✦ STUDY AREA

This study evaluated a total of five sites within GTNP using shallow seismic survey methods (Figure 1). At the Taggart Lake and String Lake sites, P-wave refraction and IMASW Vs data were collected across the Teton fault scarp to evaluate vertical offset and image the fault structure in the shallow subsurface. These sites were selected because they 1) are located on the main trace of the Teton fault, 2) exhibit simple fault geometry where all or most slip appears to be accommodated on a single strand, 3) have sparse or open vegetation cover, 4) are within hiking distance from the nearest trailhead, and 5) are likely to be locations where velocity contrasts created by slower alluvium in the hanging wall directly juxtapose crystalline bedrock of the footwall and could be imaged with seismic data. The 3 remaining field sites were located adjacent to the Craig Thomas Discovery & Visitor Center, Jackson Lake Lodge, and Signal Mountain Lodge. At these sites IMASW Vs surveys were conducted as close as possible to the park facility structures, in order to determine specific site characteristics, without causing disturbance for the park guests and within the substrate in which each facility is founded.

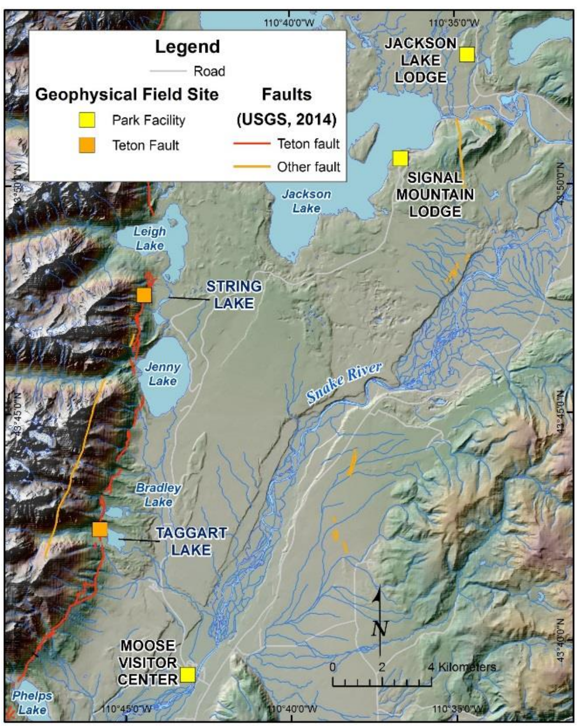

Figure 1. Location map showing five sites within GTNP studied with shallow seismic survey methods.

Teton Fault Sites

Taggart Lake

The Taggart Lake study site is located at the mouth of Avalanche Canyon, where a distinct north-striking scarp formed by the Teton fault offsets Taggart Lake basin sediments and the bounding lateral moraines (Figure 2). The basin is bounded to the north, south and east by lateral and end moraines, which formed around the toe of the Pinedale-age alpine glacier that flowed eastward out from Avalanche Canyon. Inferred sedimentary deposits within the basin include: dense glacial sediment (denoted here as till), Taggart Creek fluvial deposits, lacustrine deposits, colluvium, and organic soil. The glacial deposits are juxtaposed against layered gneiss and migmatite basement rocks (Love et al., 1992) exposed in the footwall. Cosmogenic ages from Licciardi and Pierce (2008) at Jenny Lake (Figure 1) indicate glacial retreat from the range front 13,000-15,000 years ago.

Within the vicinity of the Taggart basin the Teton fault has a northerly strike (~6°) and a distinct east-facing scarp. The fault vertically offsets the lateral moraines to the north and south of Taggart Lake and the basin floor to the west of Taggart Lake. North of Taggart Creek, most of the post-glacial slip appears to have been concentrated on a single fault trace, and to the south of Taggart Creek the fault appears to be segmented and left-stepping as it passes through the large lateral moraine (Figure 3). Small antithetic faults are visible near the crests of the lateral moraines to the north and south but are not evident in the Taggart Lake basin floor.

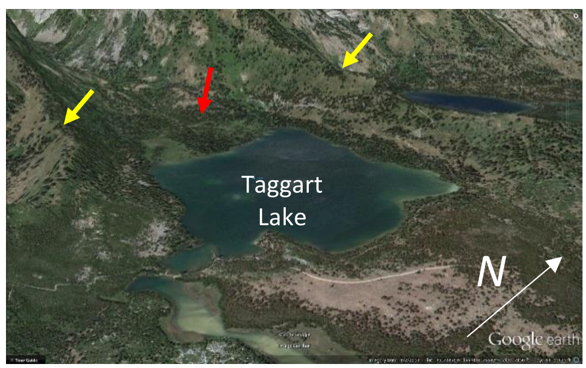

Figure 2. Oblique view of Taggart Lake basin from Google Earth. Yellow arrows show the Teton fault scarp on bounding lateral moraines. Red arrow shows the approximate location of Taggart Lake seismic survey location. Yellow arrows indicate scarps in moraine crests.

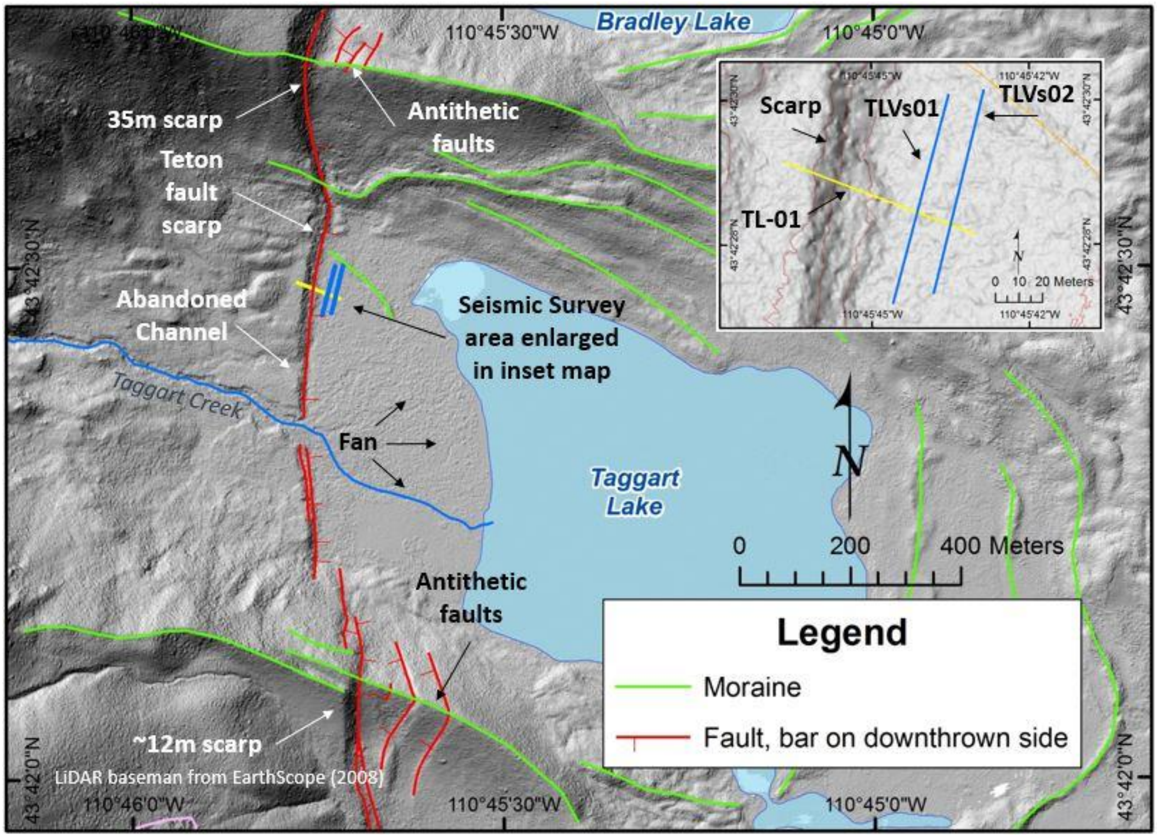

Figure 3. Taggart Lake site

The large moraine between Taggart and Bradley Lakes is vertically offset along a very distinct 35 m scarp, which indicates a longer record of surface faulting than the basin sediments or the faulted moraine south of Taggart Lake. The smaller moraine to the south is vertically offset 12 m (Thackray and Staley (in review)). The basin floor is vertically offset 12 - 15 m.

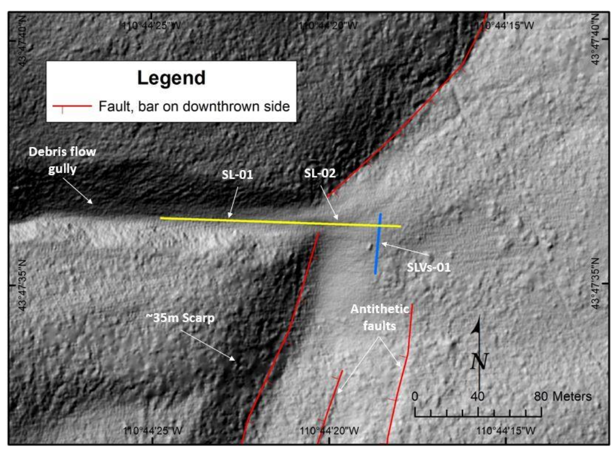

Figure 4. String Lake site

String Lake

The String Lake shallow seismic survey site is located to the south of Leigh Lake and west of String Lake (Figure 1 and 4) at the mouth of a steep debris flow gully at the point where the gully crosses the trace of the Teton fault (Figures 5 and 6) and over an alluvial fan deposited on the hanging wall. At this location the fault has a strike of approximately 20° and a scarp height of approximately 35m. Detailed scarp analysis by Thackray and Staley (in review) measured scarps in the area as high as 40 m suggesting a fault offset-based age estimate of 45-55,000 years. Antithetic faults are visible in EarthScope (2008) LiDAR to the south, but are apparently buried by the alluvial fan, sourced from by the gully, in the vicinity of the seismic survey.

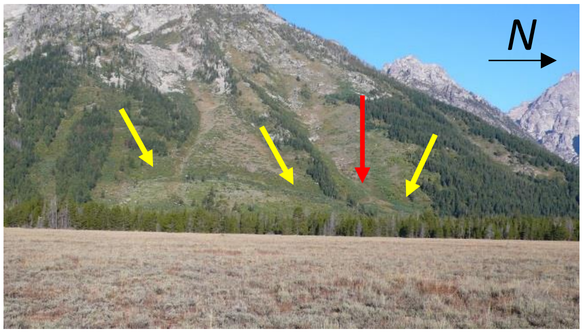

Figure 5. Looking west at the String Lake shallow seismic survey site (red arrow). Teton fault scarp is expressed as a green vegetation lineament, as indicated by the yellow arrows. The fault scarp becomes less apparent to the north of the seismic survey site.

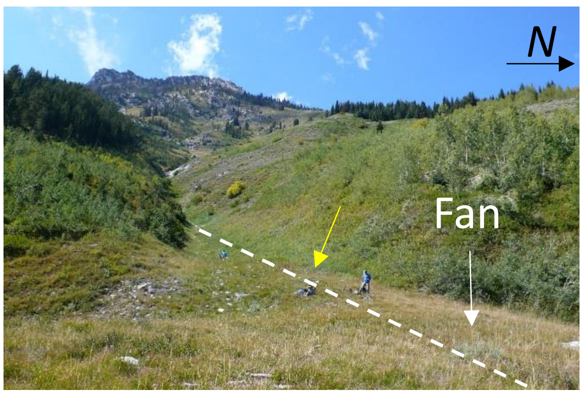

Figure 6. Looking west at the String Lake field site. The dashed line indicates the approximate trace of the SL-01 and SL-02 seismic lines. The yellow arrow indicates the approximate location where SL-02 intersected the fault. Note fan development on hanging wall.

Shear Wave Velocity at Park Facilities

Three park facility sites (Jackson Lake Lodge, Signal Mountain Lodge and the Craig Thomas Discovery and Visitor Center; Figure 1) were surveyed with IMASW Vs methods. Sites were chosen that were in close proximity to the structure of interest, on relatively flat terrain in the sediment in which each building is constructed, and in locations that would cause minimal or no disturbance to park guests and staff.

Jackson Lake Lodge

The Jackson Lake Lodge IMASW Vs site (JLLVs-01) was located approximately 325 m north-northeast of Jackson Lake Lodge (Figure 7) and on the same Pleistocene terrace surface on which the Jackson Lake Lodge complex is constructed. At this site a gravelly terrace deposit (Qtg) is inset into Jackson Lake moraine related drift deposits (Qg4j) and overlies the Teewinot Fm, which outcrops on the bluff below the lodge (Love et al. 1992).

Figure 7. IMASW Vs survey location (JLLVs-01) at Jackson Lake Lodge.

Signal Mountain Lodge

The Signal Mountain Lodge IMASW Vs site (SMLVs-01) was located approximately 25 m east-southeast of the primary lodge structure (Figure 8) over Jackson Lake moraine related drift deposits (Qg4j) (Love et al. 1992). The survey utilized a power line clearing within a wooded area adjacent to the parking lot.

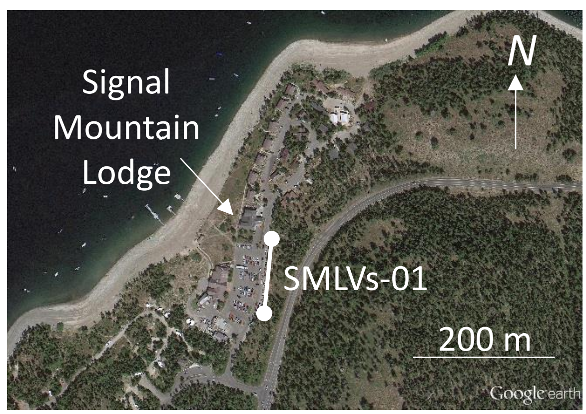

Figure 8. IMASW Vs survey location (SMLVs-01) at Signal Mountain Lodge.

Craig Thomas Discovery and Visitor Center (Moose Visitor Center)

The IMASW Vs site at the Moose Visitor Center (TVCVs-01) was located approximately 150 m north of the visitor center structure (Figure 9) in Snake River flood plain deposits (Qa) (Love et al. 1992).

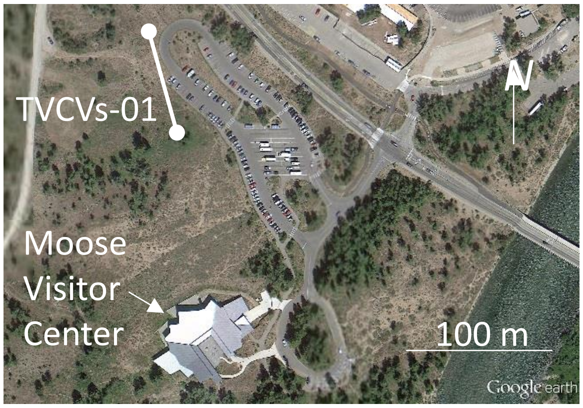

Figure 9. IMASW Vs survey location (TVCVs-01) at Moose Visitor Center.

✦ METHODS

Seismic data were collected using a DAQ Link-II seismograph with 24 10Hz geophone channels spanning 92 m and 10 Hz geophones at 4 m spacing. The energy source consisted of an aluminum strike plate and 12-lb dead-blow hammer. This highly portable system was packed into each site on foot.

Seismic data collection utilized refraction lines oriented orthogonal or near-orthogonal with local fault strike and spanning the fault scarp. IMASW Vs lines were collected on the hanging wall and oriented sub-parallel to local fault strike and intersecting the refraction lines. The refraction lines are intended to image the 2D cross section of the fault and offset geologic units, and the IMASW Vs lines are intended to constrain the fault depth on the hanging wall, and thus, fault dip.

At the Taggart Lake site, we collected a single refraction line (TL-01), extending across and perpendicular to the ~12 - 15 m high topographic scarp formed by the Teton fault. An extended survey line was precluded by marshy ground to the east of TL-01. Two IMASW Vs lines were positioned sub-parallel to the scarp on the hanging wall and intersecting the refraction line. IMASW lines TLVs-01 and TLVs-02 were 28 m and 44 m from the base of the scarp, respectively.

At the String Lake site, we collected two overlapping refraction lines along the axis of a gully slightly oblique to the fault scarp – line SL-01 was entirely on the footwall and line SL-02 was centered on the fault zone with a six-geophone (20m) overlap and extended down an alluvial fan at the mouth of the gully onto the hanging wall. One IMASW Vs line (SLVs-01), 38 m from the base of the scarp on the hanging wall, was oriented sub-parallel to local fault strike and perpendicular to refraction line SL-02.

Refraction data were processed using Rayfract software. IMASW Vs data were processed using Fugro Consultant's in-house IMASW processing software.

✦ RESULTS

Shallow 2D P-wave refraction profiles and IMASW Vs *vs.* Depth plots from both the Taggart Lake and String Lake sites imaged subsurface velocity structure that reveal down-to-the east vertical offset across the Teton fault and provide a basis for assessing the fault at depth. The subsurface is not constrained with borehole data at these locations, so interpretations are based on geologic and geomorphic context and correlation charts for relating Vp and Vs to material (Table 1).

Table 1. Correlated P-wave and S-wave velocities for material types. Modified from Bourbie et al. (1987).

Type of Material	P wave velocity (m/s)	S wave velocity(m/s)
Scree, Vegetal soil	300-700	100-300
Dry sands	400-1200	100-500
Wet sands	1500-2000	400-600
Granite	4500-6000	2500-3300
Gneiss	4400-5200	2700-3200

Taggart Lake

The single Taggart Lake 2D P-wave refraction profile spanned the Teton fault scarp and imaged both the hanging wall and footwall to depths of approximately 10 - 20 m (Figure 10). The refraction profile shows a layered velocity structure that vertically offsets the Vp 2000m/s iso-velocity surface ~13 m down-to-the east across the Teton fault. Each IMASW Vs *vs.* Depth plot (TLVs-01 and TLVs-02) (Figures 11a and 11b) shows a clear Vs increase from ~500 m/s to ~1000 m/s at ~5 m below the ground surface (bgs). TLVs-01 also shows a Vs increase to ~1500 m/s at ~70 m bgs and another increase to >2000 m/s at ~130 m bgs and TLVs-02 shows a Vs increase to ~1500 m/s at ~110 m bgs.

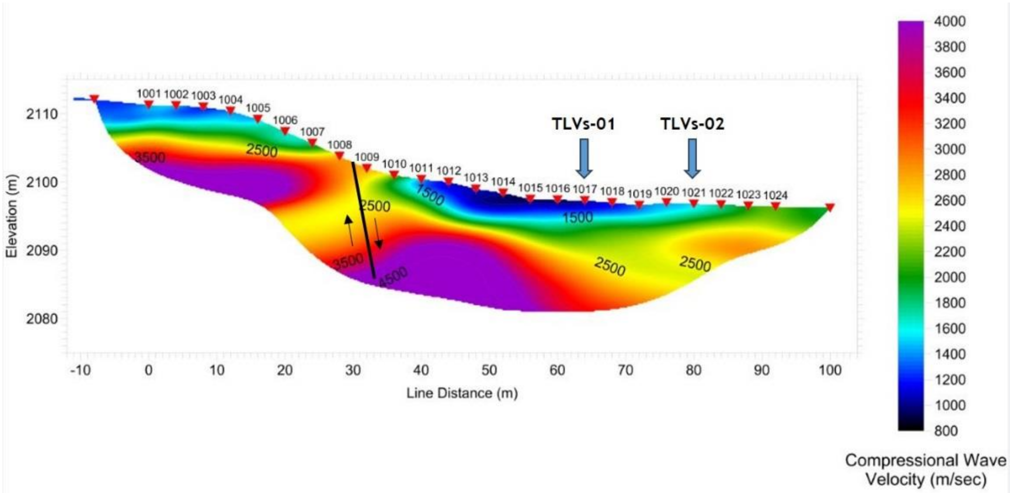

Figure 10. Taggart Lake 2D P-wave refraction profile (TL-01). The approximate location of the Teton fault is shown, and the black arrows indicate the relative vertical motion. Locations where IMASW Vs surveys TLVs-01 and TLVs-02 intersects the refraction survey are indicated.

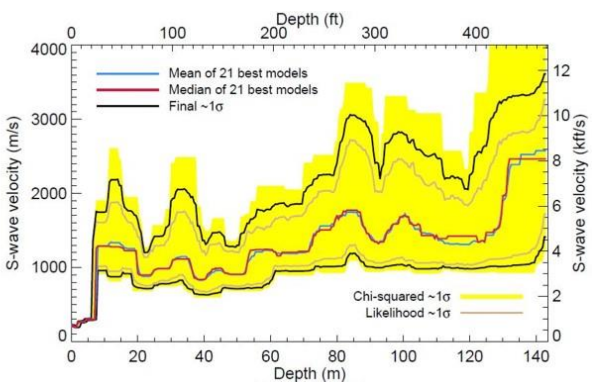

Figure 11a. IMASW Depth vs. Vs plot for TLVs-01

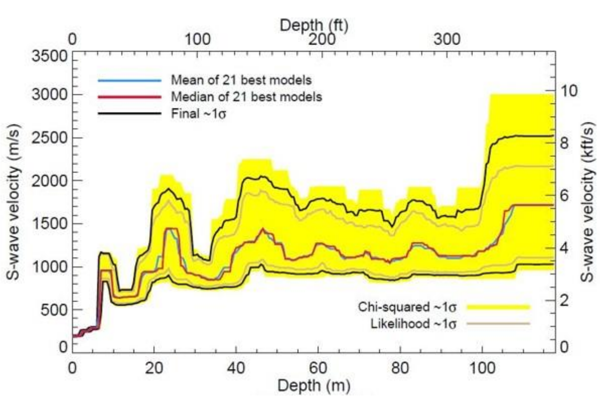

Figure 11b. IMASW Depth vs. Vs plot for TLVs-02

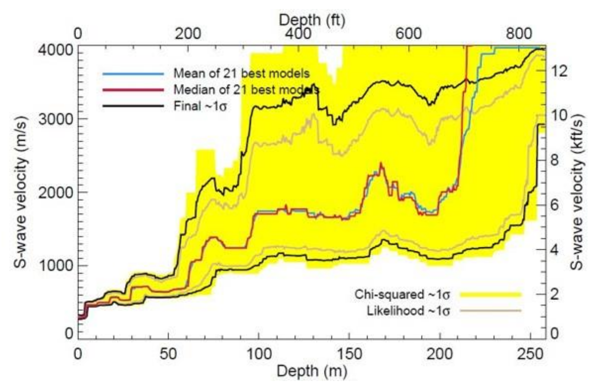

Figure 11c. IMASW Depth vs. Vs plot for SLVs-01

At Taggart Lake, we interpret the shallow, slow (Vp <1500 m/s / Vs ≤ 500 m/s) velocity zone to be unconsolidated post-glacial sediments overlying glacial till. The measured vertical offset of the velocity structure is approximately 13 m, which is very similar to the measured vertical height of the topographic scarp at this location, inferred by Thackray and Staley (in review) to have developed since deglaciation, ca. 14,000 years ago. The P-wave and IMASW Vs geophysical data were interpreted in context with the geomorphology and geology to develop a more detailed understanding of the fault structure at depth. Shown in Figure 12 are two topographic profiles (one of the faulted moraine between Taggart and Bradley Lakes and another of the Taggart Lake basin scarp at the survey site), simplified representations of the IMASW Vs surveys in a 1:1 scaled profile view, and preliminary structural interpretations.

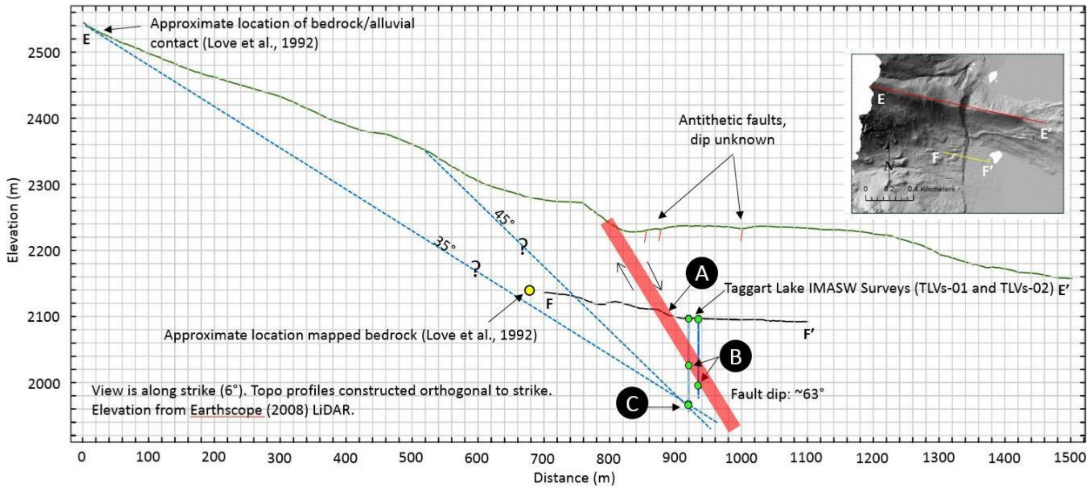

Figure 12. Structural schematic based on new seismic data collected as a part of this study, geomorphology from EarthScope (2008) LiDAR and geology as presented in Love et al. (1992). The green line is a topographic profile on the moraine marking the northern boundary of the Taggart Lake basin, while the black line is a topographic profile at the geophysical site in Taggart Lake basin. Teton fault (Note A) is projected through moraine scarp, valley floor scarp and IMASW Vs increases in TLVs-01 and TLVs-02 (Note B, See Figures 11a and 11b). Blue lines represent an approximate range of dips for bedrock/alluvial contact based on geologic map (Love et al. 1992), projection of nearby outcrops from LiDAR and Google Earth and velocity horizon in TLVs-01 (Note C, See Figure 11c).

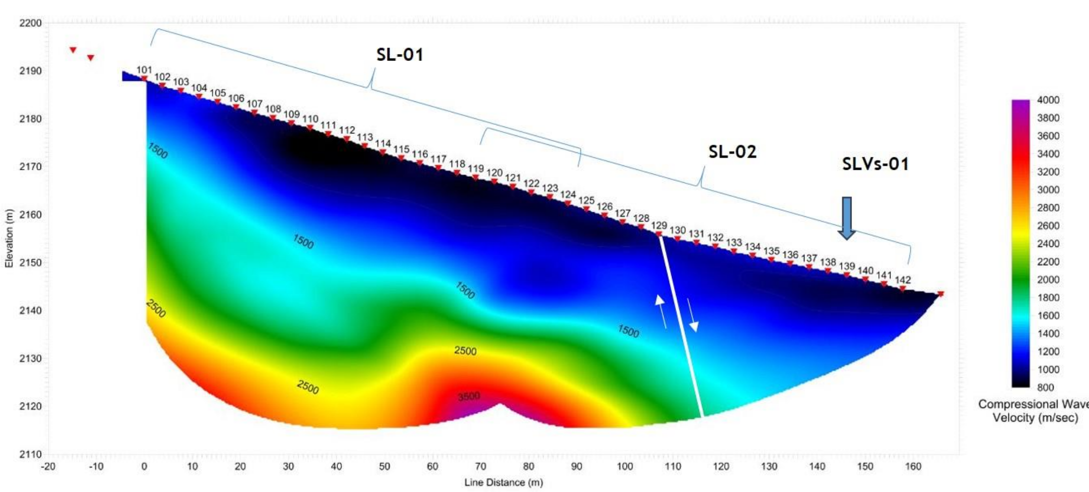

Figure 13. String Lake 2D P-wave refraction profile (SL-01 and SL-02). The approximate location of the Teton fault is shown, and the white arrows indicate the relative vertical motion. Locations where IMASW Vs survey SLVs-01 intersects the refraction survey is indicated.

String Lake

The two overlapping 2D P-wave refraction profiles collected at the String Lake site are displayed as a single 2D profile and imaged the hanging wall and footwall to depths of 20 to 60 m (Figure 13). The velocity structure of the refraction profile infers relatively deep (~40 m) deposits of unconsolidated sediment (till, colluvium, and alluvium) on both the hanging-wall and footwall, based on moderate to low P-wave velocities, and the overall geomorphic context observed in the Lidar imagery. The refraction data show a relatively low velocity zone (<1000 m/s) that is spatially coincident with the center of the gully and appears to be vertically offset 10 - 14 m across the Teton fault (Figure 13). Scarp heights adjacent to the gully to the north and south are ~35 m (Figure 4). This offset measurement is intriguing, given the site context. The 10 - 14 m subsurface offset is similar to post-glacial offset of 14,000 year old deglacial surfaces on the floors of the main valleys (e.g., our Taggart Lake site). However, this site has not been glaciated since ca. 130,000 years ago (Licciardi and Pierce 2008, Thackray and Staley, in review). The offset, dense sediments must therefore be a non-glacial deposit derived from the unglaciated gully itself. As glacial climates throughout the region tended to activate hillslope processes and fan aggradation, the subsurface sediment may be a bouldery fan deposit or debris flow deposit.

The Vs *vs*. Depth plot from the single IMASW Vs profile (SLVs-01) on the hanging wall side of the fault (Figure 11c) shows a Vs of 500 - 700 m/s to a depth of 60 m, a Vs increase to 1000 - 1200 m/s at 60 m and a Vs increases to >1500 m/s at 100 m.

Structural interpretations of this site are pending further analysis.

Park Facility Sites

Vs30 was calculated for each of the 3 Grand Teton National Park facility sites from the IMASW Vs survey data. The Vs30 values for each site are presented in Table 2. The Vs *vs*. Depth plots for each site are presented in Figures 14 a, b, and c.

Table 2. Calculated Vs30 values for park facility sites.

Site	Line ID	Vs30 (m/s)
Jackson Lake Lodge	JLLVs-01	574
Signal Mountain Lodge	SMLVs-01	560
Moose Visitor Center	TVCVs-01	413

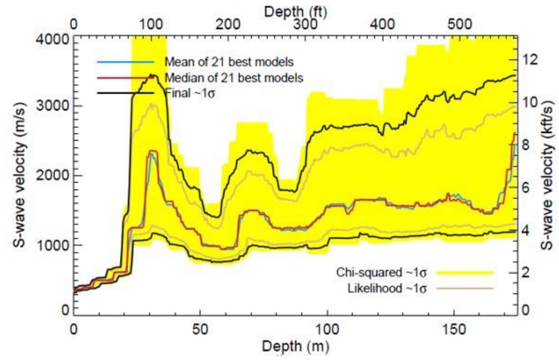

Figure 14a. IMASW Depth vs. Vs plot for JLLVs-01

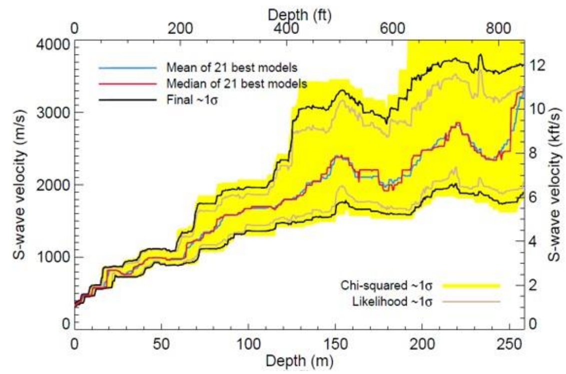

Figure 14b. IMASW Depth vs. Vs plot for SMLVs-01

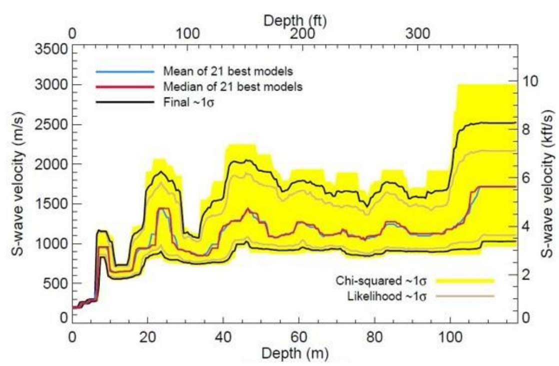

Figure 14c. IMASW Depth vs. Vs plot for TVCVs-01

✦ CONCLUSION

This project imaged the Teton fault in the shallow subsurface at two sites (Taggart Lake and String Lake) through P-wave refraction and IMASW shear-wave (Vs) survey techniques. At three other sites (Jackson Lake Lodge, Signal Mountain Lodge, and the Moose Visitor Center) 30 m depth-averaged shear wave velocities (Vs30) were determined through IMASW Vs surveys. Because the equipment is light and portable, these surveys were performed in remote locations with very minimal environmental impact.

The Taggart Lake site provides an ideal setting for structural analysis of the fault. The basin floor is relatively flat on both the hanging wall and footwall sides of the fault and provides a good setting for geophysical surveys. Slower post-glacial sediments overlie higher velocity glacial deposits to create a stratified velocity structure, which can be used for measuring vertical offsets caused by faulting. The fault has a relatively consistent northerly strike through the basin and bounding lateral moraines. The site is accessible via existing trails.

Preliminary analysis of the Taggart Lake seismic data suggests that the P-wave refraction and IMASW Vs data provide a basis for assessing the structure of the Teton fault at the Taggart Lake site. Figure 13 depicts a preliminary structural analysis based on the geophysical data collected in this study, site geology, and geomorphology. The schematic shows that the Teton fault plane, projected through the moraine crest scarp to the north of Taggart Lake and the Taggart basin fault scarp, is correlative with Vs increases (Figure 11a and 11b) in both of the Taggart Lake IMASW Vs surveys (TLVs-01 and TLVs-02). In addition, the Vs increase to ~2500 m/s in TLVs-01 (Figure 11a) could likely represent the bedrock/alluvial contact, as inferred from velocity and material correlations in Table 1 and geologic context.

The P-wave refraction profile shows vertically offset velocity structure (Figure 10). The measured offset (13 m) of dense subsurface sediment (inferred to be glacial till) is very similar to the surface fault scarp measurement of 12-15 m, indicating that the surface scarp height faithfully reflects total offset since deglaciation, and supports an average fault offset rate of 0.82 m/ka determined by Thackray and Staley (in review).

The Taggart Lake site also contains numerous alluvial surfaces on the uplifted footwall that are suggestive of uplift-driven creek incision. These features hold promise for independent determination of fault offset event frequency and magnitude, and deserve closer scrutiny.

At the String Lake site, the overall length of the seismic refraction survey line was not long enough to clearly image the hanging wall and Teton fault zone to greater depth. The single IMASW Vs survey shows velocities that correlate with crystalline bedrock, so it is plausible that we have imaged the bedrock/alluvial contact at this site. However, the fault geometry is more complex than at Taggart Lake. The fault trace geometry changes a short distance north of the data collection site, and antithetic faults are present that have an unknown impact at the geophysical survey site. Additional data collection is necessary to resolve the subsurface structure at this location.

These results are preliminary in nature, based on new shallow seismic data collected at two sites. These data require additional analysis and interpretation. Additional geophysical and geomorphological investigation will further constrain these results and further improve understanding of the specific characteristics of the Teton Fault, its seismic hazards, and its impact on the evolution of the Teton landscape.

✦ ACKNOWLEDGEMENTS

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