Annual Report Vol. 39 (2016)

Paleoseismic investigation of the Teton fault at Leigh Lake, Grand Teton National Park, Wyoming

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Abstract To improve knowledge of the Teton fault's ground-rupturing earthquake history, we excavated trenches across two fault scarps near the southwest shore of Leigh Lake. Detailed stratigraphic and sedimentologic analyses allow preliminary inferences regarding the fault history. The trenches exposed faulted glacial sediments and overlying hillslope colluvium sediments, documenting at least two fault ruptures since deglaciation of the range front at ∼15 ka. Samples are currently being analyzed using radiocarbon and luminescence dating techniques to determine the ages of the sediments and constrain the timing of fault rupture.

Introduction

This report documents our paleoseismic investigation of the Teton fault at Leigh Lake and presents preliminary findings of the study. This study was performed to improve knowledge of the large-magnitude, surface-rupturing earthquake history of the Teton fault to better understand the seismic hazard it presents to the surrounding region. A location map showing the Leigh Lake project site and the Teton fault is provided in Figure 1.

The Teton fault is the major seismogenic, range-bounding normal fault on the eastern flank of the Teton Range (Smith et al., 1993; O'Connell et al., 2003; Petersen et al., 2014). The fault dips east beneath Jackson Hole valley, has an estimated vertical slip rate of ∼0.2 – 2 mm/yr (White et al., 2009), and is included as a seismic source in the U.S. Geological Survey (USGS) National Seismic Hazard Maps (NSHMs) (Petersen et al., 2014). The fault is expressed by prominent scarps that offset glacial and deglacial surfaces near the base of the range. Thackray and Staley (2017) measured offsets of deglacial surfaces and sediments and used a ∼15 ka BP time of deglaciation (Licciardi and Pierce, 2008; Licciardi et al., 2015) to estimate an average postglacial slip rate of 0.9 mm/yr.

Several questions remain regarding the late Pleistocene and Holocene surface-faulting earthquake history of the Teton fault. This is in part due to the fault being located almost completely within the Grand Teton National Park boundary and generally in remote and rugged terrain. Prior to this study, the fault's earthquake history was based on results from a single paleoseismic trench at Granite Creek and liquefaction features observed in the northern part of Jackson Lake. At the Granite Creek site, Byrd (1995) interpreted two Holocene surface-faulting events: one at about 7.9 ka and a broadly constrained second event between about 7.0 and 4.8 ka. Pierce and Good (1992) documented two liquefaction features in the northern part of Jackson

Lake and estimated their ages at ∼4 ka and ∼1.6 ka. These features imply strong ground shaking caused by a nearby fault, but because they are only secondary (shaking-related) features, they cannot be uniquely tied to movement of the Teton fault.

The paleoseismic investigation at the Leigh Lake site was conducted to improve understanding of the earthquake history of the Teton fault. Our study was motivated by several questions:

1. Do fault displacement and slip rate vary spatially and (or) temporally?
2. What is the recurrence time between large earthquakes on the fault?
3. When did the most recent earthquake occur?
4. How much of the fault breaks in large earthquakes (that is, is the fault segmented)?
5. Why are faulted offsets of Leigh Lake glacial sediments so small compared to those of other scarps in deglacial surfaces of similar age?

To address these questions, we excavated two trenches across moderate (∼1–2.5-m high) fault scarps at Leigh Lake in the central portion of the fault.

Leigh Lake site

The study site is a low-relief, glaciated surface adjacent to Leigh Lake (Figure 2) at the outlet of Paintbrush Canyon. The site is located within moraines formed during the latest phase of the Pinedale glaciation (Pierce and Good, 1992). Geologic mapping suggests that surficial deposits at the site consist of late Pinedale-aged till (Love, 2003). The age of the surface has not been directly dated, but can be inferred to be 14.7±1.1 ka based on extensive dating of glacial sediment at nearby range-front valleys along the Teton Range (Licciardi and Pierce, 2008; Licciardi et al., 2015). In this report, we thus use 15 ka as an approximate age for the surface.

The deglacial surface at the Leigh Lake site is vertically displaced by three subparallel, north-south to north-northeast oriented fault scarps (Figure 2). These scarps are ∼1–2.5 m high, in contrast to the 10–13-m-high scarps that offset similar Pinedale-age surfaces at Taggart Lake, Bradley Lake, and Granite

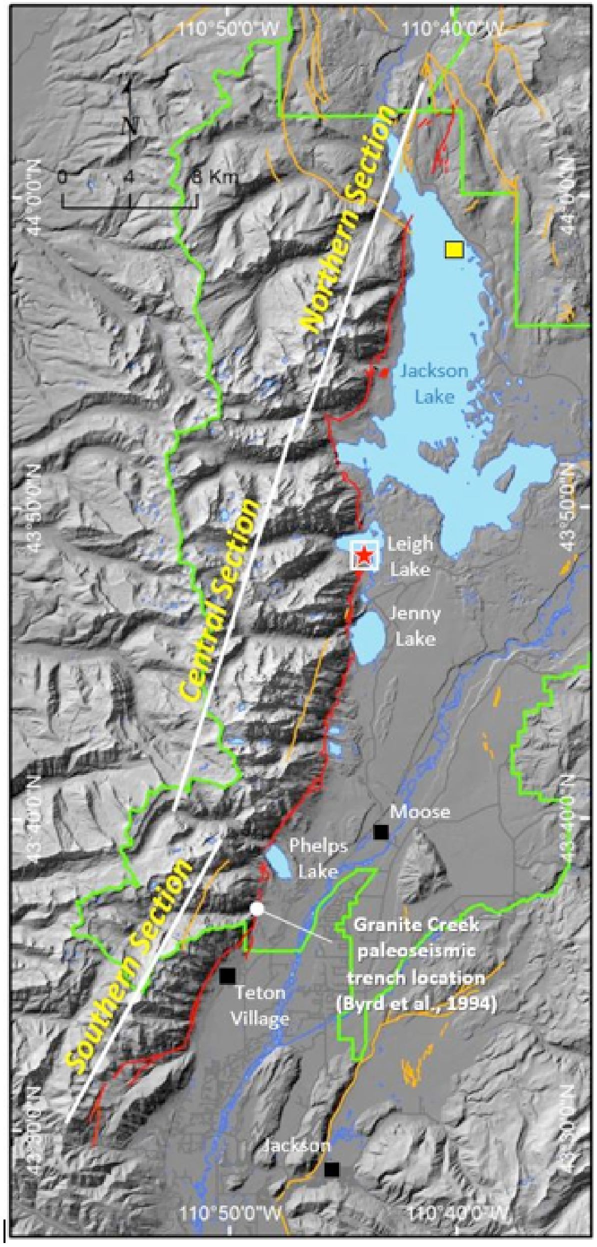

Figure 1. Location map showing the Leigh Lake project site (red star) and faults from U.S. Geological Survey (2016) (red = Teton fault and Phyllis Cyn fault [far south], orange = other faults). The Teton fault dips to the east. Approximate location of Pierce and Good (1992) paleoliquefaction features shown as yellow square. Location of Byrd et al. (1994) paleoseismic trench site and approximate fault section boundaries (yellow labels) from O'Connell et al. (2003) are shown. The Grand Teton National Park (GTNP) boundary is represented by the green line. Blue lines are major rivers and streams, and the location of Figure 2 is shown with a white box. Basemap from U.S. Geological Survey (2016).

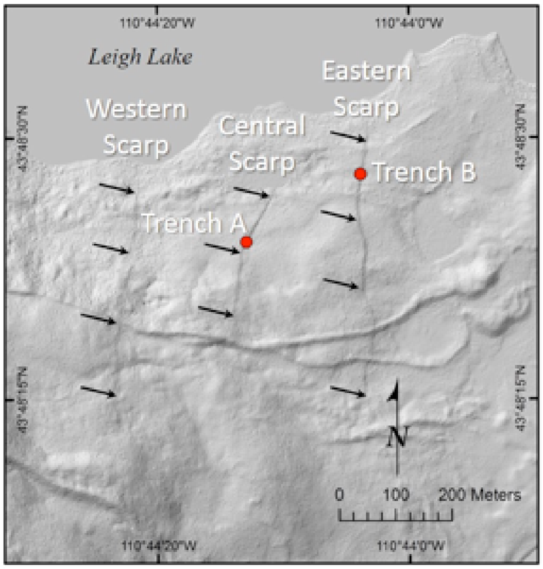

Figure 2. The Leigh Lake study site showing Teton fault scarps, including the untrenched western scarp. Red circles show the location of paleoseismic trenches. Black arrows show fault scarps. Elevation data (slopeshade map) from Grand Teton National Park lidar data. Basemap from GTNP, 2014.

Creek (Gilbert et al., 1983), and are even observed in apparently older Leigh Lake moraines as seen in the southern portion of Figure 2. It remains unclear why offsets are relatively small at the site compared to other offset surfaces of similar age along the fault.

We targeted the Leigh Lake fault scarps because several factors make this site ideal for performing a paleoseismic study and addressing our motivating research questions. First, the scarps are low (< 2.5 m high) and thus amenable to hand trenching. Conversely, the Teton fault scarp in many areas is typically 10–30 m high and thus very difficult to trench. Second, the scarps are located within the central segment of the Teton fault (Figure 1), a section which has not been subject to previous paleoseismic investigations. Third, geomorphic mapping strongly suggests that the Teton fault scarps extend into Leigh Lake (Zellman et al., 2016). Finally, this site provides a unique opportunity to directly compare paleoseismic trenching results against results from lake-bottom geophysical surveys and studies of lake sediment cores being planned by other park researchers.

Figure 3. Trench A, which exposed the Teton fault beneath the middle of three fault strands. View is to the west-southwest.

Methods

We excavated two trenches and a test pit across two of the three fault scarps at the Leigh Lake study site (Figure 2). These sites were selected where the scarp is well defined and less than ~2 m high and where natural gaps in trees and vegetation exist. Trench A (Figure 3) was excavated across the central scarp with an orientation of 100° and measured 22 m long, 80 cm wide, and 1–1.5 m deep. Trench B and the test pit (Figure 4) were excavated across the eastern scarp. Trench B was oriented 90° and measured 17 m long, 80 cm wide, and 1–1.25 m deep. The test pit measured 1 m long, 1 m wide, and 1 m deep and was located approximately 3 m north of trench B on the hanging wall side of the fault. We created orthophoto mosaics for the north and south walls of trenches A and B and the north wall of the test pit using Agisoft Photoscan software and following the methods of Reitman et al. (2015). We recorded primary stratigraphic units and structures exposed in the trenches on acetate sheets overlying the orthophotos (Figures 5 and 6).

Twenty-one samples were collected for sediment dating to establish estimated ages of stratigraphic units and surface-faulting events. Four optically stimulated luminescence (OSL) samples and seven radiocarbon samples were collected from trench A, and six OSL and four radiocarbon samples were collected from trench B. The orientation of the trenches and strike and dip of fractures and faults were measured with Brunton pocket transits calibrated to a declination of 11°35' E, and the "right hand rule" was applied to all attitude measurements.

Clast shape characteristics were recorded from selected units exposed in the trenches. Clast data include a, b, and c axis lengths and angularity (n1⁄450) collected and analyzed using the methods of Benn and Ballantyne (1993). The numbers of striated and faceted clasts were also counted, but owing to the coarse-grained lithology of many clasts, striations are typically not preserved. Clast lithologies were also recorded to determine the most likely sediment sources.

Figure 4. Trench B, which exposed the Teton fault beneath the easternmost of three fault strands. The black arrow points to the test pit to the right. View is to the west.

Preliminary Results

The Leigh Lake trenches exposed vertically offset glacial till and scarp-derived colluvial sedimentary units that we interpret as evidence of one to three late Pleistocene to Holocene surface-faulting earthquakes at the central section of the Teton fault. However, because of complex faulting (for example, instances of alternating sense of displacement) observed in trench B, a component of lateral motion cannot be ruled out. Here, we document the site stratigraphy and structure exposed in the trenches (Figures 5 and 6). Processing and analysis of 6 OSL and 7 radiocarbon samples is ongoing and final age analysis results are pending as of late March 2017.

Trench A Stratigraphy and Structure

Trench A exposed the Teton fault beneath the central scarp at the Leigh Lake site. The exposure consisted of glacial deposits and scarp-derived colluvium displaced by down-to-the east normal faults. A younger deposit of scarp colluvium caps the fault zone and is not displaced (Figure 5).

Trench A Stratigraphy

Unit SD—Subglacial diamicton. The oldest unit. Poorly sorted sand and gravel with green-tinted matrix. Rounded cobbles and boulders. Base of unit not exposed. Clast analysis indicates dominance of subangular and subrounded clasts of a dominant blocky shape. Of the clasts, 8 percent are striated and 8 percent are faceted. These results suggest direct glacial deposition as a subglacial till.

Unit GS—Late-stage glacial sediment (ablation till?). Poorly sorted sand and gravel with brown-sand matrix. Angular to rounded cobbles and boulders. Base of unit not exposed, but laterally, has an irregular, east-dipping contact with SD. Clast analysis indicates that this unit contains dominantly angular and subangular clasts with clast shapes being approximately evenly distributed among block, slab, and rod fields. No striated or faceted clasts were observed. The characteristics and setting of this unit suggest that it was derived from a glacial ablation till.

Unit C2—Lower colluvial wedge. Poorly sorted sand and fine gravel with cobbles and occasional boulders. Likely derived from unit SD. Maximum thickness of 40 cm adjacent to westernmost fault trace, tapering to zero over a lateral distance of 2.4 m. Clear basal contact unconformably overlies contact between units SD and GS. In the south wall, an ~10–15 cm thick, weak Bw soil has formed in the uppermost part of the unit.

Unit C2B—Weak soil (B horizon) formed in Unit C2.

Unit C1—Upper colluvial wedge. Poorly sorted sand and gravel with silt and boulders. Very coarse. Silt layers are ~5–15 cm thick, laterally discontinuous

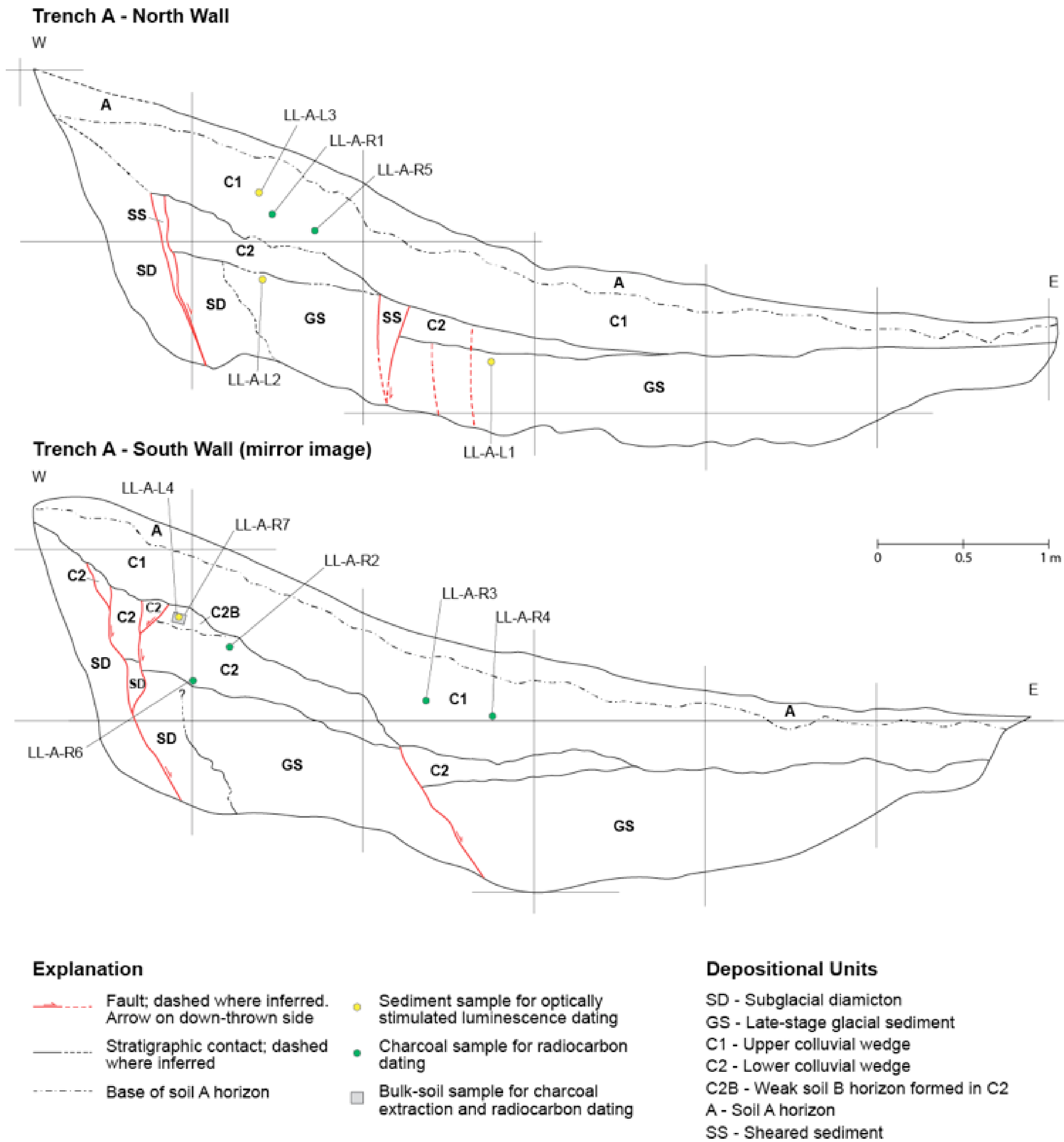

Figure 5. Stratigraphic and structural relations exposed in the north and south walls of Leigh Lake trench A. Grid lines are 1 m apart horizontally and vertically.

(continuous for ~10–40 cm), and include charcoal fragments. Clear basal contact unconformably overlies faulting in unit C1. Maximum thickness is 60 cm (north wall) to 70 cm (south wall).

Unit A—Modern soil (A horizon) formed in the uppermost 10–20 cm of unit C1. Poorly sorted silt and gravel with abundant organic material (e.g., roots and forest duff).

Unit SS—Sheared sediments. Material within faulted zone, derived from adjacent in-situ units. In some cases, unit SS contains more fines than adjacent units and is a concentrated zones of root growth.

Trench A Teton fault zone

In trench A, two zones of apparent down-to-the-east normal faulting were observed: a western zone and an eastern zone (Figure 5). The primary fault of the narrow western zone has a north-northeast strike, which is similar to the apparent strike of the faults in the broad eastern zone, and slightly oblique to the northeast trend of the central scarp at the trench site.

The westernmost fault zone is expressed on the north wall as a single zone up to ∼5 cm wide that is filled with silt and fine gravel and concentrated root growth. On the south wall, this fault zone is expressed as a single trace at the bottom of the trench that widens and branches into multiple traces higher in the trench. The faults dip ∼60° to ∼90° to the east and vertically offset units SD and C2. The fault is clearly expressed on both walls from the bottom of the trench up to the base of unit C1, the upper colluvial wedge.

The easternmost fault zone is near the center of the trench and expressed as a zone of thin, near-vertical faults that vertically offset unit SD and unit SC. On the north wall, this zone consists of multiple, steeply dipping faults (∼90°) over a zone ∼0.75 m wide, and on the south wall, offsets appear to have occurred on a single fault plane with a dip of ∼65° east. Clear expression of faulting terminates against the base of unit C1.

Faults in both the western and eastern zone offset unit C2, the lower colluvial wedge.

Trench B Stratigraphy and Structure

Trench B exposed the Teton fault beneath the eastern scarp at the Leigh Lake site. The exposure consisted of glacial deposits and colluvium displaced by a zone of steeply dipping faults with an overall down-to-the east sense of motion. A younger deposit of scarp colluvium caps the fault zone and is not displaced (Figure 6).

Trench B Stratigraphy

Unit SD—Subglacial diamicton. The oldest unit. Silty (fine to coarse) sand with gravel, cobbles, and boulders; clasts are angular to subrounded. Greenish gray matrix color. Largest clast is ∼1 m (minimum). Base of unit not exposed. Clast analysis indicates that this unit is very similar to unit SD in trench A (dominantly subangular and subrounded clasts of block shape, 8 percent striated clasts and 4 percent faceted clasts). It is also interpreted as a subglacial diamicton.

Unit SC—Slope Colluvium. Silty sand with cobbles and boulders; clasts are angular to rounded. Yellowish brown matrix color. Largest clast is ∼25 cm. Includes unit SC and fissure fill sourced from unit GS. In western part of exposure, unit is ∼20–50 cm thick and conformably overlies unit SD. In eastern part of exposure, unit SC thickens significantly to the east (to ≥90 cm, base of unit not exposed), forming an irregular east-dipping contact with unit SD. The clast analysis for this unit indicates that clasts are dominantly subangular with less angular and subrounded clasts of dominantly blocky shape. Striated and faceted clasts are both 2 percent of the total. These clast characteristics and the overall description suggest that this unit is colluvium derived from the subglacial diamicton.

Unit C—Colluvial wedge. Silty sand with cobbles and boulders, likely sourced from unit SC. Clear basal contact unconformably overlies fault-related deformation (fissures) in unit SC. The unit, not including capping silt (unit S), is ∼20–25 cm thick.

Unit S—Silt. Silt with cobbles; maximum clast size is ∼20 cm. Root penetrated and some mixing with underlying unit SC. Silt is about 10–15 cm thick but locally disturbed by bioturbation (including sediment-filled tree wells).

Unit A—Modern soil (A horizon). Poorly sorted silt and gravel with abundant organic material.

Unit D—Sediments disturbed by root mixing and (or) bioturbation.

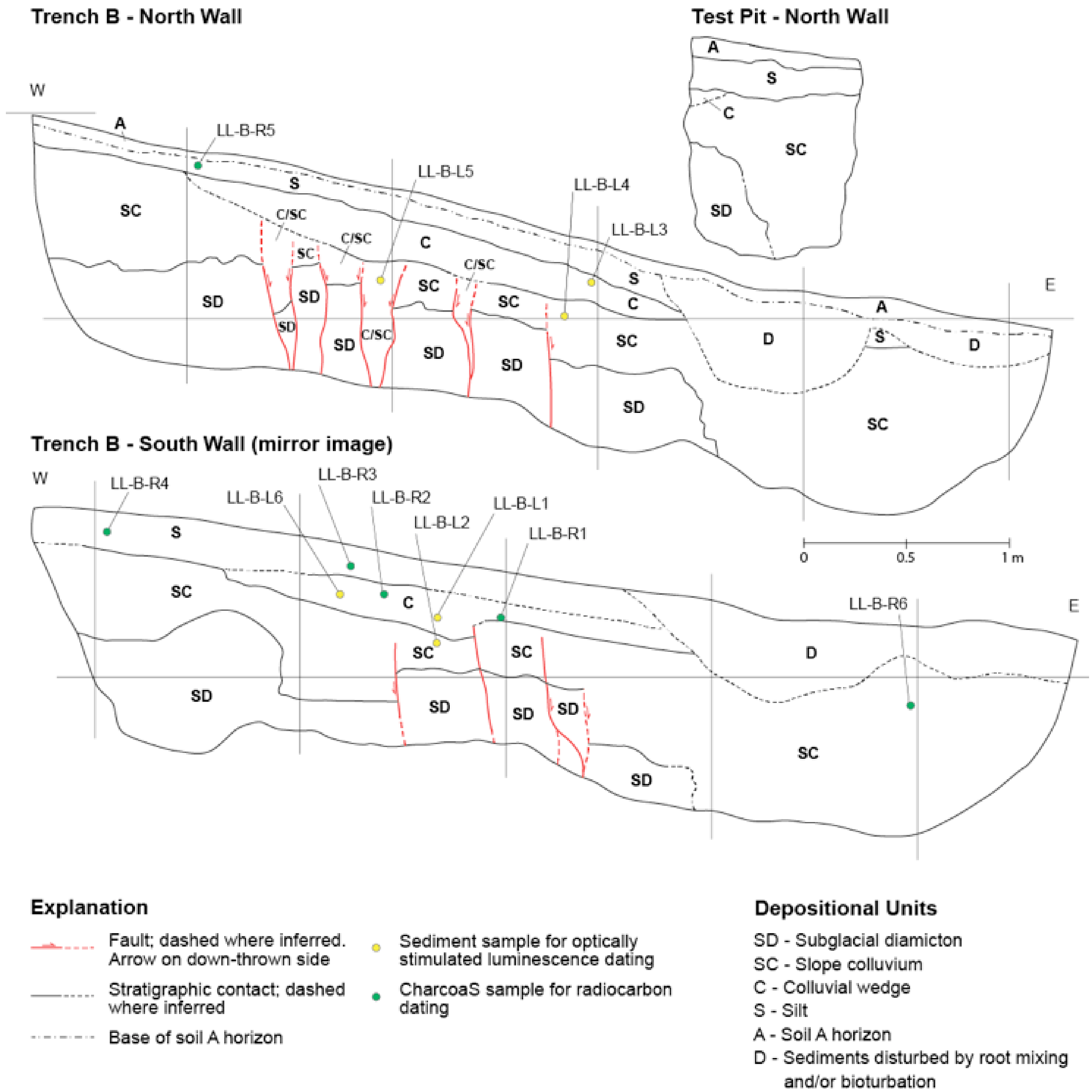

Figure 6. Stratigraphic and structural relations exposed in the north and south walls of Leigh Lake trench B. Grid lines are 1 m apart horizontally and vertically.

Trench B Teton fault zone

In trench B, a 2-m wide zone of complex distributed faulting was observed and documented near the center of the trench (Figure 6). The faults are steeply dipping (75°–90°), and are best expressed on the north wall where eight faults bound narrow grabens, which vertically offset the top of unit SD down-to-the east. On the south wall, the fault zone consists of only three faults, which vertically offset unit SD down-to-the-east but individually exhibit apparent opposing senses of vertical displacement (up and down). The faults clearly offset unit SD and terminate against the base of unit C. Individual faults could not be traced across the trench floor and correlated on opposite walls. The apparent strike of the fault zone is to the north, which is slightly oblique to the north-northeast trend of the scarp at the trench site.

Geochronology

We sampled soil, faulted sedimentary units, and colluvial wedges for radiocarbon and OSL dating. Analysis of the OSL samples is being completed by the USGS Luminescence Laboratory; Lawrence Livermore National Laboratory is analyzing the radiocarbon samples. Sample analysis is ongoing and results are pending as of March 2017. The results will constrain the ages of the fault offset and surface disturbance events.

Interpretation and Conclusions

Prominent, continuous fault scarps that vertically offset the Leigh Lake deglacial deposits provide evidence for late Pleistocene (∼15 ka) or younger displacement on the central section of the Teton fault. The Leigh Lake trenches exposed faulted glacial till and scarp-derived colluvial wedges, which we interpret as evidence of at least two surface-faulting earthquakes since 15 ka. Pending OSL and radiocarbon ages will help constrain individual earthquake times and allow for comparison to previously identified earthquakes at the Granite Creek site (Smith et al., 1993; Byrd, 1995). Complete results will be published after the final age analyses are complete.

Our Leigh Lake paleoseismic investigation supports two broad conclusions: (1) fault scarps at Leigh Lake are directly related to post-Pinedale surface-faulting earthquakes, and (2) there is clear evidence to support at least one post-Pinedale surface-faulting earthquake at Leigh Lake.

Acknowledgements

This research was funded by the University of Wyoming-National Park Service Research Station small grants program, Idaho State University, USGS, and Fugro Consultants, Inc. Steve Personius and Nadine Reitman of USGS, Darren Zellman and Cooper Brossy, and Nick Patton, Carl Jurkowski, and Alison Trcka of Idaho State University assisted with many aspects of this paleoseismic investigation. We also thank Kathy Mellander and Breelyn Van Fleet of the National Park Service for interest in this project and for assisting with National Park Service permitting. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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