A HIGH-RESOLUTION GEOPHYSICAL SURVEY OF JENNY LAKE: USING LAKE SEDIMENTS TO CONSTRUCT A CONTINUOUS RECORD OF TECTONIC ACTIVITY AND EARTHQUAKE-TRIGGERED DISTURBANCES AT GRAND TETON NATIONAL PARK

DARREN J. LARSEN ✦ OCCIDENTAL COLLEGE ✦ LOS ANGELES, CA
MARK B. ABBOTT ✦ UNIVERSITY OF PITTSBURGH ✦ PITTSBURGH, PA

✦ ABSTRACT

The Teton Range, WY contains a legacy of late Cenozoic uplift and periodic Quaternary glaciations. Well-preserved fault scarps along the Teton fault displace glacier deposits from the most recent (Pinedale) glaciation and provide evidence for high fault activity during the past ~15,000 years. Observations of these scarps and previous field investigations indicate that postglacial fault offset occurred through a series of major, scarp-forming earthquakes. However, the postglacial paleoseismic record of the Teton fault remains incomplete. The goal of this project is to use lake sediments, contained in lake basins positioned on the fault, to construct a history of the timing and frequency of past earthquakes at Grand Teton National Park, and assess seismic impacts on sediment erosion (e.g., landslides, debris flows, slope failures) and future hazard potential. Here, we report on multibeam sonar bathymetry and seismic reflection images from Jenny Lake, collected as part of an effort to identify glacial and tectonic landforms and to characterize infill stratigraphy. Our overarching objective is to combine these datasets with lake sediment cores from Jenny Lake and other nearby lakes to construct a continuous, accurately-dated record of past earthquakes and earthquake-generated slope failures in the Tetons.

✦ INTRODUCTION

The spectacular geomorphology of the Teton Mountain Range attracts over 4 million visitors to Grand Teton National Park (GTNP) each year and is attributed to a combination of active uplift along the Teton fault, a major range-bounding, eastward-dipping normal fault that extends for ~70 km along the base of the mountains, and periodic Quaternary glaciations (Figure 1; Love et al. 1992, 2003, Smith et al. 1993, Byrd et al. 1994, Byrd 1995). Total stratigraphic offset across the fault exceeds present topographic relief (~2 km) and is estimated to be 6-9 km since normal faulting initiated 5-13 Ma (Smith et al. 1993). More recent fault activity is evidenced by fault scarps displacing glacier features deposited at the end of the Pinedale glaciation ~15 ka (Figure 1). Surface offsets of these postglacial scarps vary from approximately 3 m to over 30 m, with the largest offsets found in the central part of the range (Smith et al. 1993, Machette et al. 2001, Thackray and Staley 2017). Scarp ages and cumulative offsets have been used to calculate average postglacial slip rates, with estimates ranging from 0.2 to 1.8 mm/a (Smith et al. 1993, Byrd et al. 1994, Machette et al. 2001, Thackray and Staley 2017).

The paleoseismic record of the Teton fault has been pieced together from a few sources but remains incomplete. Interpretations of paleoshorelines in Jackson Lake suggest postglacial faulting occurred in 8-10 discrete rupture events and data from a trench dug at the mouth of Granite Canyon indicate the two most recent events produced >4 m of displacement, and occurred at ~8.0 and ~5.5 ka, respectively (Byrd 1995, Pierce and Good 1992). Such scarp-forming events are considered to require major earthquakes of magnitude Ms = ~7 (Smith et al. 1993). Little else is known about the pattern and timing of fault movement through the late Pleistocene and Holocene time. However, the available empirical data suggest the majority of postglacial fault offset was accomplished between deglaciation and ~8 ka, and hints at a relationship between the timing of deglaciation and fault slip rate. Modeling simulations show that melting of the Yellowstone and Teton ice masses may have caused a postglacial slip rate increase (Hampel et al. 2007). However, the incomplete paleoseismic record and lack of earthquake data prior to 8 ka preclude the ability to test the model results.

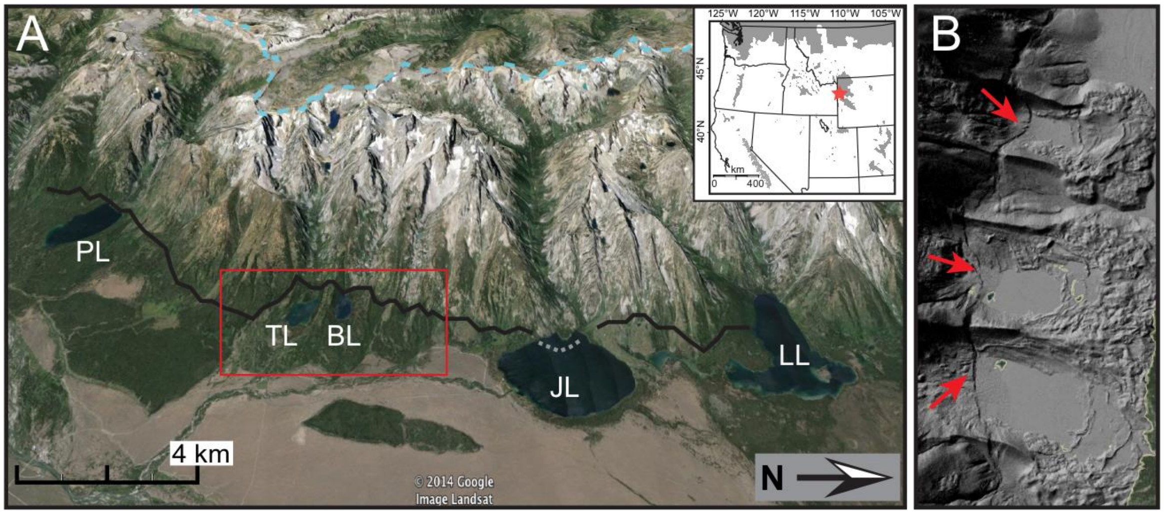

Figure 1. Geologic setting of the study region. (A) Oblique aerial view of eastern flank of the central Teton Range, GTNP. Note the series of glacially carved valleys and impounded piedmont lakes located at their base. The five piedmont lakes targeted in our broader study are identified: Phelps Lake (PL), Taggart Lake (TL), Bradley Lake (BL), Jenny Lake (JL), and Leigh Lake (LL). The position of the range-front Teton fault scarp is highlighted with a black line. Dashed blue line near the top of the frame marks the drainage divide. Inset map highlights the location of GTNP (red star) on map of western U.S. glaciers during Pinedale time (from Porter et al. 1983). A red rectangle delineates area enlarged in panel "B." (B) LiDAR hillshade of three terminal moraine complexes transected by the Teton Fault scarp (identified with red arrows). The large terminal moraines pictured here impound the lake basins and mark the greatest extent of these valley glaciers during the Pinedale glaciation.

While the impressive scenery of GTNP has benefitted from high tectonic activity in the past, future tectonic events pose serious threats to NPS infrastructure, human safety, and resource management (e.g., Smith et al. 1993). A continuous and well-dated paleoseismic record of the Teton fault is crucial for assessing seismic hazards and evaluating the influence of tectonic activity on sedimentary systems. The goal of this project is to provide a quantitative reconstruction of past earthquakes at GTNP (i.e., earthquake timing and frequency), including their impacts on sediment erosion and future hazard potential.

Over the past few years, we have employed a combination of seismic surveys, multibeam sonar bathymetric mapping, and multiple lake sediment cores from Jenny Lake and other nearby lakes, in an effort to study the combined tectonic and climatic history of the range. Our recent findings suggest that past earthquakes at GTNP triggered mass movement events in both lacustrine and subaerial hillslope environments. Sediments deposited in the piedmont lakes positioned along the fault trace (e.g., Jenny Lake) contain a continuous and well-dated archive of these slope failure events in the form of landslides, inflow delta failures, and subaqueous gravity flows (Larsen et al. 2017). These lakes also preserve a record of alpine glacier recession at the end of the Pinedale glaciation ~15 ka (Larsen et al. 2016). In this report, we present emerging findings from geophysical surveys of Jenny Lake that we performed to investigate glacial and tectonic landforms preserved in the lake and to characterize infill stratigraphy.

✦ Geological Setting

The Teton Mountain Range is a rectangular (~70 km long by ~20 km wide) fault-block mountain range that's flanked on both sides by broad, low-lying basins (Love et al. 2003). The eastern side of the range rises abruptly above the valley floor of Jackson Hole and forms the centerpiece of GTNP. A series of deep glacially carved, U-shaped valleys are cut into the mountain front (Figure 1). Each valley spans >1,000 m of elevation and transects multiple vegetation environments from high alpine tundra down to mixed conifer forests at the valley floor. Many of the valleys contain a chain of lakes composed of multiple small basins, positioned in high elevation glacial cirques, which drain into a large, moraine-dammed piedmont lake at the valley mouth (Figure 1). Lake basins at GTNP formed following regional deglaciation ~15 ka (Licciardi and Pierce 2008, Larsen et al. 2016). Sediment fill in each lake marks the timing of glacier retreat from individual basins (lake inception) and contains a continuous and datable record of subsequent upstream glacier activity and environmental conditions in the catchment. This study focuses on Jenny Lake at the mouth of Cascade Canyon (Figure 2).

Jenny Lake (43.76°N, 110.73°W; 2070 m asl) has an area of ~5 km^2, a maximum depth of ~73 m, and an average depth of ~43 m. Two main inflows to the lake are Cascade Creek, which drains Cascade Canyon, and a stream that emanates from String Lake, a moraine-dammed flowage that receives overflow from Leigh Lake to the north (Figure 2). The primary sediment source to Jenny Lake is via Cascade Creek. Sediment transported by this stream has created a small inflow delta at the mouth of Cascade Canyon along the western lakeshore. Similar to other piedmont lakes at GTNP, Jenny Lake occupies a terminal basin excavated by a major valley glacier during Pinedale times (e.g., Pierce and Good 1992). The relatively narrow terminal moraine complex encircling the lake has multiple closely nested ridges and likely contains outer segments that are buried by outwash (Licciardi and Pierce 2008; Figure 2). The height of the inner moraine crest above the lake surface varies along the lake perimeter from a maximum of ~200 m near the canyon mouth, an average of ~25 m along the eastern shore, and minimum of ~ 4m on the southern margin. Lidar imagery captures the Teton fault trace as it cuts across the moraine deposits and along the lake's western boundary (Figure 2)

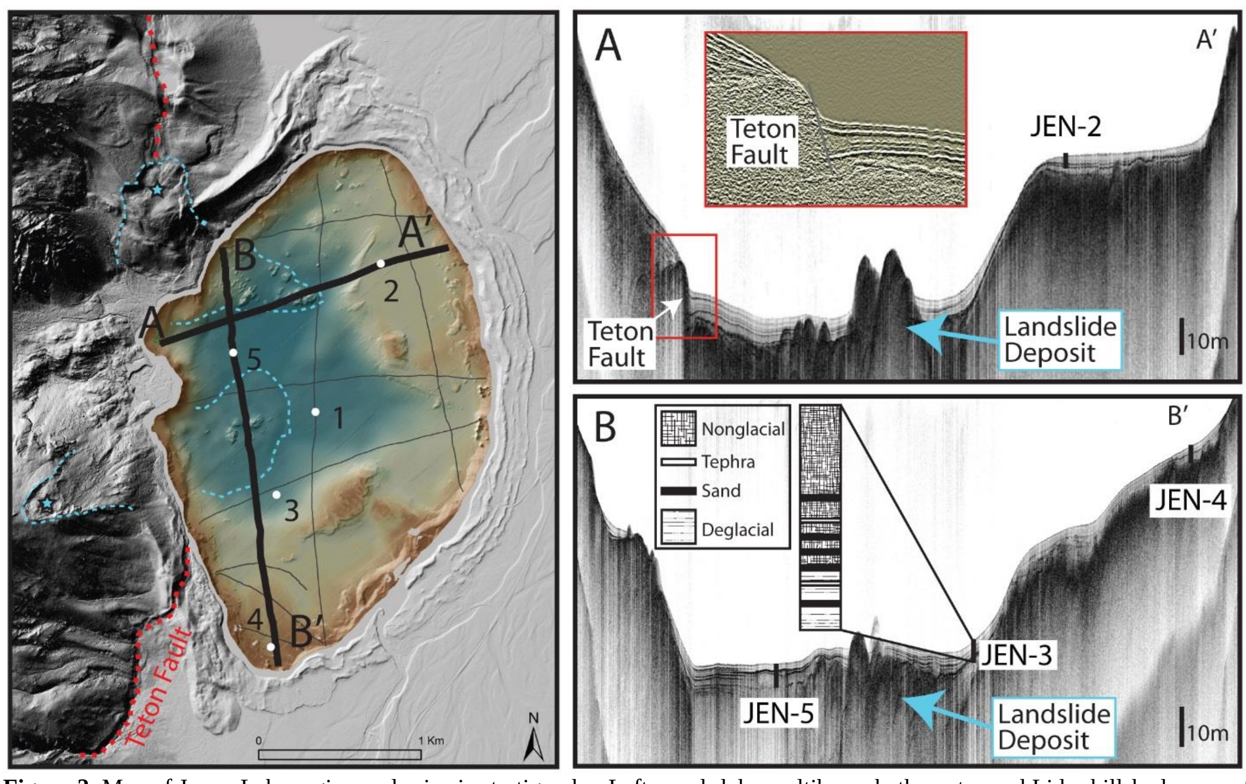

Figure 2. Map of Jenny Lake region and seismic stratigraphy. Left panel: lake multibeam bathymetry and Lidar hillshade map of Cascade Canyon mouth (note: Pinedale moraines impounding lake). Red dashed line highlights location of the Teton fault scarp, which can be traced across the western lakeshore. Blue stars and dashed lines mark the head scarps and runout paths of two major landslides identified in Lidar imagery and observed in lake bathymetry and seismic stratigraphy as block and fan deposits. Locations of sediment cores (numbered white circles) and seismic transects (black lines) are shown. Panels at right: Representative seismic profiles along east-west (A-A') and north-south (B-B') transects of Jenny Lake showing lake floor morphology, sub-bottom stratigraphy, and sediment distribution. Acoustic reflectors indicate regular undisturbed lacustrine sediment fill interrupted by the Teton fault trace and landslide deposits. The two landslide deposits and location of the submerged Teton fault scarp are identified.

✦ METHODS

We performed geophysical surveys at Jenny Lake to map the spatial distribution of lake sediment and lake bottom morphology at high resolution. Bathymetric data were obtained in summer 2015, using a SeaBat 8101 240 kHz multibeam sonar system operated from the research vessel Kingfisher (belonging to the Large Lakes Observatory, University of Minnesota, Duluth). Fieldwork was based out of the UW-NPS AMK research station. Following collection, the data were post-processed and compiled into a raster image file in ArcGIS. We obtained seismic reflection data using an EdgeTech sub-bottom profiler (CHIRP) towed from a boat along transects performed in a gridded manner covering the lake surface area (Figure 2). Each seismic transect was collected in conjunction with a differential GPS device to record spatial coordinates. Individual seismic profiles were processed and analyzed in Kingdom Seismic and Geological Interpretation software. Sediment thickness was estimated using the velocity of sound in freshwater (~1500 m). Over the course of three field seasons between 2013 and 2016, we collected sediment cores from multiple locations in Jenny Lake using percussion-style piston coring systems deployed from the frozen lake surface (e.g., Larsen et al. 2016).

✦ RESULTS

The bathymetry of Jenny Lake is complex and contains multiple sub-basins, but in general, consists of a central deep basin that is partially surrounded by a broad outer shelf (Figure 2). A ~500 m wide trough that emanates from the eastern side of the central basin splits the outer shelf in two. Trough features similar to this can be observed in the bathymetry of other piedmont lakes at GTNP (e.g., Taggart, Leigh) and suggest enhanced glacial erosion and/or meltwater discharge along the middle portion of the Pinedale glacier termini (Figure 2). Numerous small sediment piles can be observed around the shallow perimeter of the lake, most deposited within ~100 m of the moraine. We interpret these features to represent unstable backslope failures of the terminal moraine complex. Two large block and fan deposits are seen in the central basin. Both of these features are positioned below the head-scarps and run-out paths of major landslides visible on the hillsides above the Teton fault trace. We interpret these deposits to have been generated by two large, lake-terminating landslides. The multibeam data also capture the submerged fault trace cutting across the lake inflow delta (Figure 2). In this region the fault trace appears to be split into two or more, closely-spaced scarps.

The sediment fill has a stratified appearance and contains multiple strong seismic reflectors that can be traced around the lake's sub-basins (Figure 2). The strongest reflectors are present in the bottom portion of the sediment fill and are interpreted as dense, glacio-lacustrine deposits. Based on acoustic properties and in conjunction with lake sediment core stratigraphy, we identify three main seismostratigraphic units: 1) a basal till unit, 2) a minerogenic deglacial unit, and 3) an upper low-density, non-glacial unit (Larsen et al. 2016). The succession of these units broadly corresponds to the timing of glacial occupation of the lake, the subsequent deglaciation of Cascade Canyon, and the ensuing interval of non-glacial conditions during the Holocene (Larsen et al. 2016). Seismic profiles reveal high spatial variation in sediment thickness and character (Figure 2). Sediment thickness ranges from <2 m along the outer shelf to >8.0 m in the central deep basin. The two landslide deposits identified in the bathymetry register in the seismic profiles as acoustically opaque mounds that protrude above the lake floor and are partially draped with sediment (Figure 2). Also visible in the seismic imagery is the Teton fault trace, which runs under the western shoreline of Jenny Lake and offsets the lake sediments by about 10 m along the main scarp (Figure 2).

✦ DISCUSSION AND PERSPECTIVES

Multibeam bathymetry and seismic stratigraphy at Jenny Lake reflect a dynamic history of sediment deposition related to tectonic and glacial processes (Larsen et al. 2016). Integrating the geophysical data with stratigraphic information contained in lake sediment cores allows for a more complete understanding of the glacial and tectonic history at this site. All lake cores contain a two-part sequence of laminated glacial sediments overlain by a unit of low-density, non-glacial sediments. The timing of major stratigraphic transitions, dated with radiocarbon and tephrochronology, indicate Jenny Lake became deglaciated just prior to 14 ka and that up-valley glacial recession continued until Cascade Canyon was ice-free by 11.5 ka (Larsen et al. 2016).

Jenny Lake sediment cores also contain evidence for large disturbance events in the form of turbidite deposits. These deposits can be correlated between all core sites but are thicker and more prevalent in cores taken from the central deep basin. A total of nine thick (up to 23 cm thick) turbidite deposits have been identified in a composite core taken from site 1 (Figure 2; Larsen et al. 2017). The stratigraphy of each deposit begins with a sharp basal contact and is characterized by a sequence of sub-angular coarse sand that fines upward to fine silt and clay. We hypothesize that these deposits were generated by past seismic activity. Similar lake sedimentary deposits have been interpreted as earthquake-generated events in other seismically active areas, including in the Cascades (Leithold et al. 2017), Sierra Nevada (Maloney et al. 2013, Smith et al. 2013), Chilean Andes (Bertrand et al. 2008, Moernaut et al. 2017), and Swiss Alps (Kremer et al. 2017). Furthermore, many of the turbidite ages at Jenny Lake corresponds to the age of event deposits identified in cores from nearby Phelps, Taggart, and Bradley Lakes (Figure 1; Larsen et al. 2017), and to the timing of major fault rupture events identified in the Granite Creek trench (Smith et al. 1993).

Our results suggest that earthquake-generated deposits are archived in piedmont lake sediments and can be characterized and accurately dated with bathymetric data, seismic imagery, and lake cores. Based on this study, we have developed an interpretive model that relates earthquakes with lake turbidite deposits (e.g., Kremer et al. 2017). We contend that past ruptures of the Teton fault generated three different types of slope failures at Jenny Lake: landslides, subaqueous gravity flows, and inflow delta failures. In order to unambiguously correlate the slope-failure deposits to past earthquakes, this record must be replicated in other lake basins. Slope failures that occurred simultaneously in multiple lakes along the Teton range front suggest a common trigger and can most plausibly be explained by powerful earthquakes that affected broad sections of the Teton fault. Our ongoing work aims to replicate this study at other piedmont lakes at GTNP.

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