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Multi-Scale Neotectonic Study of the Clear Lake Fault Zone
in the Sevier Desert Basin
(Central Utah)

Brandon D. Heiner

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Master of Science

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ABSTRACT
Multi-Scale Neotectonic Study of the Clear Lake Fault Zone in the Sevier Desert Basin (Central Utah)
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A multi-scale high-resolution geophysical and geological study was conducted in the Sevier Desert, central Utah, found within the Colorado Plateau-Basin and Range Transition Zone. The region is marked by Quaternary volcanics and faulting as young as 660 yr B.P., with many fault scarps thought to have the potential for 7+ magnitude earthquakes. Three locations within the Sevier Desert which represent three different tectonic expressions of possible faulting at the surface were selected. These include a location found within surface sedimentation, a location with surface sedimentation and sub-surface basalts, and a location with basalts, at the surface with very limited sedimentation. A suite of geophysical data were obtained including the use of P-wave, SH-wave, ground-penetrating radar (GPR). Auger holes, microprobe glass analysis, and mapping information were also completed in order to constrain and gain a more complete understanding of the sub-surface structure. These data were used to determine if there are sub-surface expressions of the possible surface scarps and if all the faults within the fault zone have the same structural style. The possible surface fault expressions were found to be connected to sub-surface fault expressions but with differing results within both sediments and basalts. Our data show that a multi-scale approach is needed to obtain a complete view of tectonic activity. The area faulting in the Sevier Desert penetrates at depth involving multiple complex styles that include some faulting that cuts recent lava flows and some that do not. The evidence also indicates that in at least some area faulting was episodic and others may be single events having implications on level of activity and hazard.

Keywords: Sevier Desert, Colorado Plateau-Basin and Range Transition Zone, Quaternary volcanics, faulting, P-wave, SH-wave, ground-penetrating radar, microprobe glass analysis, hazard
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INTRODUCTION

The Basin and Range Province is a large region of the western United States consisting of fault-bounded mountain blocks separated by desert basins filled with fluvial and lacustrine sediment and volcanic rocks (Eaton, 1982). One of these basins is the Sevier Desert located in central Utah (Fig. 1). It has a broad low-lying basin floor underlain by thick sedimentary fill that thins toward the basin margins (Oviatt, 1989). The basin is located in the Colorado Plateau-Basin and Range Transition Zone (eastern Basin and Range Province) and has major Quaternary deformation and faulting. This study will analyze both surface and subsurface expressions of this Quaternary deformation.

The Sevier Desert was selected for this study as an ideal laboratory for geophysical studies of active faulting. Active faults are expressed in a variety of structural styles at the ground surface, including exposed scarps in both Quaternary sediments and basalt lava flows. Multiple volcanic eruptions (Hoover, 1974; Oviatt, 1989; Oviatt, 1991; Hintz, 2008) put time constraints on fault movement and ash layers from these events constrain the age of recent deformation in the shallow subsurface.

A deep seismic profile across the Sevier Desert Basin by the COCORP (Consortium for Continental Reflection Profiling) shows the basin is underlain by a putative low-angle normal fault called the Sevier Desert detachment (Allmendinger et al., 1983). The detachment dips 12° to the west, extends more than 120 km east to west, and has been traced as deep as 15-20 km. It is thought to accommodate crustal extension beneath the Sevier Desert Basin (McDonald, 1976; Wernicke, 1981; Anderson et al., 1983; Von Tish et al., 1985; Mitchell and McDonald, 1987;
Figure 1. Location map for the Sevier Desert Basin in central Utah, USA. The three study areas are indicated. Faults (red lines) are from U.S. Geological Survey (2010).

Planke and Smith, 1991; Anders, 1993; Anders and Christie-Blick, 1994; Wills and Anders, 1995; Wills et al., 1997; Wills and Anders, 1999; McBride et al., 2010).

The Clear Lake fault zone (CLFZ), within the Sevier Desert, is approximately 36 km long and 5 km wide (Black et al., 1999; Hinze and Davis, 2003). This fault zone has also been referred to as the "Black Rock fault zone" by Hoover (1974) and the "Pavant-Tabernacle-Beaver Ridge fault zone" by Oviatt (1991). Interpreted fault lineaments within the fault zone can be observed on aerial imagery, although these are more subtle at ground level. The longest continuously mapped fault, the Clear Lake fault (CLF), located on the western flank of the fault zone and central to the Sevier Desert Basin, is over 26 km long, making it one of the longest
Quaternary faults in Utah outside the Wasatch fault zone (WFZ). By comparison, the WFZ is an active extensional fault system over 370 km long (Machette et al., 1991) that roughly corresponds to the mountain front east of the CLFZ and extends from northern to central Utah. It is the major structure that separates the Basin and Range province from the transition zone in the northern Great Basin. The height of the CLF surface scarp is about 3 m (9.8 ft). It has been implicated to be kinematically linked to the Sevier Desert detachment, intersecting it at a depth of about 3.5 km (Crone and Harding, 1984; Oviatt, 1989; and Hecker, 1993); however, no existing subsurface data actually shows a linkage in the study area.

Most geophysical studies in the Sevier Desert Basin have focused on deep structure, including those done on the Sevier Desert detachment. Such studies have lower resolution at shallow depths and thus have not imaged the near surface structure of features like the CLFZ. This has resulted in a gap between the uppermost part of conventional deep seismic reflection profiles and the ground surface. Crone and Harding (1984) addressed this with a medium-resolution compressional wave (P-wave) seismic survey over the CLF. They interpreted the surface scarp to be connected to deeper fault offsets within their seismic reflection profile. Although their profile was higher resolution than previous seismic surveys in the area, it lacked clarity in the very uppermost part of the subsurface (e.g., upper ~60 m) due to the relatively wide source and receiver spacings. Compared to P-wave surveys, horizontally polarized (SH-) wave surveys produce even clearer imaging in the shallow sub-surface.

The purpose of this study was to determine if there is a shallow sub-surface expression of the mapped surface scarps and lineaments interpreted from aerial imagery within the CLFZ; assess the variation in structural style of deformation within the zone; and improve our understanding of how deformation varies across the zone (e.g., are the western and eastern
margins deformed in a similar manner). We also experiment with different waveform techniques in order to link deformation observed at the surface to the shallow sub-surface.

This study also uses a suite of geophysical, augering, and surface geologic information in order to establish the benefits of combining techniques applicable to a range of vertical scales for understanding subsurface structure and seismic hazard. The geological and geophysical data span scales from reprocessed P-wave seismic reflection data with a resolution of 10s of meters, collected P-wave profiles, horizontally polarized shear (SH) wave reflection profiles, to 200-MHz ground-penetrating radar (GPR) profiles with vertical resolution close to a decimeter. Employing multiple scales can add valuable information by actually connecting surface geologic features to deep faulting (Kaiser et al., 2009; Bruno et al., 2010). If a surface deformation feature connects downward to a deep fault, then the seismic hazard rises since earthquake magnitude increases with the surface area of the fault (Wells and Coppersmith, 1994).

GEOLOGIC SETTING OF THE SEVIER DESERT BASIN

The Sevier Desert Basin is a topographically low area of about 8,000 km² in central Utah (Fig. 1). During late Mesozoic and early Cenozoic time, this region was tectonically dominated by crustal shorting, resulting in the Sevier fold-thrust belt (Allmendinger et al. 1983; DeCelles et al., 1995). The four major thrust systems within the Sevier belt in central Utah (Fig. 1 in DeCelles et al., 1995), the Canyon Range, Pavant, Paxton, and Gunnison thrusts, account for at least 120 km of east-west shortening (DeCelles et al., 1995).

Extension in the Sevier Desert Basin followed Sevier contraction and is typically regarded as having produced characteristic basin and range morphology of the region, beginning
between 20 and 7 million yr B.P. (Lindsey, 1982). Regional geophysical data indicate that the
crust is 25-30 km thick and seismic refraction and earthquake data have been used to infer a
crustal low-velocity zone and brittle-ductile transition at 8-15 km depth (Eaton, 1980; Smith,
1982; Allmendinger et al. 1983; Oviatt, 1989). The basin is dominated by grabens and tilted
blocks and is bounded on the west by the House Range and the Canyon and Pavant Ranges on
the east (Fig. 1) (Condie and Barsky, 1972; McDonald 1976; Anderson et al., 1983; Smith and
Bruhn, 1984). The surface geology includes geologically recent basaltic volcanic flows, normal
faults, scarps, marshy areas, playas, lake sediments, terrace deposits, and sand dunes (Oviatt,
1989). There are also many linear topographic anomalies seen on aerial imagery, many of which
have been interpreted as faults.

Oviatt (1989) noted that the lack of extensive piedmont alluvial fans within the Sevier
Desert Basin suggested that tectonic uplift has not been extreme for the last 5.3 Ma. Recent GPS
data show relative extension rates of about 2.8 +/- 0.8 mm/y for central Utah, as compared to the
extension found around the WFZ of 2.0 mm/y on the eastern edge of the Colorado Plateau-Basin
and Range Transition Zone (Arabasz et al., 1992; Thatcher et al., 1999). The Sevier Desert is a
broad zone of faulting, while the WFZ is generally thought to be relatively narrow. The CLF has
a slip-rate of less than 0.2 mm/yr (Black et al., 1999). Historical seismicity in the Basin and
Range Province suggests an earthquake magnitude threshold for surface rupture to be of M 6 to
M 6.5 (Arabasz et al., 1992; Hecker, 1993). This includes seven earthquakes studied by Hecker
(1993) that are associated with earthquake magnitudes larger than 6.3. Therefore, the CLF with
a fault scarp of 3 m could theoretically be related to an earthquake equal to or greater than M 6 to
M 6.5. Although many Quaternary faults scarps are thought to have resulted from M 7+
earthquakes, and thus have a relatively high seismic hazard, the subsurface structure of such faults is poorly known (Bucknam et al., 1980).

Sevier Desert Basin extension appears to have contributed to the onset of local volcanism (Lindsey, 1982; Oviatt, 1991). The basin has been volcanically active throughout the last 2 Ma (Hintz, 2008). Condie and Barsky (1972) defined seven different volcanic fields in the southern part of the Sevier Desert (locally, the “Black Rock Desert”) from 2.35 Ma B.P. to 11 ka B.P, the majority of which are under 1 Ma B.P. The more recent activity includes Pavant Butte (Fig. 1), occurring about 15.5 ka B.P. It is 270 m (890 ft) high, making it the largest volcanic cone in the basin (Condie and Barsky, 1972). Tabernacle Hill (Fig. 1), which consists of a tuff cone and a basalt flow, erupted about 14.3 ka B.P. The most recent eruption was from Ice Springs (Fig. 1), consisting of cinder cones and a basalt flow, and occurred 660 yr B.P. (Oviatt 1991). Both the Pavant Butte and the Tabernacle Hill eruptions were synchronous with an arm of glacial Lake Bonneville. Ice Springs erupted after the lake had drained out of the Sevier Desert Basin. The lavas from both Tabernacle Hill and Ice Springs rest on lacustrine deposits and eolian sands (Hoover, 1974).

Oviatt (1991) noted that the shallow deposits within the basin include silt, sand, gravel, marl, and calcareous clay. Much of the fine-grained lacustrine marls and calcareous clays were deposited in the several lakes that were present in the area. Pleistocene lake beds suggest that a freshwater lake or a series of lakes existed in the basin for at least the time period from 2.02 to 0.74 Ma B.P. The late Pleistocene was dominated by Lake Bonneville, which made its appearance in the Sevier Desert area about 21-20 ka B.P. and lasted until about 12.5 km B.P. From about 12 to 10 ka B.P., shallow freshwater Lake Gunnison covered much of the basin (Oviatt, 1989). Following Lake Gunnison, the Sevier and Beaver Rivers deposited large
amounts of the silt and sand in fine-grained alluvium along broad low-gradient fans in the Sevier Desert. Some areas within the basin had deltaic sand and gravel deposited by these rivers and other areas had sag ponds, which are generally found on the hanging walls of faults (McDonald, 1976; Anderson et al., 1983; Oviatt, 1989). In many areas these deposits are interbedded with multiple basalt flows of Pliocene, Pleistocene, and Holocene age. Deeper basin deposits are Oligocene and possibly Miocene fluvi-lacustrine sediments, and Miocene conglomeratic deposits derived from local source areas (McDonald, 1976; Mitchell, 1979; Lindsey, 1982). During the middle and late Pleistocene, many parts of the area have been generally degrading as shown by the early Pleistocene basalt flows perched on pedestals of basin fill.

**GEOLOGIC SETTING OF STUDY SITES**

Three study locations were selected in order to span the variety of surface expressions that exist within the CLFZ. The locations include the CLF proper on the western edge and two locations near the eastern boundary of the CLFZ (Fig. 1).

The first study site is on the 26 km long CLF, at the same location of Crone and Harding (1984)’s survey for the main Clear Lake fault, west south-west of Pavant Butte (Fig. 1 and 2). The scarp is striking more or less north-south and is expressed within unconsolidated Quaternary sediment. The 3 m (9.8 ft) elevation change could hypothetically also be interpreted as a river or lake bench. Crone and Harding (1984) however have previously showed that the scarp correlated to a deep subsurface fault. The footwall at the ground surface consists of sand and gravel deposits from the Beaver River overlain by windblown silt. This sand and gravel was deposited at the margin of Lake Bonneville as it underwent its final regressive phase. The
Figure 2. Location #1 (CLF) map for study area. Top shows geologic map of study area including both the faults (red lines) from U.S. Geological Survey (2010) and mapped faults (blue and black lines) from surface mapping and aerial photographs. Also included is the location of the P-wave seismic survey and location of lower right blow up map. Geological map modified from Utah Geological Survey (2013). (For more detail on geologic units see Oviatt 1989 and 1991). Bottom right is a blowup of the dashed area of the map above and shows location of P-wave, SH-wave, and augered holes including common depth point (CDP) locations and hole number.
hanging wall is blanketed by fine-grained lacustrine sediments and beneath eolian deposits (Oviatt, 1989). The scarp cuts Lake Bonneville deposits and therefore has been active in post-Bonneville time. Due to the redistribution of weakly consolidated and highly active eolian surficial materials, other faults scarp may exist within the CLFZ but are now invisible (Bucknam and Anderson, 1979).

The second study site (Fig. 3), Tabernacle Hill, is 23.5 km south-east of the CLF site (Fig. 1). The 300 m (985 ft) wide ridge trends north-south covered by eolian silt. The ridge is covered by the Ice Springs basalt flow to the north. To the south, the ridge is covered by the Tabernacle Hill basalt flow but scarp formed in this flow appear to be co-linear with the western border of the ridge. Thus, this flow is older than the ridge. Older basalts in the area, Beaver Ridge basalts, are found to the west and south of this site. The close proximity of older basalts and drilled wells show a likelihood for sub-surface basalts lying below the ridge (Oviatt, 1991; Blackett et al. 2013). No clear evidence of surface faulting is present. This ridge is typical of many of the linear anomalies within the basin. The ridge could be a terrace but one side of the ridge appears to be co-linear with a fault found in basalt flows to the south. This relationship suggests that the subtle ridge is a horst rather than a terrace.

The third location, known as Devil's Kitchen, is also found on the eastern side of the CLFZ, 10 km north of the Tabernacle Hill site (Fig. 1 and 4). Several basalt flows are present in the area, some with abrupt vertical edges. The apparent fault scarp (instead of a flow edge) cuts the basalt flow south east of Pavant Butte. A thin veneer of mostly eolian deposits is found on the footwall. The hanging wall has an unknown thickness of fine-grained lacustrine and younger
Figure 3. Location #2 (Horst) map for study area. Top shows geologic map of study area including both the faults (red lines) from U.S. Geological Survey (2010) and mapped faults (blue and black lines) from surface mapping and aerial photographs. Yellow stars are locations of measurements on surface fault displacement. Also included is the location of the P-wave seismic survey and location of lower right blow up map. Geologic map modified from Oviatt 1991. (For more detail on geologic units see Oviatt 1989 and 1991). Bottom right is a blowup of the dashed area of the map above and shows location of P-wave, SH-wave, and augered holes including CDP locations and hole number.
Figure 2. Location #3 (Devil’s Kitchen) map for study area. Top shows geologic map of study area including both the faults (red lines) from U.S. Geological Survey (2010) and mapped faults (blue and black lines) from surface mapping and aerial photographs. Also included is the location of the P-wave seismic survey and location of lower right blow up map. Geological map modified from Utah Geological Survey (2013). (For more detail on geologic units see Oviatt 1989 and 1991). Bottom right is a blow up of the dashed area of the map above and shows location of P-wave survey including CDP locations.
eolian deposits. The surface offsets of the basalt flow are expressed as well-developed columnar jointing and are up to 18.3 m (60 ft) (see Fig. 12 of Hoover, 1974).

**METHODS**

Near-surface P-wave or SH-wave reflection methods can extend observations from the surface into the uppermost several 10s of meters where seismic hazard estimates become critical (Woolery et al., 1993; Morey and Schuster, 1999; Williams et al., 2001; Improta et al 2003; Sugiyama et al., 2003; Wang et al., 2004; Colman, 2005; McBride et al. 2008; Harris, 2009; Bruno et al., 2010; Bruno et al., 2010; Campbell et al., 2010; McBride et al., 2010; Bruno et al., 2011; Stephenson et al., 2012; Ghose et al., 2013). Ground-penetrating radar (GPR) can in some cases be used to image ultra-shallow deformation in order to further constrain seismic hazard estimates (McClymont et al., 2008; Kaiser et al., 2009; and Wallace et al., 2010). However, many past geophysical studies of the shallow sub-surface only use one technique (e.g., P or SH-wave reflection).

**Hand Bucket Auger Holes**

Hand-bucket augering was used to understand the near-surface stratigraphy and possible different depositional environments in the footwall and hanging walls of faults. It was also used to find possible offsets within the near-surface sediments. The drilling was done by a hand-driven bucket auger 3 inches in diameter and 6 inches in length. The bucket contents were logged according to sediment content and unusual features noted. Augering was employed at both the CLF scarp and Tabernacle Hill.
Volcanic ash, found in augered holes at Tabernacle Hill, were studied by using microprobe glass analysis to find chemical compositions. Analyses were performed on a Cameca 5x50 microprobe using an acceleration voltage of 15 KV, a beam current of 10 nA, and beam diameter of 10 µm. Ash from each sample was placed in epoxy and then ground down for analysis. Each slide was then analyzed 12 to 14 times for 3 minutes.

Seismic Reflection Profiles

Acquisition

P-wave surveys were collected along or just off gravel roads at the CLF and the Tabernacle Hill and Devil’s Kitchen sites. The surveys were oriented to be approximately perpendicular to the topographic ridges (Figs. 2, 3, and 4) and collected with a Bison Elastic Wave Generator (EWG) source deployed in ~3 m (10 ft) increments at the receivers and recorded for 3-s using a 0.5-ms rate. At each station a shot record was stacked from two shots to reduce random noise. An array of 96 28-Hz vertical geophones spaced ~3 m (10 ft) and connected to four Geometrics Geode seismographs was used to collect the seismic data. Common depth-point (CDP) roll-along was achieved by moving 24 receivers forward to the end of the line after the source had moved through the 24 stations. This left at least 72 phones preceding (i.e., down-line from) the source at all times. The intent of the P-wave surveys was to provide a medium-level of seismic resolution.

A vintage USGS P-wave seismic CDP stacked section across the CLF (Crone and Harding, 1984) has been scanned from paper records and vectorized into a SEGY-format file (the original digital data were no longer available). This survey used a MINI-SOSIE vibrator for its source. The vibration points were spaced at 16 m (~52.5 ft) and geophones at 8 m (~26.2 ft) (Crone and Harding, 1984). The USGS data were integrated into our interpretation of the CLF
site. This survey provided some additional depth penetration, relative to our P-wave survey; however, it lacks very shallow imaging capability.

Horizontally polarized shear (SH) wave reflection profiles were also acquired for the CLF and Tabernacle Hill following the path of the P-wave surveys (Figs. 2, 3, and 4). The source was a 1-kg steel mallet struck against a solid metal cylinder coupled to the ground by the weight of the vehicle and the weight of the cylinder at a spacing of ~1.52 m (5 ft). A land streamer technique was used by pulling a 24-channel and 14-Hz horizontal geophone spread behind a vehicle (Pugin et al., 2004). The land streamer used a ~0.76 m (2.5 ft) receiver spacing.

P-wave surveys have higher frequencies and wave velocities from a larger source than SH-wave surveys, which have lower velocity and thus shorter wavelength varying from one half to one third of that of P-waves (Woolery et al. 1993, Woolery and Street, 2002; Bexfield et al., 2006; Okojie-Ayoro et al., 2008). These differences markedly increase the resolution of shallow sediments when using SH-wave surveys versus P-wave surveys.

In order to obtain ultra-shallow imaging, we experimented with a 200-MHz GPR antenna in continuous mode at the CLF and Tabernacle Hill sites using the same gravel roads as with the P-wave surveys. Although the efficacy of the GPR surveys was limited by the high clay content and salinity of the near-surface soils, in places the results were valuable for detailed information about very shallow geological features.

**Processing**

The seismic reflection profiles were processed using a conventional strategy that included muting of first arrivals and Rayleigh waves (for the SH-wave data), adaptive deconvolution to attenuate multiple arrivals and compress the seismic wavelet, a frequency bandpass (Ormsby) filter, automatic gain control, elevation static corrections, NMO (normal move-out) correction,
CDP stacking, trace mixing (to reduce scattering effects), depth conversion, and phase-shift migration (for the P-wave profiles). Preliminary time-to-depth conversion for the CLF P-wave profile was based on the RMS (root mean square) velocity function used to CDP stack the data. Other conversions were performed using a general “average” velocity of 1500 m/s, which likely over-estimates the depth of very shallow reflectors and under-estimates deeper reflectors. RMS velocities for the processing of the shallow SH-wave profiles were naturally much lower (e.g., 175 m/s), relative to the deep P-wave reflections.

RESULTS AND INTERPRETATION

Location #1 (Clear Lake Fault Scarp)

Hand Bucket Auger Holes

The footwall bucket auger hole was drilled to a depth of 2.64 m (8.67 ft) before refusal was reached at a hard or gravelly sub-surface layer (Fig. 5). Silt and sand are the dominant sediment with some marls and gravels. The lower half of the lithology log has two fining-upward groupings that show higher-energy conditions. This is likely river sediment due to its proximity to the Beaver River consistent with work by Oviatt (1989) who indicated fine-grained lacustrine silts and sands that match the top portion of our log, with fluvial and deltaic sands and gravels that could match lower portion of the log. The sediment is similar to that found by Bucknam and Anderson (1989a) where they excavated a 1 m (3.3 ft) test pit into the CLF scarp and found loose lacustrine and eolian sediment with sparse suspended pebbles.

The hanging wall bucket auger hole was drilled to a depth of 8.92 m (29.25 ft) (Fig. 5). The first two feet encountered silt and the rest of the hole was dominated by gray to dark gray
Several horizons contained organic-rich sediments including the bottom 3 inches that was dark brown to black and very organic-rich. The lithology within the augered hole matches that mapped by Oviatt (1989) with lacustrine or playa silts, marls, and calcareous clays. The higher amounts of organics found throughout the log indicate anoxic conditions. The hanging wall is interpreted as a sag pond on the downthrown side of the fault.
The ground surface for the footwall hole is 2.5 m (8.2 ft) above the ground surface for the hanging wall hole. The larger-grained river (medium to gravel) sands at the bottom of the footwall hole start at a depth of 1.8 m (5.2 ft). This package of river sediments is not found in the hanging wall hole. With the close proximity of the holes to each other it is assumed that these sediments are present in the hanging wall but below the augered depth. This suggests that there is at minimum a 9.6 m (31.5 ft) offset on the river sediment bed at the CLF site.

**Seismic Reflection Profiles**

Coherent reflectors on the CLF P-wave section appear beginning at about 50 m (164 ft) on the profile (below datum), and continue down to at least 500 m (1640 ft) (Fig. 8). Deeper, but weaker, reflections (possibly multiples, in part) continue down to about 900 m (2953 ft) do not assist in the shallow interpretation of the fault and are excluded (Fig. 6). Linear vertical disruptions, including vertical offsets, within reflectors are interpreted as faults. A zone of disruption appears just below the surface scarp and continues down through the profile with a down-to-the-east displacement along an interpreted fault. The dip of the interpreted fault is 70° starting at the top and decreasing to about at 500 m (1640 ft) depth. The clarity from the profile’s higher resolution and closer CDP sampling is apparent when compared with the partially coincident USGS P-wave reflection profile (Fig 7). Crone and Harding (1984) presented several antithetic faults initiating from the main fault and continue up to the east. These splay faults are not as apparent in our profile. The zone of fault disruption is not only recognized by the offset of reflectors above a depth of 80 m (262 ft) but also where the reflectors slope downward directly in line with the offset reflectors (90 m to 250 m). The sloped reflectors are likely from fault drag during movement. The amount of drag suggests that faulting occurred in weak sediments. In order for these weak sediments to be so deep in the section fault
Figure 6. Cross-section of location 1 (CLF). Top is the topographic elevation of the P-wave profile with a vertical exaggeration 15x when compared with seismic section. The red arrow indicates approximate location of fault from U.S. Geological Survey (2010) and the blue arrow indicates approximate location from surface mapping and aerial photographs. Middle is an unmigrated P-wave stacked section converted from time to depth using the normal move-out velocity function. Bottom is a migrated P-wave stacked section converted from time to depth the same way as above section. Note that profile is hung on an elevation datum of 1400m. Depth converted using a variable function velocity model of 50 s – 1400 m/s, 150 s – 1500 m/s, and 400 s - 2000 m/s. Red stars indicate locations of hand augered holes drilled into subsurface (See figure 2). Black dashed lines indicate interpreted faults.
movement is likely occurring rapidly. The reflectors are convex upward in the hanging wall suggesting the presence of sag ponds. These observations suggest that the fault may have deformed by creep (e.g., aseismic creep) at times with little to no breakage and at other times broken with strong fault movement (at least at the level of vertical resolution possible). The
scarp (surface rupture) indicates a likelihood earthquake magnitude has been M 6 to M 6.5 (Arabasz et al., 1992; Hecker, 1993) on the CLF at least during some of the fault’s history. The presence of fault creep on the CLF would suggest that at times earthquake activity proceeds by repeated small events. In either case, the greater separation of reflectors on the hanging relative to the footwall with depth indicates a syn-sedimentary fault.

The first coherent reflections on the SH-wave profile starts at 5 m (16.4 ft), and continues down to about 90 m (295 ft) (Fig. 8). This fills much of the near-surface data gap remaining on our P-wave profile. A zone of disruption in the reflectors extends from the top of profile directly below the scarp and continues down through deeper reflectors with a down-to-the-east displacement along the fault. The expression of the interpreted fault on the SH-wave profile confirms the interpretation on the P-wave profile, with increased resolution toward the surface. Offsets near the top of the section are clearly visible while deeper reflectors are not. A second fault can be interpreted 110 m (361 ft) to the west of the main CLF, over the footwall, which indicates that the tectonic expression may be more complex than a single fault located at the surface scarp.

The results of the GPR surveys were excellent for the CLF site, likely owing to the well-layered sediments and removal of clay-rich, saline surficial materials from the roadbed. The vertical resolution is close to a decimeter and has clear resolution to a depth of about 1.83 m (6 ft) (Fig. 9). The profile extended across the fault scarp and shows possible evidence of tectonic deformation in footwall, but could also be sedimentological in origin (Fig. 9(A), location 1). An interpreted fault interpreted just west of the scarp with down-to-the-east offsets propagating up to the surface into the unconsolidated sediments shows clear evidence of ultra-shallow tectonic faulting (synthetic with the overall displacement) (Fig. 9(A&B), location 2). This
Figure 8. Cross-sections of location 1 (CLF). Top is the topographic elevation of the SH-wave profile with a vertical exaggeration 5x when compared with seismic section. Bottom is an unmigrated SH-wave stacked section converted from time to depth using normal move-out with a vertical exaggeration 1.5x. Note that profile is hung on an elevation datum of 1400m and \( V_r = 150 \text{ m/s} \). Red star indicates location of a hand augered hole drilled into subsurface (See figure 2). Black dashed lines indicate interpreted faults.

Confirms previous interpretations of the CLF being active in the Holocene (Condie and Barsky, 1972; Bucknam and Anderson 1979 Crone and Harding 1984; Oviatt, 1989; and Hecker, 1993). Directly below the mapped scarp are diffractions that imply a of small-wavelength disruption (Fig 9(B), location 3). The scarp location corresponds to the west margin of a small sag basin (Fig 9(B), location 4).

The integration of all available geological data and the multi-scale geophysical profiles allows for a more complete reconstruction of the tectonics of the CLF. The P-wave, SH-wave,
Figure 9. (A) and (B) are unmigrated GPR cross-sections from one continuous survey. Box in A indicates location of blowup C. See text for descriptions of arrows 1-4. (C) Unmigrated GPR cross-section (not topographically corrected) blowup of location 1 in A. The fault scarp is to the east of this section. Black arrow indicates the location of small fault zone west of the surfacescarp, which occurs further east, off the section. Black dashed lines indicate interpreted fault. Black solid lines indicate interpreted horizons and their respective offsets across the fault trace. A dielectric constant of 5 was used for time to depth conversion.

and the GPR sections all project the fault from the deep sub-surface up to the scarp. The U.S. Geological Survey (2010) placement of the CLF matches our observations. The SH-wave and P-wave seismic profiles and the GPR profile all show sagging of the hanging wall reflectors. The
sagging being seen in all of the sections indicates the development of a persistent sag pond in the hanging wall over time. This conclusion is supported by the augered holes and by the presence of sag ponds that have been interpreted as tectonic features (McDonald, 1976; Anderson et al. 1983) elsewhere in the basin. The sagging is also in the Crone and Harding (1984) P-wave section although it is not as clear.

**Location #2 (Tabernacle Hill)**

**Hand Bucket Auger Holes**

Fifteen auger holes were constructed to depths ranging from 3.11 m (10.2 ft) to 8.26 m (27.1 ft) (Fig. 10), intersecting coarse, basaltic ash at their base. All the holes had surface alluvium in the top 0.53 m (1.75 ft) to 1.83 m (6 ft). The remainder of most of the holes consisted of silty marl. In addition, six of the holes also had clay marl just above an ash layer. The auger holes on the western side of the ridge also had a nodular calcite hard pan layer at 3.66 m (12 ft) to 4.57 m (15 ft) with a thickness of 1 to 2.5 cm (0.5 to 1 in). This layer could be penetrated everywhere except hole 1. Gypsum nodules occurred within nine of the holes and gastropod shells within holes 2 and 11.

The ash layer shows an offset at three locations (see cross-section in Fig. 10). Two large offsets were found at both of the ridge edges. An offset of the ash layer of 7.29 m (23.9 ft) appears along the eastern margin of the ridge with down-to-the-west displacement. Similarly, an offset of 5.68 m (18.6 ft) appears along the eastern margin of the ridge with down-to-the-east displacement. These offsets are interpreted as bounding an uplifted horst block bordered by scarps at the Tabernacle Hill site. A third offset of the ash layer occurs between holes 2 and 3 west of the ridge. This offset showed a down-to-the-west movement on the ash with an offset of
Figure 10. Cross-section of augered holes ranging in depth from 10.2ft (~3.11m) to 27.1ft (~8.26m) in order to reach an ash layer at study site 2 (Horst). Vertical exaggeration in cross-section is 50x. All holes have 1.75ft (~0.53m) to 6ft (~1.83m) of surface alluvium at the top and varying amounts of silt and clay marls. The high-angled normal faults (shown in red) have offsets in the ash layer going from left to right of 10.2ft (~3.12m), 23.9ft (~7.29m), and 18.6ft (~5.68m). Hole 6 is 0.64 ft (~0.20m) below the elevation datum of 1440m used in the seismic cross-sections (See figures 12 and 13).

3.12 m (10.2 ft). The ash layer within each hanging wall, on either side of the ridge, exhibits some variation in elevation.
Determining the source and in turn the age of the ash allows for finding a slip rate. Microprobe glass analyses were employed to determine chemical compositions and the source of the ash in the augered holes (Table 1). Logic suggests that the Tabernacle edifice is the most likely source given its proximity, as the 660 yr. Ice Sprigs ash is unlikely to be found at these depths. However, Oviatt and Nash (1989) documented broad dispersal of Pavant Butte ash.

The average chemical compositions of each hole were normalized to, and compared with the basalt compositions of Oviatt and Nash (1989) for both the Pavant Butte and Tabernacle Hill ashes (Fig. 11). Normalization was achieved by dividing our values into the values given by Oviatt and Nash (1989). A perfect match to Pavant Butte or Tabernacle Hill would be represented as a straight horizontal line at a value of 1. Figure 11 shows that the data are inconclusive whether the ash comes from Pavant Butte or Tabernacle Hill. This is because the normalized data from Tabernacle Hill (red colors, Fig. 11) were not discernibly closer to a straight line at 1 than the normalized data from Pavant Butte (blue colors, Fig. 11).

<table>
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<tr>
<th>Hole #2</th>
<th>Na₂O</th>
<th>MgO</th>
<th>Al₂O₃</th>
<th>SiO₂</th>
<th>P₂O₅</th>
<th>K₂O</th>
<th>CaO</th>
<th>TiO₂</th>
<th>MnO</th>
<th>FeO</th>
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<tr>
<td>Average (1 std dev)</td>
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<td>6.533</td>
<td>15.031</td>
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<td>0.272</td>
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<td>9.521</td>
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<td>MgO</td>
<td>Al₂O₃</td>
<td>SiO₂</td>
<td>P₂O₅</td>
<td>K₂O</td>
<td>CaO</td>
<td>TiO₂</td>
<td>MnO</td>
<td>FeO</td>
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<tr>
<td>Average (1 std dev)</td>
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<td>16.250</td>
<td>49.637</td>
<td>0.153</td>
<td>0.964</td>
<td>9.812</td>
<td>1.962</td>
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<td>MgO</td>
<td>Al₂O₃</td>
<td>SiO₂</td>
<td>P₂O₅</td>
<td>K₂O</td>
<td>CaO</td>
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<td>MnO</td>
<td>FeO</td>
</tr>
<tr>
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<td>15.517</td>
<td>48.636</td>
<td>0.278</td>
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<td>Hole #12b</td>
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<td>MgO</td>
<td>Al₂O₃</td>
<td>SiO₂</td>
<td>P₂O₅</td>
<td>K₂O</td>
<td>CaO</td>
<td>TiO₂</td>
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<td>FeO</td>
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<tr>
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<td>9.208</td>
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<td>11.594</td>
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Table 1. Average chemical compositions of ash found in holes 2, 5, and 12. A sample slide from each hole (2 for hole 12) was analyzed 12 to 14 times for 3 minutes with invalid runs removed. Included is one standard deviation when comparing all data included in average.
Figure 11. Microprobe glass analysis completed to find chemical compositions of ash in holes 2, 5, and 12. The average chemical compositions of each hole is normalized to the findings of Oviatt and Nash (1989) for both the Pavant Butte and Tabernacle Hill ashes.

The large grain size of the ash particles (medium to coarse grains) indicates that it most likely was deposited close to its volcanic source. The drill holes and ash are located 3.4 km from the Tabernacle Hill eruptive center and 21.3 km from the Pavant Butte eruptive center. Given the proximity to Tabernacle Hill, the ashes in the augered holes most likely came from the 14.3 ka Tabernacle Hill volcanic event (Oviatt, 1991). The time of ash emplacement occurred when a water lake was present due to the presence of diatom-bearing marl above and below the ash. Thus, the ash must be related to Tabernacle Hill given the constraints of proximity and the fact that the Pavant Butte eruption occurred earlier and that ash, if present, is concealed beneath the ash encountered.

The ash layer defined in the holes over the ridge slopes gently to the east (Fig. 10). The marl layer above the ash over the ridge thins to the west. This thinning suggests that the tilt on the horst occurred syndepositional with the movement on western fault but after deposition of the ash layer. This is also supported by surface mapping and measurements. Four measurements south of the augered holes and within the Tabernacle Hill basalt flow on the western fault scarp
were taken that show the amount of post-eruption movement on the fault (Fig. 3). They were made by measuring the distance and angle from the top of the scarp to the base of the scarp. The vertical displacement from these measurements had an average of 24.4 ft (7.45 m), which is very close to the offset on the ash layer observed in the holes. Because the western fault is covered to the north by the Ice Springs basalt flow (Fig. 3), that fault movement must have happened sometime during the 13,640 years between the extrusion of the Tabernacle Hill and the Ice Springs lavas. An offset on the ash of 23.9 ft (7.29 m) (Fig. 10) indicates the average vertical movement on the western fault is 0.53 mm/yr. The marl layer on the eastern side of the ridge is thicker than on the west side. This suggests that there could have been syndepositional movement on the eastern horst fault.

The marls in the augered holes are likely sediment from Lake Bonneville and Lake Gunnison (Oviatt, 1991), which covered this area before and after the eruption of the Tabernacle Hill flow. This is supported by the gastropod shells within the marls, which implies that marls were deposited in shallow fresh water, whereas gypsum nodules are due to displacive evaporative discharge of groundwater in the area. Evaporation led to the precipitation gypsum nodules found in the sub-surface.

**Seismic Reflection Profiles**

The Tabernacle Hill P-wave profile shows coherent reflections starting at about 50 m (164 ft), with the first strong reflections at 75 m (246 ft) (Fig. 12). Reflectivity continues down to about 350 m (1148 ft). Zones of disruption appear in the reflectors below both sides of ridge. These disruptions extend down from the two interpreted surface scarps. The eastern faults have down-to-the-east displacement, dipping at about 70º and the western faults have down-to-the-west displacement and dip at about 75º as recognized by small offsets in the reflectors. The
reflections between 75 m and 175 m (246 ft and 574 ft) are interpreted as basalt flows due to their high reflectivity. This interpretation is also supported by the older Beaver Ridge basalts found to the west and south and basalts found in the subsurface in near-by wells (Oviatt, 1991; Blackett et al. 2013). We also interpret an antithetic fault that appears near the eastern surface scarp and dips to the west. The eastern fault appears to pre-date the eruption of the basalt flows that appear at a depth of 100 m to 175 m (328 ft to 574 ft). The basalts draped over the fault scarp that existed at that time. The basalts then filled topographic low above the hanging created by the slip.

The overall character of the seismic profile is quite different from that acquired over the CLF to the north-west. No well-layered sediments appear on the Tabernacle Hill profile as seen on the CLF profile. There is also no evidence of growth faulting or sag-pond development. The Tabernacle Hill profile is dominated by subsurface basalts, which effectively reflect energy from their upper surface and severely attenuate and scatter seismic energy deeper (Maresh et al., 2006; Pujol and Smithson, 1991). A GPR profile was surveyed along the seismic profile, but produced poor data, possibly due to higher clay content in the near-surface at this site.

The SH-wave profile provides a clearer view of the sub-surface above the basalt flows imaged on the P-wave profile. The first coherent reflections are at 5 m (16.4 ft) below the datum and continue down to about 90 m (295 ft) (Fig. 13). Reflectors within the horst block are interpreted as unconsolidated sediment and have a small tilt to the east, which confirms the dipping stratigraphy in the augered holes.

As with the CLF site, we can integrate a geological and geophysical interpretation in order to better constrain a complete geological picture. Although the U.S. Geological Survey (2010) placement of faults was correct on our western fault location at the site, their placement
Figure 12. Cross-section of location 2 (Horst). Top is the topographic elevation of the P-wave profile with a vertical exaggeration 15x when compared with seismic section. Red arrows indicate approximate location of faults from U.S. Geological Survey (2010) and blue arrows indicate approximate location from surface mapping and aerial photographs. Middle is an unmigrated P-wave stacked section converted from time to depth using normal move-out velocities. Bottom is a migrated P-wave stacked section converted from time to depth as above. Note that profile is hung on an elevation datum of 1440 m. Depth converted assuming an average velocity of 1500 m/s which will overestimate very shallow depths and underestimate greater depths. Red stars indicate locations of hand-augered holes drilled into subsurface (See Fig. 4). Black dashed lines indicate interpreted faults.
Figure 13. Cross-section for the Tabernacle Hill site. Top is the topographic elevation of the SH-wave profile with a verticle exaggeration of 3.75 when compared with the seismic section. Bottom is an unmigrated SH-wave stacked section converted from time to depth using normal move-out velocities with a vertical exaggeration 2. Note that profile is hung on an elevation datum of 1440 m, using a replacement velocity of 150 m/s. Red stars indicate location of hand-augered holes drilled into subsurface (See Fig. 3).
of the eastern fault is too far to the west by about 35 m (115 ft). This is supported by the projection of the fault on the P-wave section from the subsurface to the surface scarp (Fig. 12), by the horizontal location offset of ash in the augered holes (Fig. 10), and by the location of the scarp east of the USGS mapped fault (Figs. 2 and 10). Faulting along the western side of the horst is episodic as evinced by displacement happening at least twice: once as shown by the drape of basalts over an existing fault scarp in the subsurface and once by the offset ash layer in the augered holes.

**Location #3 (Devil's Kitchen)**

*Seismic Reflection Profiles*

The Devil's Kitchen P-wave profile shows coherent reflections at about 50 m depth (164 ft) (Fig. 14). Reflectivity continues down to about 500 m (1640 ft). The overall quality of this profile is not as good as CLF or Tabernacle Hill site. This is likely due to a more complicated series of basalt flows at or very near the ground surface. Most of the good reflectors appear between depths of about 75 m and 250 m (246 ft and 820 ft). Like the reflectors on the Tabernacle Hill P-wave profile, we interpret these as basalt flows, likely intercalated with sediments, due to their high amplitude and near proximity of basalt outcrops to the profile (Fig. 4) (Oviatt, 1989; Oviatt, 1991). As with the interpretations from Tabernacle Hill, faults are interpreted by offset and truncated reflectors. Diffractions on the section are likely caused by the abrupt edges of offset basalt layers. Faults are interpreted through the profile with about 70º - 75º with a mostly down-to-the-west displacement. We also interpret an antithetic fault that initiated at depth from the western-most fault that continues up to the west where it is expressed as small offsets in shallow reflectors. Between profile locations 500 m and 750 m is a highly
Figure 14. Cross-section of location 3 (Devil’s Kitchen). Top is the topographic elevation of the P-wave profile with a vertical exaggeration 15 when compared with seismic section. Red arrows indicate approximate location of faults from U.S. Geological Survey (2010). Middle is an unmigrated P-wave stacked section converted from time to depth using normal move-out velocities. Bottom is a migrated P-wave stacked section converted from time to depth using normal move-out. Note that profile is hung on an elevation datum of 1440 m. Depth converted assuming an average velocity of 1500 m/s, which will overestimate very shallow depths and underestimate at greater depths. Black dashed lines indicate interpreted faults.
fragmented rupture zone. Although the U.S. Geological Survey (2010) placements of the Devil's Kitchen faults are somewhat similar to our interpretations based on the geophysical and field observations, the extension of their fault interpretations into the study area may not be completely correct. This is illustrated by Figure 4 where the fault locations extend past the scarps observed on the ground and aerial photographs. The Devil’s Kitchen site is interpreted as exhibiting relay structures with a highly faulted ramp at the seismic profile location. The two faults seen through aerial and surface mapping do not extend to the rupture zone found on the P-wave profile. The ramp is between the two mapped faults as illustrated in Figure 15.

Figure 15. 3-D illustration of location 3 (Devil's Kitchen). Red lines indicate the location of main (mapped) Devil’s Kitchen faults. Black biconvex lens shapes are faults within the ramp area. Blue line is the approximate location of the P-wave Survey. The area is interpreted as relay faulting with a highly faulted ramp at the seismic profile location. The main faults do not extend to the rupture zone on seismic profile and the ramp is present between the two main faults.
SUMMARY AND CONCLUSION

The CLF scarp corresponds to both a deep sub-surface and near-surface expression of a high-angle normal fault. The near-surface geology, however, is more complex than previously interpreted, with significant shallow faulting occurring in the footwall of the fault and remnant sag basins in the hanging wall. The sag pond interpretation is supported by data from augered holes. Our geophysical data has augmented the USGS profile with higher resolution shallow data. The higher detail attained by our surveys suggests a significant component of fault creep with little to no large reflector offset. This implies that seismic hazard associated with the CLF at times may be less than that if the fault had formed only during larger single episode slips. Using equations from Wells and Coppersmith (1994), the length of the CLF of 26 km would produce a M6.7 earthquake. If the 9.6 m (31.5 ft) offset of river sediment at the CLF was produced with a single rupture event it would also have been associated with a M7.3 earthquake.

The P-wave survey at Tabernacle Hill reveals that the low-lying ridge is actually an uplifted horst block bordered by a pair of subtle topographic scarps. These scarps are surface expressions of high-angle normal faults that cut through a package of basalt. Augered holes and a SH-wave seismic profile provide critical information on the structure of shallow, unconsolidated sediments that mantle the buried lava flows. Both the SH-wave and the auger data show that the horst tilts to the east. The ash bed was derived from the Tabernacle Hill eruption. The marl layer above the ash bed within the horst thins to the west, indicating syn-depositional faulting. In addition, the vertical movement on the horst’s western fault is calculated to be about 0.53 mm/yr. The measured length of the Tabernacle Hill ground surface scarp is 3.5 km, which equates to a M5.6 earthquake (Wells and Coppersmith, 1994); however, this would be an minimum value. The actual scarp must be longer than 3.5 km, but cannot be
measured because it is covered by the Ice Springs basalt flow to the north. If the ash bed offset of 7.29 m (23.9 ft) were produced with a single event, it would have produced a M7.2 earthquake (Wells and Coppersmith, 1994).

The high-resolution P-wave survey at Devil's Kitchen shows a 250 m (820 ft) wide highly rupture zone with the main, synthetic faults having a down-to-the-west movement. The survey also shows an antithetic fault located well within the hanging wall cutting thru well-layered reflectors that are at least in part offsets of volcanic rocks. We interpret the complexity of the profile to be due to a ramp within an area of relay faulting. This is important because in a relay fault system, it is likely that multiple segments would rupture at the same time. Such would increase the magnitude of an associated earthquake and thus increase the seismic hazard. The measured length of the Devil's Kitchen scarp of 8.5 km would produce a M6.1 earthquake (Wells and Coppersmith, 1994). Again, this is possibly a minimum value. This would increase the magnitude of an earthquake. If the surface offset of 18.3 m (60 ft) were produced with a single event, it would result in a M7.5 earthquake (Wells and Coppersmith, 1994).

Our studies conducted at the three sites in the Sevier Desert show that faulting penetrates at depth and involve multiple complex styles (Fig. 16). The CLF shows that some faulting occurs in unconsolidated sediments and that movement could be a combination of both creep and small offset events. It also has characteristics of a syn-sedimentary fault, as shown by the greater separation of reflectors on the hanging relative to the footwall.

Unlike the CLF, Tabernacle Hill shows a more complex, but roughly symmetric faulting that produced a horst. It also shows that, on at least the western edge, faulting appears to have been episodic. This is important because it indicates that the fault may continue to produce
earthquakes in the future. Tabernacle Hill and Devil’s Kitchen both reveal that faults that cut recent and sub-surface lava flows. Devil’s Kitchen additionally reveals relay faulting within the Sevier Desert basin. The Devil’s Kitchen fault may be a single event evidenced by the apparent lack growth strata in the hanging wall. Generally, our results show that surface faulting in the Sevier Desert penetrates to significant depth and is expressed with multiple complex styles.

The integration of geological, geochemical and petrographic, GPR, and seismic-reflection techniques is important in assessing the likelihood of surface geologic features (e.g., lineaments/fractures) being connected to deep faulting. The strategy allows the tracing of fractures or fracture zones from the ground surface through the sub-surface rather than assuming connectivity at depth. This allows for a more complete understanding of the subsurface structure and seismic hazard. If a surface deformation feature connects to a deep fault, then the seismic hazard rises since earthquake magnitude increases with the surface area of the fault. The multi-scale strategy can also help in the assessment of whether a fault is episodic or not, as found with
the Tabernacle Hill site. Knowing that a fault is episodic, and thus likely to experience recurrent
movement, also aids in seismic hazard assessment.
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