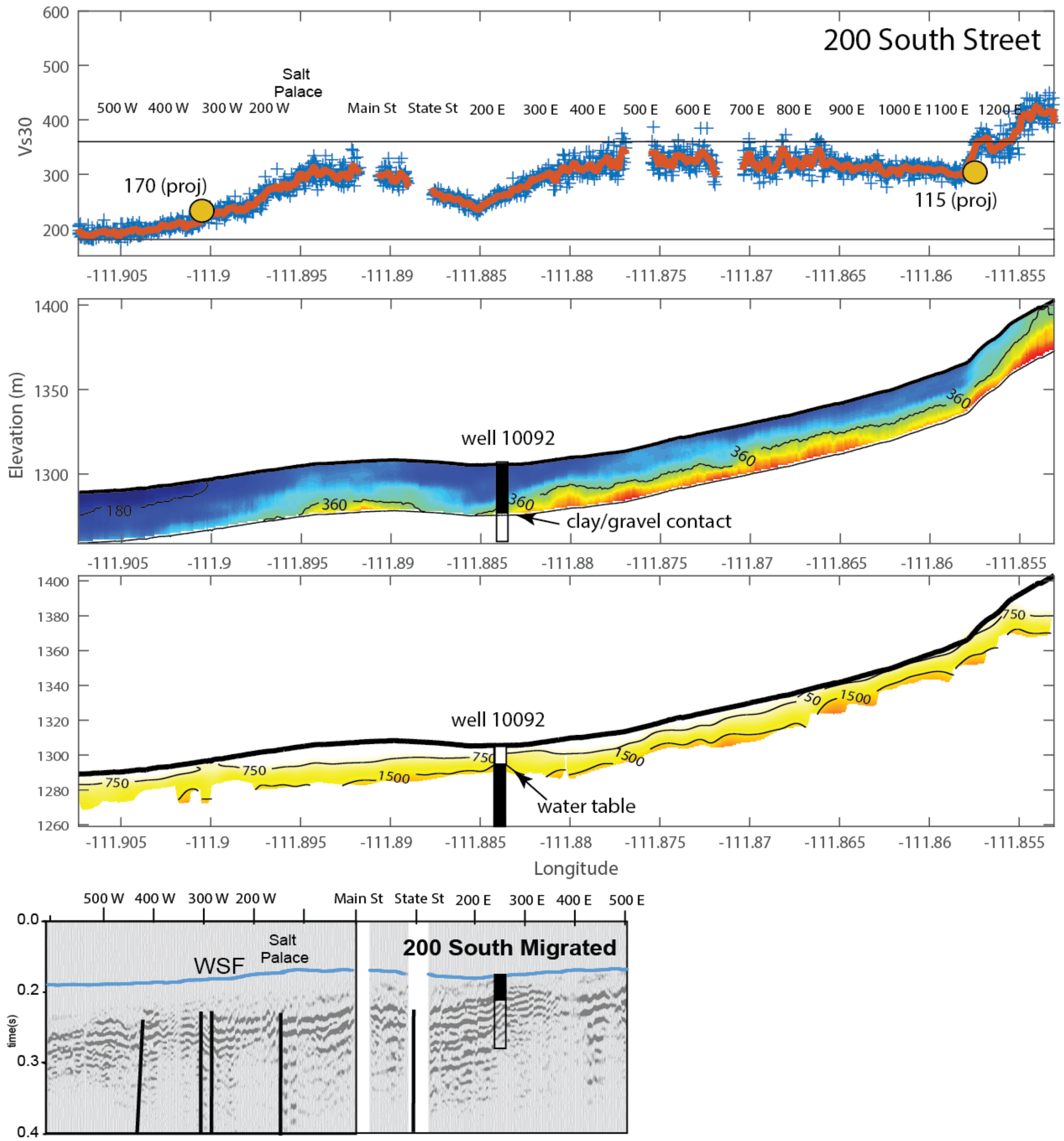


Figure 11. 200 South seismic profile showing (a) Vs30 profile with published measurements (circles) from McDonald and Ashland (2008), (b) Vs profile for upper 30 m with the location of borehole 10092 and inferred depth to top of Apline Formation, (c) Vp map with location of borehole 10092 with depth to water table, and (d) reflection image for the western portion of the profile. Mapped strands of the Warm Springs fault are interpreted on this profile based on reflector truncations and lateral changes in velocity.

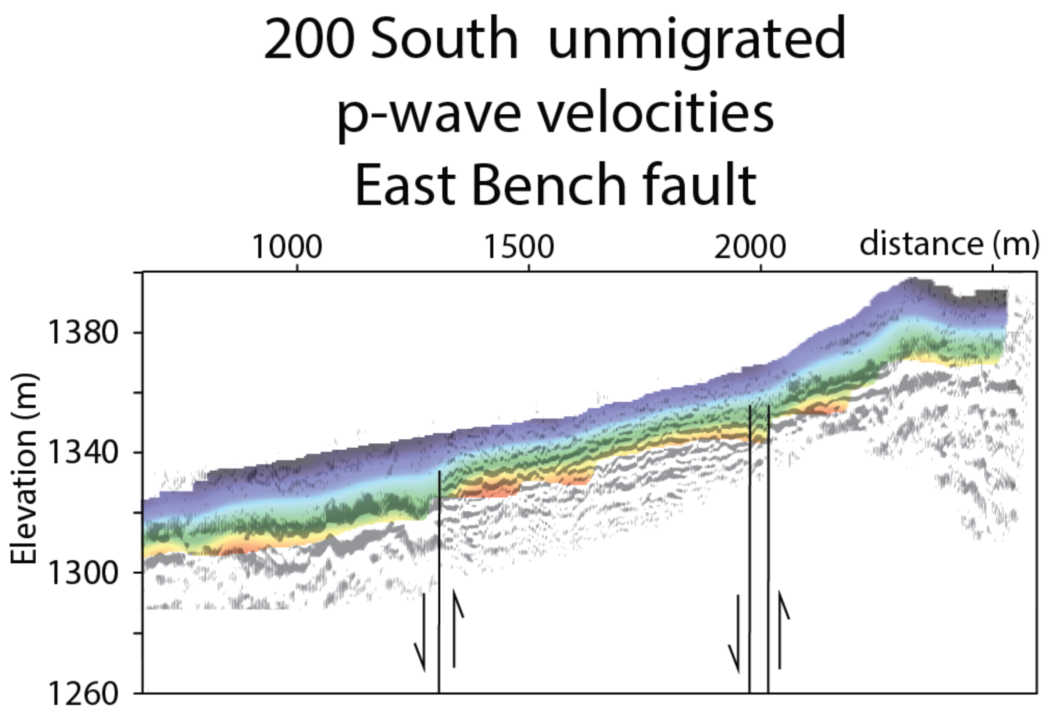


Figure 12. Eastern portion of the 200 South seismic profile showing Vp velocities with seismic reflection image. Note the thinning of low Vp velocities at the location of offset reflectors (position 1300). The end of profile is located along University Drive and East Bench fault (position 2000) is located near 1100 East Street.

<u>700 South</u>

The 5 km long700 South Street profile extends from between 600 W and 500 W east to the Mount Olivet cemetery (Figures 2 and 3). Elevation generally increases along the length of the profile from west to east, with an inflection in topographic slope near 900 East Street (Figure 13). The Warm Springs fault is mapped near the Salt Palace between 200 W and West Temple Streets (McKean, 2014) and the East Bench fault is mapped near the intersection of 1200 East Street (Personious and Scott, 1992).

Shear wave seismic velocities for the 200 North profile range from 160-700 m/s with an average Vs30 value of 251 m/s (NEHRP Class D2 stiff soil) for the profile (Figure 13). NEHRP E-class soils appear in the upper 15 m below the western portion of the profile, consistent with mapped Bonneville lake sediments (Personious and Scott, 1992) and with past Vs30 surveys (McDonald and Ashland, 2008; Figure 5). To the east, mapped alluvial fan deposits are consistent with higher measured shear wave velocities with a notable drop in Vs values near 1100 East Street. High Vs values are measured near 1000 East and 1300 East Streets. The East Bench fault is mapped at about 1000 East, consistent with the large lateral Vs and Vs changes.

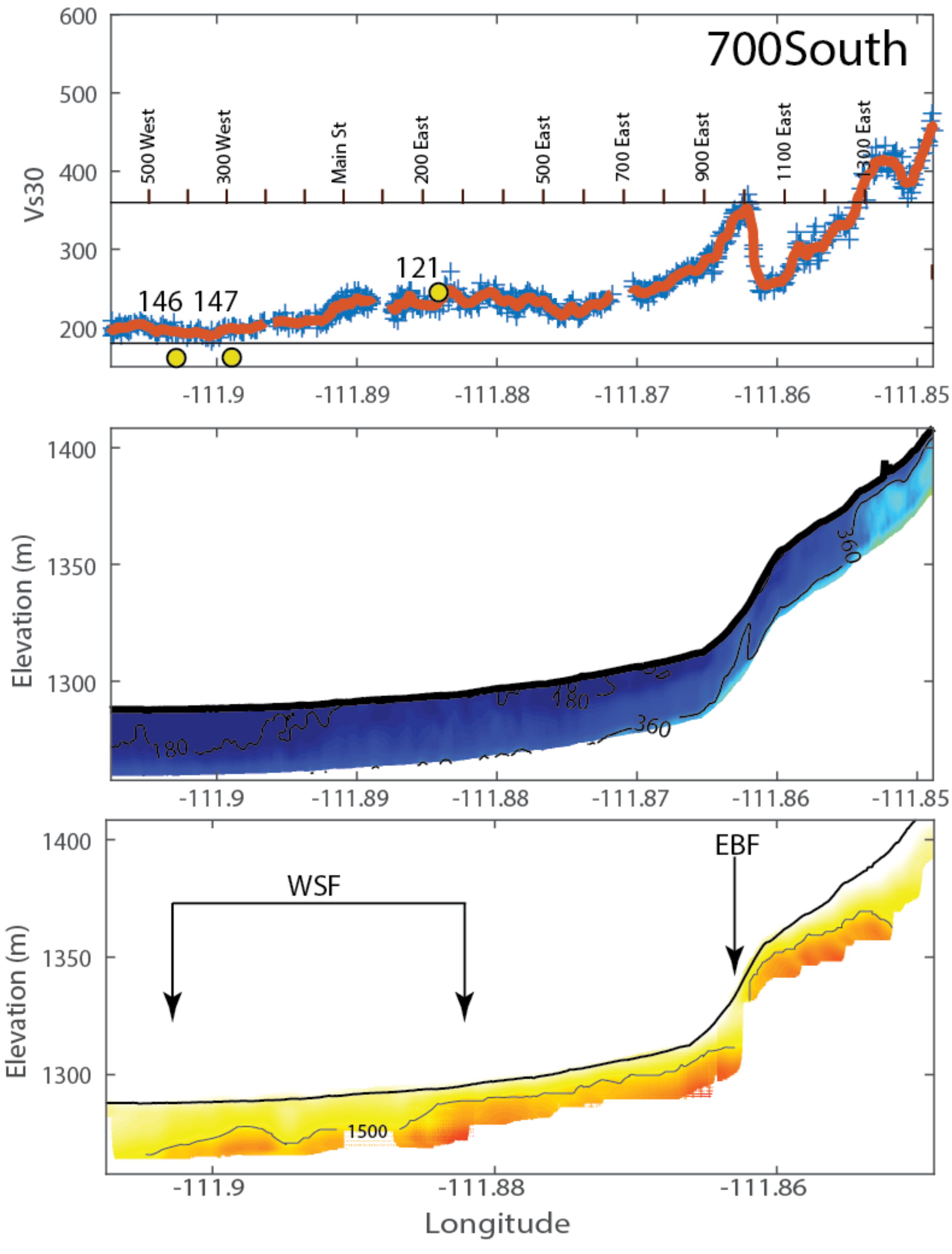


Figure 13. 700 South seismic profile showing (a) Vs30 profile with published measurements (circles) from McDonald and Ashland (2008), (b) Vs profile for upper 30 m, (c) Vp map with location of inferred faults related to the Wasatch fault system.

At about 1000 East, I interpret a prominent low p-wave velocity zone as colluvium related to sediments infilling in the hanging wall of the East Bench fault (Figure 14). Reflectors beneath this colluvial wedge are folded over the East Bench fault, with a 40 m offset along the shallowest reflector. This interpretation of draped strata within the East Bench fault zone are consistent with the monoclonal warping documented in the nearby Dresden Place trenches by Machette (1992).

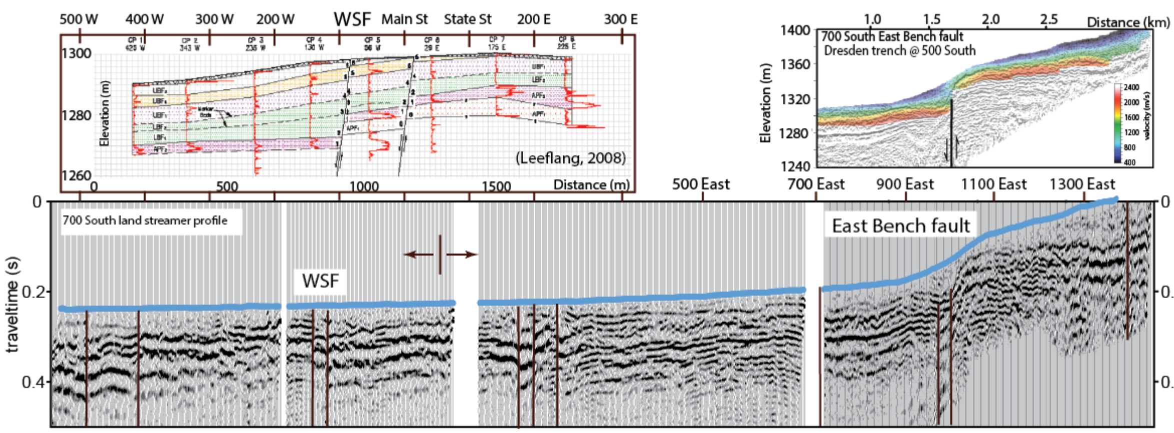


Figure 14. (top left). 400 South cone penetrometer profile from Leeflang (2008). Leeflang interpreted offset strata at the base of Bonneville deposits near 100 West to define the southern extension of the Warm Springs fault (McKean, 2014). (bottom) The 5 km long 700 South land streamer reflection profile (aligned with CPT street crossings) shows folded and offset reflectors of Bonneville and older deposits. Note the offset reflectors near 100 West and near 200 East that bound folded Bonneville strata on both CPT and seismic profiles. I interpret as strands of the Warm Springs fault. (Upper right) Tomographic image showing low velocity colluvium in the hanging wall of the East Bench fault. Note the warped reflectors are consistent with the Dresden Place trenches.

Vs30 map

Figure 15 shows a Vs30 map derived from our MASW results where we combine both previous point measurements with new land streamer profile data. I superimposed this map on the geological map of Personious and Scott (1992) to emphasize the relationship between shallow Vs measurements and mapped geologic units and contacts. This map shows a direct relationship between mapped lithologies and Vs30 values acquired both with the land streamer and from downhole Vs point measurements. Where Bonneville lake deposits are mapped, I observe slow shear wave velocities (NEHRP Class E and D1 soft soils) and where alluvial fan deposits are mapped, generally NEHRP Class D2/D3 stiff soils are measured. Known fault locations of the Warm Springs and East Bench fault show soft rock (NEHRP Class C1) materials in the footwall block of the fault adjacent to NEHRP Class D soils in the hanging wall block.

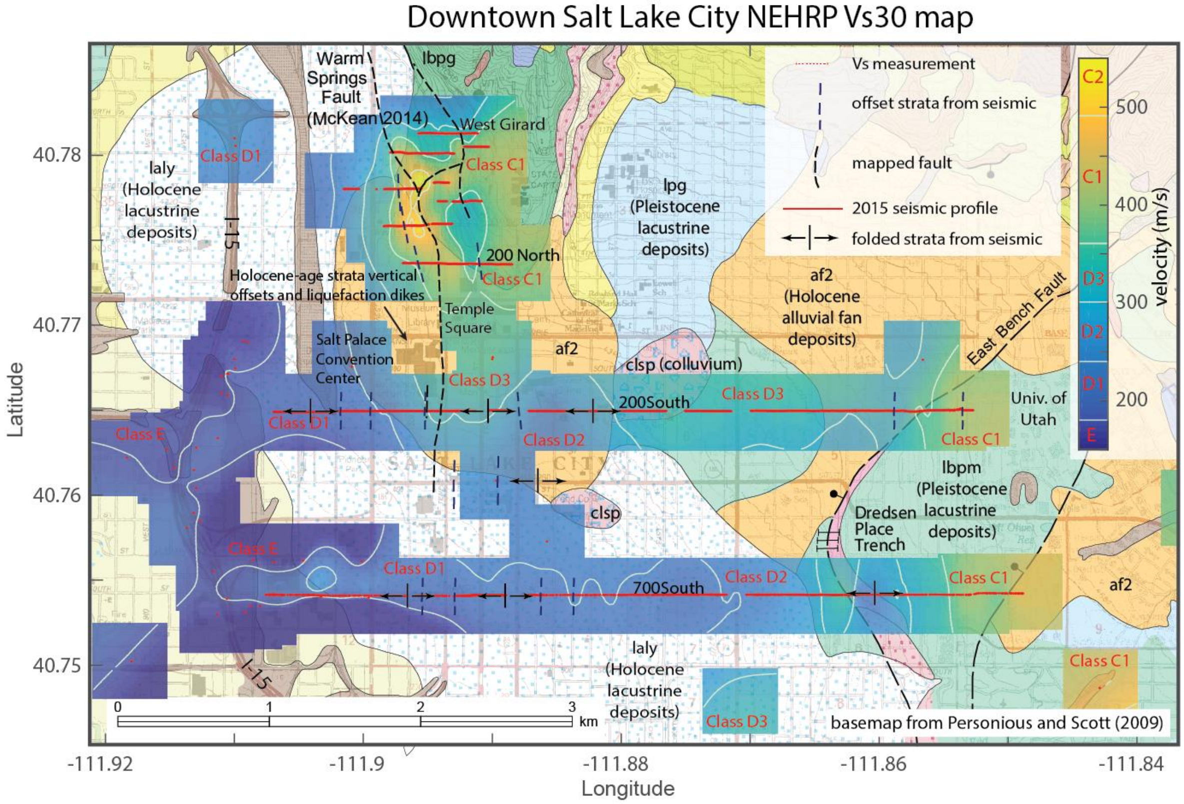


Figure 15. Composite Vs30 map with NEHRP site classifications from 2015 seismic land streamer survey and from past downhole Vs point measurements (McDonald and Ashland, 2008). Discrete red points represent past measurements while red dots in profile represent land streamer results. Beneath the Vs30 map is the modified Personious and Scott (2009) surficial geologic map showing

Summary

This report summarizes results from a seismic survey through the Salt Lake City urban corridor where I identify and describe offset and folded strata related to both known and inferred active faults and Vp/Vs properties for the upper 30 m below land surface. The seismic results suggest a transition from a clear surface and subsurface expression of the Warm Springs fault beneath north Salt Lake City to a diffuse fault zone with related folding of Bonneville age strata beneath the downtown corridor. There is no surface topographic expression of the Warm Springs fault within the downtown corridor and the seismic results are consistent with the Leeflang (2008) cone penetrometer interpretation for active faults related to the Warm Springs fault along a 400 South transect. The East Bench fault shows a clear topographic expression near the University of Utah campus and folded strata beneath a well-developed colluvial wedge in the hanging wall of the fault.

Acknowledgments

Use of ProMAX seismic processing software was provided by Landmark Graphics Corporation Strategic University Alliance Grant Agreement No. 2013-UGP-009000. Field work support included Thomas Otheim and Gabe Gribler from Boise State. Permitting and background support was provided by Jim Pechman (University of Utah), and Steve Bowman and Adam McKean from the Utah Geological Survey.

References

Baskin, R. L., and H. L. Berryhill Jr. (1998). Geologic analysis of continuous high-resolution, seismic-reflection data from the Lincoln Point-Bird Island area, Utah Lake, Utah, U.S. Geol. Surv. Water-Resources Investigations Rept. 96–4236, 34 pp.

Benson, A. K., and N. B. Mustoe (1991). Delineating concealed faults and shallow subsurface geology along the Wasatch front, Utah, USA, by integrating geophysical and trench data, Q. J. Eng. Geol. 24, 375–387.

Benson, A. K., and N. B. Mustoe (1995). Analyzing shallow faulting at a site in the Wasatch fault zone, Utah, USA, by integrating seismic, gravity, magnetic, and trench data, Eng. Geol. 40, 139–156.

Black, B. D., S. Hecker, M. D. Hylland, G. E. Christenson, and G. N. McDonald (2003). Quaternary fault and fold database and map of Utah, Utah Geol. Surv. Map 193DM, scale 1:500,000.

DuRoss, C.B., (2008). Holocene Vertical Displacement on the Central Segments of the Wasatch Fault Zone, Utah, Bulletin of the Seismological Society of America, Vol. 98, No. 6, pp. 2918–2933, , doi: 10.1785/0120080119

DuRoss, C. B., & Hylland, M. D. (2014). Synchronous Ruptures along a Major Graben-Forming Fault System: Wasatch and West Valley Fault Zones, Utah. Bulletin of the Seismological Society of America, 105, 1, doi: 10.1785/0120140064.

Gribler, G., Liberty, L.M., Michaels, P. and Mikesell, T.D. (*in press*). Isolating retrograde and prograde Rayleigh wave modes using a polarity mute, *Geophysics*.

Korbay, S.R., and McCormick, W.V. (1999). Faults, lateral spreading, and liquefaction features, Salt Palace Convention Center, Salt Lake City, Association of Engineering Geologists, 42nd Annual Meeting Program with Abstracts, p. 73.

Leeflang, B. A. (2008). Ground displacement investigations in downtown Salt Lake City, Utah, using the cone penetrometer, University of Utah M.S. thesis, Salt Lake City, 160 pp.

Lund, W. R. (2005). Consensus preferred recurrence-interval and vertical slip-rate estimates: review of Utah paleoseismic-trenching data by the Utah Quaternary Fault Parameters Working Group, Utah Geol. Surv. Bull. 130, 109.

Machette, M. N., S. F. Personius, and A. R. Nelson (1992). Paleoseismology of the Wasatch fault zone: a summary of recent investigations, interpretations, and conclusions, in Assessment of Regional Earthquake Hazards and Risk along the Wasatch Front, Utah, P. L. Gori and W. W. Hays (Editors), U.S. Geol. Surv. Profess. Pap. 1500-A, A1–A71.

McBride, J. H.,W. J. Stephenson, R. A.Williams, J. K. Odum, D. M.Worley, R.W. Keach II, J. V. South, A. R. Brinkerhoff, and A. O. Okojie-Ayoro (2010). Shallow subsurface structure of the Wasatch fault, Provo segment, Utah, from an integrated compressional- and shear-wave seismic reflection profile with implications for fault structure and development, Bull. Geol. Soc. Am. 122, 800–1814, doi 10.1130/B30174.1.

McCalpin, J. P., and S. P. Nishenko (1996). Holocene paleoseismicity, temporal clustering, and probabilities of future large (M >7) earthquakes on the Wasatch fault zone, Utah, J. Geophys. Res. 101, no. 3, 6233–6253.

McKean, A. (2014). Interin geologic map of the Salt Lake City North quadrangle, Salt Lake and Davis Counties, Utah, contract deliverable to US Geological Survey NEHRP award G13AC00169, 43 p.

Park, C.B., Miller, R.D., and Xia, J., 1999, Multichannel analysis of surface waves, *Geophysics*, 64, 800–808.

Personius, S.F. and W.E. Scott (1992). Surficial geologic map of the Salt Lake City segment and parts of adjacent segments of the Wasatch fault zone, Davis, Salt Lake, and Utah Counties, Utah, *U.S. Geol. Surv. Misc. Inv. Series, Map I-2106*, scale 1:50,000.

Robison, R. M., and T. N. Burr (1991). Fault-rupture hazard analysis using trenching and borings: Warm Springs fault, Salt Lake City, Utah, in Proceedings of the 27th Symposium on Engineering Geology and Geotechnical Engineering J. P. McCalpin (Editor), Boise, Idaho Dep. of Trans., 26-1–26-13.

Schwartz, D. P., and K. J. Coppersmith (1984). Fault behavior and characteristic earthquakes: examples from theWasatch and San Andreas fault zones, J. Geophys. Res. 89, no. B7, 5681–5698

Scott, W.E. and R.R. Shroba (1985). Surficial geologic map of an area along the Wasatch fault zone in the Salt Lake Valley, Utah, *U.S. Geol. Surv. Open-File Report. 85-448*, scale 1:24,000.

Simon, D.B., and R.J. Shlemon (1999). The Holocene "Downtown Fault" in Salt Lake City, Utah, Association of Engineering Geologists, 42nd Annual Meeting Program with Abstracts, 85.

Swan, F. H., D. P. Schwartz, and L. S. Cluff (1980). Recurrence of moderate to large magnitude earthquakes produced by surface faulting on the Wasatch fault zone, Utah, Bull. Seismol. Soc. Am. 70, no. 5, 1431–1462.

Wheeler, R. L., and K. B. Krystinik (1992). Persistent and nonpersistent segmentation of the Wasatch fault zone, Utah: statistical analysis for evaluation of seismic hazard, U.S. Geol. Surv. Profess. Pap. 1500-A-J, B1–B47.